Final Report

Title of the project:

Biochar in Agriculture – Perspectives for Germany and Malaysia

Leibniz-Institute: Leibniz Institute for Agricultural Engineering Potsdam-Bornim

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1 Executive summary

The project "Biochar in Agriculture – Perspectives for Germany and Malaysia" was aimed to build a biochar network to provide a better understanding of economic and environmental potentials of biochar by analyzing its impact on plants, soil, environment, and economy in the temperate zone and in the tropics, considering the examples of Brandenburg (Germany) and Selangor (Malaysia). This holistic challenge was analyzed in an interdisciplinary and international consortium led by the Leibniz-Institute for Agricultural Engineering Potsdam-Bornim e.V. (ATB) in cooperation with the Leibniz Centre for Agricultural Landscape Research (ZALF), the German Institute for Economic Research (DIW), the Technische Universität Berlin (TU-Berlin), the Humboldt-Universität zu Berlin (HU-Berlin) and the University of Putra Malaysia (UPM). Analyses covered the impact of different biochars from pyrolysis and hydrothermal carbonization (HTC) technology, digestate and fertilizer add-ons on soil fertility in terms of yield potential, nutrient dynamics and soil biology in laboratory and field experiments (Germany and Malaysia).

Results showed that biochars used in Germany in field and pot experiments had no statistically significant effects on crop and plant biomass. However, grain quality and nutrition contents were affected by biochars. An interesting interaction effect of pyrolyzed wood biochar and N fertilizer levels on N uptake of oil radish was found in the field experiment. More precisely, in biochar treatments without fertilization a higher N uptake, higher soil ammonium content and elevated cumulative CO_2 emissions was detected in the presence of biochar. At 195 kg N ha^{-1} (over-fertilization) lower N uptake and lower cumulative N_2O emissions were found which highlight that biochar can have a greenhouse gas mitigation effect at high levels of N supply and may stimulate nutrient uptake at low levels of N supply. Besides, pot experiments showed particularly positive effects on root development and shoot growth of biochar. Soil microbial biomass and basal respiration were highly variable, due to unexpectedly high spatial variability and trends of soil properties across the field site. Further results suggest that biochar may increase earthworm populations in nutrient-poor soils. Lab experiments indicated an increased stability of organic substrates in soil by biochars. HTC-char induced higher respiration in soil compared to Pyro-char.

In pot experiments in Malaysia, oil palm empty fruit bunch biochar (EFBB) significantly reduced cumulative leachate volume by 29-52% when compared to the control. The EFBB was shown to be effective in reducing N leaching and improve N fertilizer recovery at an application rate up to 10 Mg ha^{-1}. Lower leachate volume and leached mineral N seems to indicate higher retention in the soil with EFBB, attributing to improvement of N fertilizer recovery in the plant. Pots treated with EFBB significantly increase maize dry matter weight up to 72%. And also in a field experiment results showed that addition of EFBB significantly increased dry matter weight and yield up to 46% and 74% respectively, compared to plots without biochar. The crop uptake of N and K were significantly improved by 38% and 65%, respectively. For soil properties, EFBB increased soil pH, extractable P (up to 34%), and exchangeable K (64%), but no significant difference for other elements were found. There were mixed results in emissions of N_2O, where some treated plots had higher flux rate than the control, while others were lower. As a result, the total N_2O emission for this planting season was insignificantly different among the treated and non-treated plots.

An analysis of the greenhouse-gas (GHG) mitigation potential and costs of biochar soil carbon sequestration showed that biochar allows for an annual technical GHG mitigation potential in Germany in the range of 2.1-3.2 million tonnes (Mt) of carbon dioxide equivalents (CO_2e) in 2015, 2.8-10.2 Mt CO_2e by 2030 and 2.9-10.6 Mt CO_2e by 2050. Thereby, forestry residues are associated with the greatest GHG mitigation potentials of biochar. In terms of the net GHG emissions that can be avoided per dry tonne of feedstock, biochar from biomass with a low water content (e.g., cereal straw) appears superior to biochar from wet feedstocks (e.g., solid cattle manure).

