Risk assessment for the application of biochar and hydrochar in temperate soils – a way to stable C-sequestration

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The basic idea of using biochar or hydrochar (biomass carbonization products) in soils is to create terrestrial carbon dioxide removal (tCDR), i.e. a shift of C (CO_2) from the atmosphere to terrestrial C pools via photosynthesis combined with carbonization techniques (conversion of biomass C into a more recalcitrant form). The production of biomass carbonizates or chars can take place by pyrolysis of mostly dry biomass (biochar), or hydrothermal carbonization of mostly wet biomass (the reaction medium is either steam (vapochar) or water (hydrochar). [Using "hydrochar" as a substance class term will, in the following, include the steam-carbonized vapochar variety, which is a technological variation of the same process (hydrothermal carbonization).] Using biochars or hydrochars in soils aims at delivering tCDR with positive effects for soil fertility and the environment, such as using the surplus thermal energy of the production process for substituting fossil fuels (heat or electricity generation), and at nutrient recycling from biomass waste streams. In particular the char products are intended for increasing the soil fertility in degraded, poor acidic soils and the reduction of greenhouse gas (GHG) emissions from agriculture. Biochar research roots in research on the man-made (anthropogenic) Amazon Dark Earths in the Amazon basin (also known as "Terra preta", Portuguese for "black earth"). The 450 to 2000 years old ADE soils contain significant proportions of charcoal (biochar) and they have higher humus and nutrient contents, and pH values compared to the surrounding, highly weathered oxisols.

When our project started, hardly anything was known on the benefits or risks of using chars in temperate soils. Thus, the aims of the project were to evaluate potential risks such as increased GHG emissions, toxic contaminations (ecotoxicity) and to evaluate the persistence of the chars in comparison to their uncarbonized feedstocks.

The work packages consisted of short-, intermediate- and long-term experiments and studies. Initially we investigated the effects of a range of different chars on plant germination and -growth and on earthworm avoidance (Chapter 3). We modified four different ecotoxicity test procedures following ISO guidelines or guidelines for compost quality testing to enable char evaluation. The procedures were tested for reproducibility before they were used to test 15 different biochars, hydrochars or a vapochar for their effects. Biochar never had negative effects, as long as it was "clean" in analytical terms. Rather, biochar often had positive effects, e.g. increasing seedling biomass or attracting earthworms to the biochar side of the test vessel. One PAH-contaminated wood gasifier biochar was reliably identified by the biotests. However, all vapo- and hydrochars had negative effects on germination and growth of plants or earthworm behaviour with the animals avoiding the hydrochar side. Interestingly, all analytical tests (PAH, Dioxins, heavy metals) failed to indentify the substances in the hydrochars responsible for the negative effects, underlining the importance of the biotox test procedures.

For the laboratory studies (intermediate duration, Chapter 4) and the field study (long-term, Chapter 5), we used the same feedstock (*Miscanthus x giganteus* or China grass, a vigorous growing bioenergy plant) as well as hydrochar and biochar produced from this feedstock. *Miscanthus*, as a C4 metabolism plant, has a distinct ^{13}C isotopic signature, which enabled tracing the fate of the applied carbon in the grassland soil which only consists of C3 plants. The longest of the lab incubation studies (13 months, Chapter 4.4) used the *Miscanthus* feedstock, a weakly carbonized vapochar, a strongly carbonized hydrochar and a biochar, mixed into two different soils (sandy and loamy), i.e. the study investigated a "carbonization-strength gradient". We created alternating soil conditions designed to accelerate decomposition. The cumulative CO_2 emissions (as a measure for C stability) and the N_2O emissions increased in the following order: biochar ≤ soil-only control < hydrochar < vapochar << feedstock. The cumulative CO_2- and N_2O emissions correlated positively with each other, and with the chemical properties of the C additives that were used, e.g. the aromaticity content or the H/C to O/C ratio. However, only biochar was able to reduce the N_2O emissions compared not only to the feedstock (which enhanced N_2O emissions) but also to the control (soil without C additive). Compared to the feedstock treatment, the N_2O emissions with biochar were always significantly reduced. All C additives increased the methane consumption in the soils.

A plant growth pot experiment was conducted with soil-C-substrate mixtures (i.e. feedstock and both chars and a mixture hydrochar with biochar) after lab incubation with swine manure. Ryegras (*Lolium perenne*) growth was significantly increased by 29% with biochar, likely due to improved N (nitrate) retention. The ryegrass growth was also increased with the vapochar, in contrast to the negative effects observed in the biotox tests, but to a lesser extent than with biochar. Further experiments (all C substrates were applied to the soil surface) showed that the alkaline biochar can increase ammonia emissions, however, NH_3 emissions were highest with the feedstock and lowest with the (acidic) hydrochar soil applications.

