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Biochar for climate change mitigation: Tracing the *in-situ* priming effect on a forest site

Viktor J. Bruckman[a,b] *, Toru Terada[b], Basak B. Uzun[c], Esin Apaydın-Varol[c], Jay Liu[d]

[a] *Commission for Interdisciplinary Ecol. Studies, Austrian Academy of Sciences, Dr. Ignaz Seipel-Platz 2, 1010 Vienna, Austria*
[b] *Department of Natural Environmental Studies, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8563, Japan*
[c] *Department of Chemical Engineering, Anadolu University, Iki Eylul Campus, 26470 Eskişehir, Turkey*
[d] *Department of Chemical Engineering, Pukyong National University, 365 Sinseon-ro, Nam-gu, Busan 608-739, Republic of Korea*

Abstract

A significant amount of Carbon (C) on global soils consists of black carbon or charred organic matter. Biochar amendment in soils is therefore seen as a potential geoengineering method for climate change mitigation and adaptation. We tested the effects of biochar amendment (10 $t.ha^{-1}$) on soil respiration trace a potential priming effect until 15 months after amendment. Our results indicate that after a short period of initially weak positive priming, there was no significant difference between control and biochar plots during the entire project duration. From a carbon sequestration point of view, it can be concluded, that biochar amendment leads to higher stable C stocks in the organic horizon.

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Keywords: Biochar; carbon sequestration; priming effect; forestry; soil respiration.

* Corresponding author. Tel.: +43-1-51581-3200.
E-mail address: viktor.bruckman@oeaw.ac.at

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1. Introduction

Biochar amendment in agricultural soils is of interest for a growing research community in the soil system sciences and environmental domain. It is defined as organic matter, which was subject to thermal treatment under low or oxygen-free ambient conditions. The solid residual material, often referred to as "black carbon" [1], represents the transformed stock of carbon, that was present in the original biogenic feedstock.

The process of heating biogenic material under low-oxygen conditions is defined as pyrolysis, where several specific types exist. Fast and slow pyrolysis are the two most common systems and the choice upon a specific system is determined mainly according to the desired final products. Whereas slow pyrolysis produces considerable amounts of char and syngas (that can be used to maintain the pyrolysis-process), fast pyrolysis is suitable if bio-oil is the main product. A good overview of current pyrolysis technologies for non-specialists can be found in the recently published book "Biomass Power for the World" that was presented during the 23rd European Biomass Conference and Exhibition in Vienna [2] and in a more theoretical but holistic review [3].

In general, biochar and similar aromatic black carbons are more stable in the environment than any other form of organic carbon [4]. The reason for this is the transformation of carbon on molecular level towards unsaturated forms, such as aromatic rings and the progressive loss of H and O [5] as the volatile components are driven off. The most significant impact on the grade of transition, and therefore the final biochar properties, has the process peak temperature or highest treatment temperature (HTT), among others, such as pyrolysis type, reactor residence time, feedstock material, and pre-and post-treatment.

As a consequence of climate change, there are a number of mitigation efforts discussed. Such efforts can be summarized under the common term of "geoengineering", which aims at either reducing incoming solar radiation or removing carbon dioxide (CO_2) from the atmosphere to counter the greenhouse effect [6]. Biochar amendment to soils is one particular proposed method in the latter category as a consequence of the high carbon content (typically > 80%) and the above mentioned recalcitrance against decomposition, especially if a high aromatic composition is present [7]. In combination with its unique properties that significantly influence soil chemistry (e.g. pH, cation exchange capacity (CEC), nutrient levels and retention) physical properties (e.g. bulk density, porosity, water holding capacity (WHC)) and soil biota in a wider context (habitat for microbial and fungal communities, invertebrates, algae etc.), biochar may provide an important mitigation and adaptation potential [1, 8-11] However, certain trade-offs, as for instance soil enhancing properties versus C sequestration potential, need to be considered during the production process [12].