2 Aim of the project

The project "Biochar in Agriculture – Perspectives for Germany and Malaysia" was aimed to build a biochar network to provide a better understanding of economic and environmental potentials of biochar by analyzing the impact of biochar on plants, soil, environment, and to the economy in the temperate zone and in the tropics, considering the examples of Brandenburg (Germany) and Selangor (Malaysia). This holistic challenge was organized in an interdisciplinary and international consortium led by the Leibniz-Institute for Agricultural Engineering Potsdam-Bornim e.V. (ATB) in cooperation with the Leibniz Centre for Agricultural Landscape Research (ZALF), the German Institute for Economic Research (DIW), Technische Universität Berlin (TU-Berlin), Humboldt-Universität zu Berlin (HU-Berlin) and the University of Putra Malaysia (UPM). Analyses cover the impact of different biochars from pyrolysis and hydrothermal carbonization (HTC) technology, digestate and fertilizer add-ons on soil fertility in terms of yield potential, nutrient dynamics and soil biology in laboratory and field experiments (Germany and Malaysia). A three-factorial field experiment near Potsdam builds the center of research in Germany, supplemented by several pot experiments. It was aimed to estimate the potential environmental impacts together with cost effects at the farm level and welfare effects at national and international levels to provide most efficient concepts for biochar use in the tropics and the temperate zones. The work was structured in seven work packages (WP).

<u>Specific scientific issues/work packages:</u>

WP 1. Field experiment at research station Berge

WP 2. Effects of biochar on the Soil-Plant-System

WP 3. Gas flux measurements and biochar stability

WP 4. Impact of biochar on soil biota and microbial activities

WP 5. Effects of biochar on the dynamics of soil aggregation

WP 6. Field and pot experiments with biochar in Selangor, Malaysia

WP 7. Welfare analysis

3 Work packages

(Including discrepancies from the original concept, scientific failures, problems in project organization or technical implementation, results)

WP 1. Field experiment at research station Berge

The field experiment in Berge aimed to provide empirical data of a wide range, collected under real-life conditions. A three factorial experimental design was providing the basis for investigating effects of biochar application on soil physical and chemical properties, soil ecology, crop growth, and gaseous emissions. Experimental factors include the type of biochar (origin of material and processing), digestate incorporation before application and the fertilization intensity. Research objectives are the determination of the (I) impact of different non-treated and treated (digestate incorporation) biochars, (II) interaction of N-fertilization and biochar and (III) interaction of N-fertilization, digestate incorporation and biochar.

In summer 2012 the most suitable area for the field experiment, having regard to topography and electrical conductivity (EM38 scanning), was chosen. The trial area was divided in 4 blocks (replications) consisting of 16 plots (treatments), respectively. Treatments were randomized in each block. In September 2012 biochar was applied to the plots.

Following biochars and digestate incorporation were used:

- HTC char from maize silage (HTC-char)

For HTC char ensiled whole crop maize was used as feedstock harvested in autumn 2011. The maize silage was processed by batch-wise HTC at 210°C and 23 bar for 8h. Afterwards the resulting HTC slurry was separated by means of a chamber filter press. The solid phase (the HTC char) was filled in flexible intermediate bulk container (FIBCs) and transported to ATB Potsdam for further treatment.

- Pyrolysis char from maize silage (Pyro-char)

For this pyrolysis char ensiled whole crop maize was used as feedstock harvested in autumn 2011. The maize silage was processed by continuous pyrolysis at 600°C for 30 min. Afterwards the hot char was quenched by means of water sprinkling, filled in FIBCs and transported to Potsdam for further treatment.

- Pyrolysis char from wood (Pyreg-char)

For this pyrolysis char screenings from wood chip production were processed by continuous pyrolysis at 850°C for 30 min. Afterwards the hot char was quenched with water, filled in Big Bags and transported to Potsdam for further treatment.

- Digestate from maize silage (Digestate)

As feedstock for digestate incorporation by fermentation and soil application ensiled whole crop maize harvested in autumn 2011 was used. The maize silage was digested by a batch-wise solid-state process at mesophilic temperatures (approx. 35°C).