When the C substrates were applied in the grassland field experiment (Chapter 5; experimental start April 2011; still ongoing) the harvested biomass did hardly respond. However, with the vapochar addition, we observed a significant yield reduction in the first two years 2011 and 2012 but not after that time, while the biochar treatment tended to (non-significantly) increase the harvested biomass in 2015. With biochar, a significant shift towards a larger percentage of forbs at the expense of grasses was observed. The proportion of legumes was typically low in all treatments (in this grassland community) and the quality of the nutrient contents of the yield did not change (analyses for 2012 and 2013). The average ecosystem respiration (CO_2 efflux of the plant-soil system in the dark) revealed a slight but non-significant reduction compared to the other treatments; the same biochar effect was detected in the soil respiration. The treatments with feedstock and vapochar, however, showed increased soil respiration rates because the substances were easier to degrade, as seen in the lab experiments. After field application, from the second summer on, the treatment "feedstock" had significantly higher N_2O emissions; cumulated up to end of 2013, this led to a doubling of the N_2O emissions compared to those observed in the unamended control. The same has not been observed for the char applications where N_2O emissions equalled the control. Biochar caused a noticeable but (due to the high spatial variability) non-significant *reduction* of the N_2O emissions during a freeze-thaw cycle in winter 2011/2012. The C additives did not change the CH_4 uptake (due to microbial methane oxidation) in the grassland. The C decomposition and effects on GHG emissions emerged retarded compared to those observed in the the lab studies. In the lab studies, the C-additives had been mixed into the soil and not been applied onto the surfaces. In the field study, they invaded the mineral soil horizon slowly over time through a thick layer of plant roots. Moreover, temperatures were on average higher in the lab studies. Aggregate fractionation (wet sieving) before the experimental start in spring 2011 and afterwards in spring 2012 and spring 2013 did not reveal negative effects of the C additions on soil aggregation or aggregate stability; aggregate-protected soil C remained protected. After two years, the ^{13}C isotopic signature of the applied C additives was visible down to 30 cm depth; the effect was most pronounced with the vapochar (most likely due to high amounts of soluble labile C). Interestingly, 2.6 years after the experimental start, the microbial biomass of the soil was increased by 56%, particularly that of the soil fungi (substrate induced respiration method).

In summary, biochar in soils was the more promising C additive for C sequestration and reduction of N_2O emissions when compared to hydrochar or feedstock and it had neutral to positive effects on plant growth (e.g. greenhouse pot experiment). The hydrochars, however, did not reduce N_2O emissions when used in soils and were considerably less persistent (degrading quickly), even when strongly carbonized (high temperature, high pressure). Hydrochars had negative, toxic effects on plant germination and growth, as well as on earthworm behaviour. The biotox tests identified the problem but analytics did not identify the chemical substances responsible for the detrimental hydrochar effects. Hence, we do not recommend the use of freshly produced hydrochar in soils.

At the end of the report, we summarize our results (Chapter 6.1 to 6.3), give an overview regarding the current pathways of biochar use in agriculture (Chapter 6.4), and we propose (economically) meaningful research and development strategies for biochar use (Chapters 6.3 and 6.4) to enable its use along its potential for serving as a tCDR strategy.

With the table below, we summarize the effects of adding C substrates (feedstock and chars) to different soils in lab and field studies regarding GHG emissions and give our assessment of their suitability for C sequestration.

Study	**Applied material**	**CO_2 emissions**	**CH_4 consumption**	**N_2O emissions**	**Suitability for C sequestration**
Lab	feedstock				no
	vapochar				no
	hydrochar				only short-term
	biochar				yes
Field	feedstock				no
	vapochar				no
	biochar				yes

colour coding / legend:

	as control/no change
	neutral to slightly improved (CO_2 / N_2O emissions reduced, CH_4 uptake increased)
	improved
	neutral to slightly worsened (CO_2 & N_2O emissions increased, CH_4 uptake reduced)
	worse

The table above enables a quick, qualitative overview regarding the results of the two lab studies and the field experiment carried out within this project. Significant reductions of the GHG emissions (or significant increases of the CH_4 consumption) are shown in green, trends or tendencies or short periods of improvement are shown in yellow-green. No changes compared to the control are given in yellow while increased emissions are shown in red (temporary increases or tendencies for increases are depicted in orange).

The summary clearly shows that biochar had the more desirable effects on GHG fluxes, in both, the field experiment and the lab studies.