The aim of this study was to investigate soil respiration patterns after amendment of biochar in *in-situ* conditions, as this would determine if a significant priming effect can be observed. A positive priming effect would indicate elevated microbial activity and respiration and thus a decrease in soil organic carbon, originating from the amended biochar, intrinsic organic matter or both. On the contrary, a negative priming effect would indicate inhibition of microbial activity, likely triggered by sudden changes in soil chemistry and consequently an increase of total organic carbon stocks.

2. Materials and methods

The study site is located in Lower Austria close to the border to Czech Republic at 48°40' 49.7"N, 14°44'26.1"E, and 900 m a.s.l. The area receives a mean annual precipitation of 680 mm at an average temperature of 6.9°C. The lowest monthly mean temperature was observed in February (-2.4 °C), and the highest in July (16.6°C). Snow cover can be expected on 65.1 days per year in the months October to April.

The soil at the experimental plot location is classified as Dystric Cambisol according to WRB [13] on Eisgarn granite, which is characterized by its coarse grains and a high quartz content.

The forest management is dominated by conventional logging with rotation periods of around 100 years, however, the specific plot location is prone to windthrow events. The last event was in 2002, removing almost 100ha of spruce (*Picea abies*) dominated forest. Consequently, the major part of the plot consists of regeneration of up to 12 years, with some remaining individuals of the previous 110 years old pure spruce stand on the southern edge of the plot. The regeneration is dominated by spruce and some early successional broadleaved species, germinating on bare soil exposed by uprooting during the windthrow event.

10 t/ha of biochar from pure spruce woodchips (HHT: 550 °C, Pyreg process, pH 9.5, grain size up to 5 mm) was applied on 4 out of 9 subplots manually in early July 2013. Soil respiration was measured at 48 permanent sampling points (24 on biochar-amended plots and 24 on control plots respectively) after 1, 6, 14, 21, 37 and 47 weeks of amendment, using a LICOR LI-8100A Soil CO_2 flux system with an attached 10-cm survey chamber. Soil cores (18) were obtained immediately after biochar amendment, in order to assess the current stock of organic carbon to a depth of 20cm, and to confirm the amount of amended biochar. Vegetation on the study plot was mapped by using photos taken from an unmanned aerial vehicle (UAV; DJI Phantom V1.1.1) with an attached wide angle camera (GOPRO Hero 4).

Total carbon was analysed by means of dry combustion, following the procedure described in [14], however, it was assumed that total carbon = organic carbon (C).

Geostatistical methods were applied to produce spatial soil respiration models by using R, version 3.2.0 (201504-16) with the packages “GrapheR” and “RGeostat” [15].

3. Results and discussion

The mean pH value (H_2O) in all soil horizons was determined to be 4.39 ± 0.25. As a consequence of this result and the expected absence of carbonate material in the study region we skipped determination of soil inorganic carbon. C determination revealed no significant difference of C stocks of soil horizons (p-values of 0.19, 0.68, and 0.69 for soil horizons 0-5 cm, 5-10 cm, and 10-20 cm, respectively). This indicates a comparable baseline in terms of C stocks between the treatments. In addition, the organic horizon reveals a trend towards a higher C stock, but the difference was insignificant with a p-value of 0.07 and an overall standard deviation of the mean (sd) of ± 13.21 $Mg.ha.cm^{-1}$. The reason can be explained by the relatively small sample area of soil cores (38 cm^2 per core x 2 = 76 cm^2 per sample point) and the high deviation as a consequence of the heterogeneity of the forest floor and therefore carbon stocks, as well as the micro surface roughness and the resulting uneven distribution of biochar particles. However, the trend shows clearly the effect of biochar amendment versus the control plot as shown in Fig. 1.