The incorporation of digestate to the Pyro- and HTC-chars was realized by methanogenic fermentation. In order to obtain suitable conditions for methanogenic fermentation each char was mixed with inoculum (the digestate) and water. For this, a carbon-based inoculum to substrate ratio of 1:2 was aspired. By means of water addition each mixture was intended to reach a dry matter (DM) content of 25-30%. Afterwards the mixtures were filled in “Flexible Intermediate Bulk Containers” (FIBCs). In order to establish anaerobic conditions the FIBCs were wrapped in silage plastic. To ensure mesophilic conditions all FIBCs were placed on a water-heated concrete plate and covered with an additional plastic sheet. After 29 days the fermentation was stopped and the FIBCs were removed from the heated concrete plate and transported to the field testing site in Berge. Pyreg-char was not fermented but mixed with digestate before application.

The application rate of each biochar (HTC-char, fermented HTC-char, Pyro-char, fermented Pyro-char and Pyreg-char) was equivalent to 7.7 t biochar-C ha^{-1}. Half of Pyreg-char and control treatments were mixed with digestate before field application with an amount of 3.85 t C ha^{-1} corresponding to the digestate-C:biochar-C ratio of 1:2 of the fermented biochars. Cultivated crops were winter wheat (*Triticum aestivum* L.) (2012) and winter rye (*Secale cereale* L.) (2013) followed by the catch crop oil radish (Raphanus sativus var. Oleiformis) (2014) and maize (*Zea mays* L.) (2015). In each cultivation year, N demand was examined and estimated at 150 kg N ha^{-1} for each crop. Mineral N fertilizer (Calcium ammonium nitrate, CAN 27% N) was applied in rates of 0%, 50%, 100% and 130% of the estimated crop demand. In total 16 treatment combinations varying in origin of input material for biochar production, biochar production methods, type of digestate incorporation and fertilization intensity were randomized in each block. Not all combinations of treatments were realized; therefore, three specific orthogonal groups (OG’s) were selected to evaluate the research questions with the present design. Treatments of OG1 were used to analyze the impact of HTC-char, Pyro-char and Pyreg-char, treated with or without digestate. The OG2 evaluated the interaction of Pyreg-char and mineral

N-fertilization whereas OG3 investigated the interaction of Pyreg-char, mineral N-fertilization and digestate incorporation.

Deviation from initial plan:

Due to delays in the production of the different biochars the field experiment started in summer 2012, so that in 2012 no results on crop response to biochars could be monitored. To achieve comprehensive results from three consecutive years in a cropping sequence the field experiment was prolonged to 2015.

WP 2. Effects of biochar on the Soil-Plant-System

In the 3-year field experiment, located in Berge (Brandenburg), regarding the effects of differently produced biochars (Pyreg-char, Pyro-char, HTC-char) in interaction with digestate incorporation and mineral N fertilizer application the HU-Berlin and the ATB determined the effects on soil C and N, crop yields of winter wheat, winter rye, oil radish and maize, and the quality of winter wheat. Soil C and plant available potassium were found to be positively affected by Pyreg-char whereas the latter only in combination with N fertilization. All crop yields over the 3 years were not affected by biochar and showed no interaction effects with N fertilizer supply. Wheat grain quality and nutrition contents were affected by biochar application, e.g. highest amounts of phosphorous, potassium and magnesium were determined in treatments amended with Pyro-char. Furthermore, an interaction effect of Pyreg-char and N fertilizer levels on N uptake of oil radish was found. More precisely, in biochar treatments without fertilization a higher N uptake in the presence of biochar was detected, higher soil ammonium content and elevated cumulative CO_2 emissions. At 195 kg N ha^{-1} (over-fertilization) lower N uptake and lower cumulative N_2O emissions were found.

To quantify the influence of biochars and the addition of digestate and/or nitrogen fertilizer on the yield of different crops the HU-Berlin conducted a 3-factorial pot experiment with 4 replications. The factor biochar was included with four levels (without biochar, Pyro-char, Pyreg-char, HTC-char). The two factors digestate and nitrogen fertilizer were included with two levels (with and without). Four crops were planted in sequence: spring wheat - spring barley - rapeseed - corn. While significant differences between the treatments on yield of spring wheat were observed, treatments with only biochar and without any addition showed no yield increase in comparison to the corresponding treatments without biochar. To investigate the effects of biochars and the addition of digestate, the pots were all fertilized after harvest of spring wheat. Spring barley and rapeseed showed no differences in plant biomass between the treatments.

To compare effects of the biochars on root growth of spring wheat, two rhizobox experiments were set up where physical contact of roots with biochars was prevented using nylon gauze. Rhizoboxes were filled with unamended soil as a control or with three different soil-biochar mixtures (Pyro-, Pyreg- and HTC-char). Shoots and roots of two spring wheat seedlings were harvested before flowering and at tillering in the first and second experiment, respectively. Chemical soil properties (N_t, K, C_t, pH) were affected differently by the different biochars, whereas P levels were not significantly influenced. Both above-ground and below-ground dry matters were affected differently by biochars. Pyro-char had particularly positive effects on root development and shoot growth.

To analyze the effects of different biochar types Pyro-char, Pyreg-char, HTC-char and treated HTC-char on the collembolan Protaphorura fimata the HU-Berlin exposed 150 individuals for 5 weeks to 2.5 kg defaunated soil mixed with the different biochars in pots. Three spring wheat seedlings per plot were planted. There were no significant differences between treatments regarding shoot and root biomass and the abundance of P. fimata. In a second experiment the amount of treated HTC-char varied. Therefore treated HTC-char was added to raise the organic carbon content to 1 %, 2 % and 4 %. With increasing amounts of treated HTC-char the abundance of P. fimata declined, whereas shoot biomass of spring wheat increased. A third greenhouse pot experiment was set up to test Pyro-char and Collembola interactions. Soil or soil-char mixture was inoculated with or without Collembola. Pyro-char altered root morphology and resulted in thicker roots with a higher volume. This was not apparent when Collembola are present.

WP 3. Gas flux measurements and biochar stability

The aims of this work package were to assess the stability of the biochars and to test if biochar can reduce the nitrous oxide (N_2O) emissions after application in the field. Every week, gas flux measurements with closed chambers have been performed. Gas samples were taken and the concentrations of carbon dioxide (CO_2), methane (CH_4) and N_2O were determined, together with the isotopic signature of carbon in the carbon dioxide ($\delta^{13}CO_2$). Once a month, soil samples for the determination of the available, mineral nitrogen (N) were taken. The amount of CO_2, N_2O and CH_4 emissions depend on the season. Within the first cultivation year (winter wheat), treatments with biochar application (HTC-char, Pyro-char, fermented HTC-char, fermented Pyro-char, Pyreg-char), digestate application and control (all treatments with 150 kg N ha^{-1} fertilization) were investigated. In all treatments, N_2O emissions were comparatively low. That was the result of a heterogeneous distribution of the biochars and the high sand content of the soil impeding N_2O production (Dicke et al. 2015). However, digestate treatments showed highest N_2O emissions compared to control and biochar treatments (Dicke et al. 2015).

As of 2014 gas measurements in the field were conducted on treatments with/without Pyreg-char and different fertilizer N levels (0, 75, 150 and 195 kg N ha^{-1}). In unfertilized soil, cumulative CO_2 emissions of biochar treatments were significantly higher ($P<0.05$) compared to control treatments without biochar. In contrast, significantly higher cumulative N_2O emissions ($P<0.1$) were measured in over fertilized (195 kg N ha^{-1}) without biochar application compared to treatments amended with biochar.

CO_2 flux studies were conducted on two scales:

(1) Lab experiments in cooperation with ZALF used the soil and the substrates which have been studied in the field experiment in Berge.
CO_2 release was measured from several soil-biochar mixtures in a dynamic system with continuous air exchange. This approach mimics the climatic conditions in the field and allows a high sampling volume as well as a frequent data acquisition.