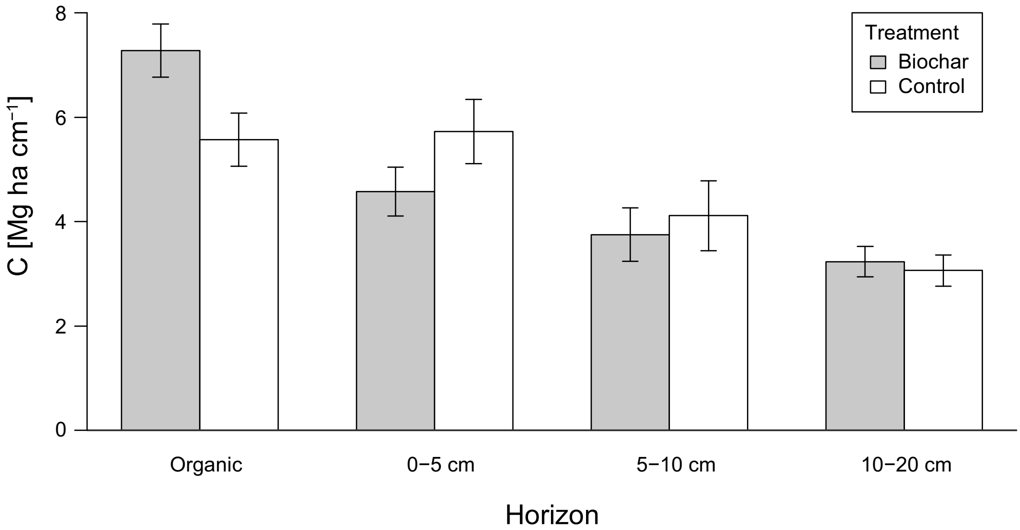

Fig.1. Total carbon (C) stocks per horizon and cm. The effect of biochar amendment on the surface can be observed from the significant higher C stocks in the organic horizon (litter layer). Error bars: ± 1 SE.

Soil respiration (R_S) consists of mainly two elements, namely autotrophic respiration (root respiration, R_A) and heterotrophic respiration (respiration by soil organisms, R_H) and the share between these components varies on the forest carbon balance and the photosynthate supply [16]. The authors further reported, that the fraction of root respiration on total soil respiration may range from 30-50% based on their model, which is a range consistent to other studies cited in this report. In general, increasing soil temperatures are positively correlated with R_H as soil microbes become more active [17, 18]. Fig. 2 indicates the relationship between the soil temperature and R_S measured *in situ*. While the mean temperature recorded on 12.10.2013 was 8.1 ± 0.4 °C, we observed 12.2 ± 1.1 °C on 26.05.2014. Therefore, we assume stable and unbiased results, despite the temperature effect on R_S, here especially those related with R_H.

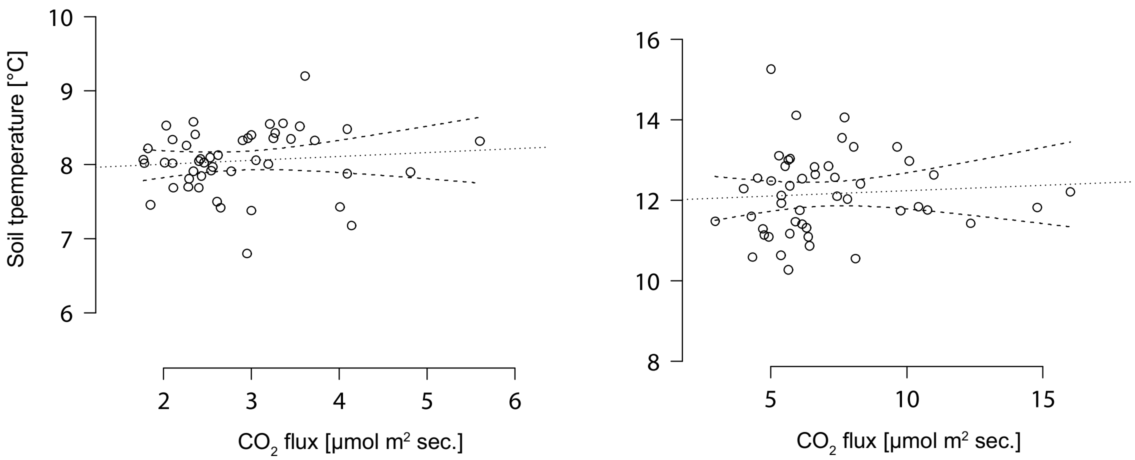

Fig. 2. Soil temperature versus CO_2 flux on 12.10.2013 (left) and 26.05.2014 (right). Dashed lines indicate the confidence interval.