(2) Investigation of the effect of N and glucose on the CO_2 flux, when added to the soil-biochar mixtures

(3) Field gas measurements ($CO_2+\delta^{13}CO_2$) 1×/week for two years. Soil analyses (soil-C + soil-$\delta^{13}C$) 2×/year. The Picarro facility used for analyses of ^{12}C and ^{13}C isotopes had to be sent two times to the company in the USA for repair. Therefore the duration of measurements were shorter as planned at the beginning of the project.

Within the 10-day incubation lab experiments different degradation dynamics have been identified between two soil-biochar-substrates mixtures amended with nitrogen and glucose:

- All treatments with biochar decreased soil respiration compared to unmodified maize straw indicating an increased stability of organic substrates in the soil.
- Respiration in soil-HTC-char mixtures was higher than in soil-pyrolysis char (Pyreg-char and Pyro-char) mixtures.

- HTC-char showed a two-step decay kinetics, which could not be explained with a simple double-pool model. This phenomenon in the context of biochar application to soil substrates has been published the first time by Lanza et al. (2015).

WP 4. Impact of biochar on soil biota and microbial activities

Concerning the soil zoological studies in the field experiment in Berge, the ZALF found spatially and temporally highly variable abundances of earthworms ranging from 20 to 84 individuals (mainly Aporrectodea caliginosa) in 2013 and 2014. However, impacts of biochars on the abundance of earthworm were detected in a subarea of field site. The analysis of carbon transfer between biochar and earthworms was postponed until evidence of biochar impacts from other isotopic studies from other WPs will be provided. A solution was found for studying microbial population parameters by dividing the field in two subareas and by using discriminant analysis including a pre-monitoring data set. On this basis, taxa-specific reactions in 2013 but not in the following years were found (Rebensburg et al. 2016).

With regard to biochar as constituent of soil organic matter (SOM) and potential primary organic matter for SOM reproduction (Franko et al. 2015), predictions were made (Reinhold 2015) to the topic of humus reproduction.

For the interactions of biochar and nitrogen under different fertilizer levels in oil radish, where N uptake was significantly enhanced by application the of biochar (WP2) no significant differences in the investigated microbial parameters between the biochar-mediated treatment and the treatment without biochar were found, i.e., microbial biomass as a measure of the overall physiologically active microflora, basal respiration as a measure of overall microbial activity, qCO_2 as a measure of specific respiration response of microbial biomass, as well the abundance of different special ecotypes.

In their experiments, ZALF revealed clear impacts of the type of char, char production and processing or of additional nutrient supply. The main findings are the following:

- Pyrolysis char (Pyreg-char and Pyro-char) had no effect on soil respiration or microbial community structure. HTC-char increased soil respiration and promoted dominance of fungi. Both biochars reduced the DNA amount of several common microbial taxa over time. biochars decreased glucose-induced respiration and shifts in microbial community.
- After 76 days of incubation, two variants of the same sandy agricultural soil (Su3) established similar eubacterial abundance, but different community structures – one strongly dominated by β-proteobacteria, the other one by acidobacteria, actinobacteria and fungi, which represent an additional DNA amount.
- Biochar impact on established and augmenting soil microbial populations. The influence of different biochar amendments on the microbial community structure of a soil ecosystem can be described focusing on the phylogenetic level of taxa and their shifts in biochar variants and control. For single taxa, changes in absolute and relative abundance are classifiable using a system of four reaction types in shaking culture, reactor incubation and in field. In field, microbial community shifted 1 year after application of pyrolyzed biochar the switch back. As a shift in abundance of a taxon can result in a modification of relevant ecological processes, changes in ecosystem quality can be indicated.
- Soil zoological studies in the field experiment Berge showed spatially and temporally highly variable abundances of earthworms ranging from 20 to 84 individuals (mainly *Aporrectodea caliginosa*). The results at the first sight did not reveal statistically significant differences according to treatments or variants. In 2013 and 2014, however, impacts of biochar on the abundance of earthworm were detected in one low-fertile sub-area of the experimental field.

The results suggest that pyrolyzed biochar may increase earthworm populations in nutrient-poor soils.