R_S was recorded eight times within 15 months after amendment (Fig.3), but a significant positive priming effect (although weak) was only observed at the first observation, 2 weeks after biochar amendment ($p = 0.03$). The magnitude of further observations is mainly influenced by ambient temperature and thus microbial activity (R_H) and R_A, latter probably being the main cause for the larger variation during summer months. In addition soil moisture patterns that result from spatial vegetation water uptake may also play a significant role in the observed higher respiration variation in summer months. Observations on site during the measurements suggest that the O-horizon of biochar amended plots was wetter than on the control plots. However, this difference was not significant as revealed from soil moisture measurements in the mineral horizon. We assume that the improved water holding capacity might have an effect on soil respiration only after the biochar is incorporated into the mineral soil topsoil horizon. Subsequent respiration measurements indicate that the initially weak positive priming effect may reverse towards a negative priming effect, although the differences were insignificant ($p = 0.17 – 0.59$).

The trend, however, points at an effect that was previously described as “synergistic C sequestration” in which biochar stabilizes labile organic matter (OM) derived from compost [19], but is in contrast to a study that found forest humus losses triggered by fire-derived charcoal in boreal forests [20]. Priming can be generally positive or negative. For instance, priming directions and magnitude ranging from -52 to +89% were observed after one year in an experiment with different biochar-soil mixtures [21]. The authors further noted that biochar produced at higher temperatures (> 500°C) and where the feedstock is wood, typically showed a low C mineralization (negative priming). More specifically, the higher content of volatile organic compounds (VOC’s) in biochar produced at lower temperatures seems to benefit higher mineralization rates and hence a stronger positive priming effect [22].

Our results compared with the above mentioned findings in other studies suggest that we likely have the situation of a synergistic C sequestration on our biochar amended plots. However, we probably still not understand if this remains the case once biochar is moving downwards and enters the mineral topsoil horizon. Based on the results we assume that the negative priming effect might be even more pronounced in future. Therefore we will further investigate soil respiration and C pools on our *in-situ* plots.

Freshly produced biochar contains various amounts of C in different fractions according to its stability [4], resulting from feedstock properties and the pyrolysis conditions.

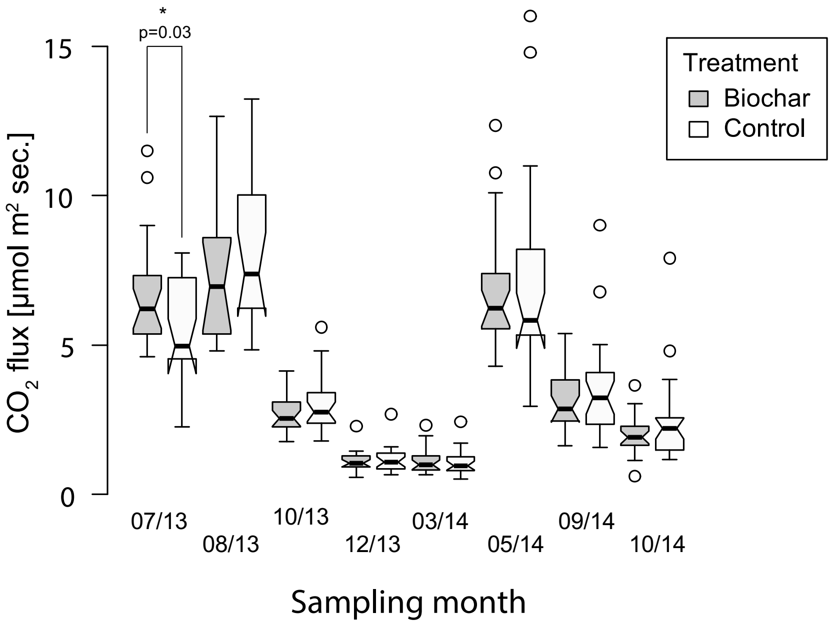

Fig. 3. Total soil respiration (R_S) observations until 15 months after biochar amendment on the forest soil surface (10 Mg ha^{-1}). No significant difference was observed despite immediately (2 weeks) after amendment.

The initial weak positive priming can be explained by a small labile fraction of the fresh biochar that was rapidly utilized by soil microorganisms as described in a report that determined priming potentials [23].

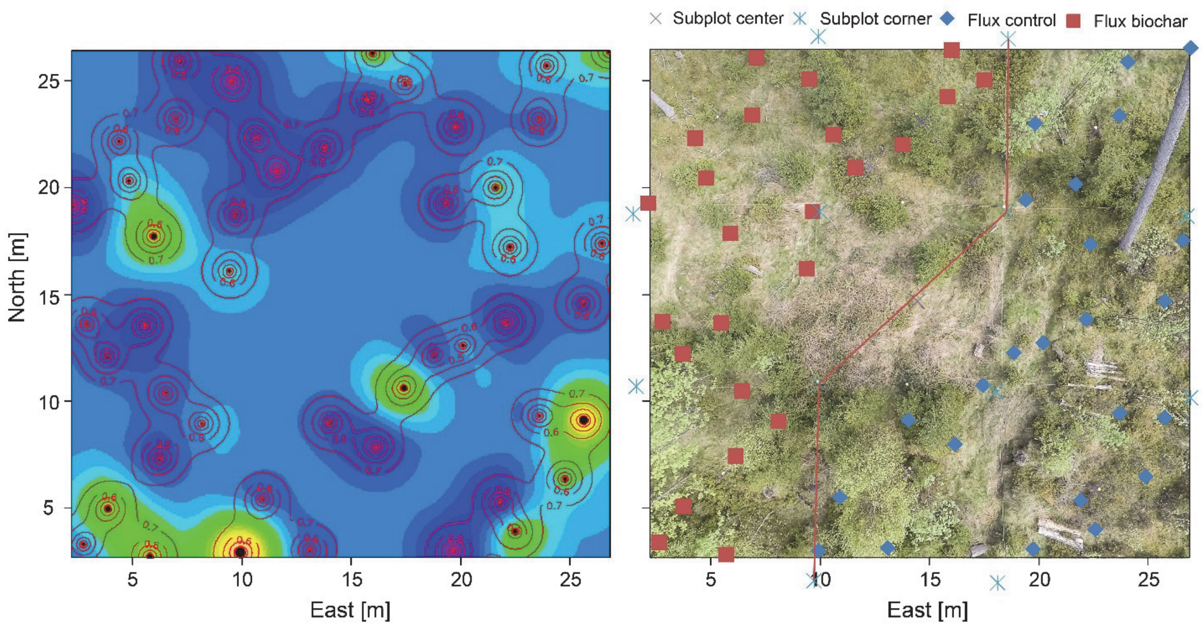

Fig. 4. Spatial soil respiration model based on respiration data from 12.10.2013 (see Fig. 2.) and associated standard deviations of the estimated fluxes (left) and an aerial photograph indicating sample point locations of biochar and control subplots (right).

Spatial analysis of respiration patterns (Fig. 4.) suggests a high influence of R_A over R_H, especially in summer months, therefore leading to complex patterns. In general, higher respiration rates were observed in the lower part of the plot, corresponding with higher vegetation density and tree height, as well as more dense vegetation of *Vaccinium myrtillus*. On the contrary, locations in open spaces dominated by grass and moss (*Deschampsia flexuosa* and *Pleurotium schreberii*) tended to show lower mineralization rates, especially on biochar amended sites.

4. Conclusion

Our findings suggest that from a C sequestration perspective, biochar amendment on forest floors in acidic spruce ecosystems can lead to an increase of surface carbon stocks. A weak initial positive priming effect was caused likely by microbial utilization of a small labile fraction of the amended char. After about one month, the effect vanished and the subsequent measurements until 15 months after application showed that the mineralization rates remain comparable to the control plots, with a tendency (not significant) towards slightly negative priming.

Spatial analysis showed a complex and variable respiration pattern that is masked by R_A, especially in the vegetation period. The influence of vegetation was clearly higher than the effects of biochar amendment. There are no substantial losses of C from biochar or SOM during the first 15 months.

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