Deviations from the initial plan

According to initial planning, soil microbiological studies were started with samples from the field experiment in Berge (Brandenburg) in September 2012, followed by annual samplings in August 2013, November 2014 and finally April 2015. Soil microbial biomass and basal respiration were highly variable, due to unexpectedly high spatial variability and trends of soil properties across the site which were a major problem to identify impacts of different treatments at the field scale. Accordingly, a model prediction of C_{mic} using soil parameters was highly correlated to the field measurements, showing the same spatial variability. Additional laboratory experiments were performed to reveal effects of chars on soil microbial properties and soil microbial communities under controlled conditions.

WP 5. Effects of biochar on the dynamics of soil aggregation

As biofilms are supposed to play a major role in aggregate stabilization, our work focused on bacterial extracellular polymeric substance (EPS). In a first trial, EPS contained in soil aggregates from the field trial in Berge was pretreated with different concentrations of α-glucosidase, β-galactosidase, lipase and DNAse. These enzymes are known to destabilize EPS by digesting biofilm components. A measured decrease of aggregate stability as well as an increase of bacterial cell release after these treatments indicates a stabilization of soil aggregates by bacterial biofilms (Büks and Kaupenjohann, in rev.). However, the quantification of the contribution of biofilms to total aggregate stability was not possible, yet. Also the application of the method to samples with different biochars has to be part of future investigation, as adsorption behavior and activity of enzymes to biochars are still erratic.

In a second trial, mechanically disaggregated soil from the field trial in Berge containing 5% pyrolyzed biochar was incubated with 2 different microbial communities, one extracted from the soil and dominated by acidobacteria, actinobacteria and fungi, the other one derived from air-borne bacteria and dominated by β-proteobacteria. Contrary to our expectations, different biofilm populations did not develop different aggregate stability, although there is a tendency to higher aggregate stability in samples containing a fungal population (Büks et al., in rev.).

In a third trial, influence of grazers on aggregate stability was measured. Soil aggregates from the field trial in Berge were incubated for 14 days with high concentrations of the soil nematode Acrobeloides buetschlii grazing on bacterial biofilms. Aggregate stability, development of nematode population (brightfield microscopy counting), metabolic activity of microorganisms (soil respiration in control) as well as fatty acid concentrations (PLFA) were measured during the experiment. Results showed no influence of nematode feeding and motion on aggregate stability, which is probably due to inaccessibility of biofilms within the soil aggregates (Büks et al., in prep. (a)).

The influence of microbial manganic precipitations on aggregate stability was tried to be determined in samples from Rebensburg et al. (in rev.). Therefore, ultrasonication and fractionation of SOM free light fraction (fLF), SOM lable occluded light fraction (loLF), SOM stable occluded light fraction (soLF) and SOM heavy fraction (HF) of sterile and microbial incubated biochar soils were conducted. After NH_2OH-HCl extraction, concentrations of manganese oxides show significant differences between variants. However, data were not quantifiable as a transfer of nanocrystalline manganese between fractions during ultrasonication could not be ruled out.

In a separated trial, soil from the field trial in Berge was incubated for 35 day in 8 variants (with/without biochar x sterile/unsterile x addition of lime/no addition). The data are currently evaluated and shall give insight in the influence of pyrolyzed biochars on manganese cycling and heavy metal mobilization (Büks et al., in prep.).

Coupled with our participation in a round robin for comparison of different types of ultrasonic devices, a co-authorship is in preparation (Graf-Rosenfellner et al., in prep.).

Evidence for bacterial biofilms being aggregation agents in sandy agricultural soils was found. This property is not necessarily influenced by biofilm microbial composition. Also, biofilms seem to be protected against grazing nematodes due to their position inside the aggregate's micro-pore system. These date give insights in processes of aggregate formation and stabilization and emphasize bacterial life as a factor of soil quality to be included in agricultural management practice.

Deviations from the initial plan

As the original concept of this work package comprised the influence of physico-chemical interactions between the soil matrix and biochar amendments, the final focus was on biofilms and microbial products as stabilization agents for soil structure. Pot and field experiments were therefore excluded from investigations due to the size of applied biochar pieces unsuitable for microbial experiments in both trials. Instead, the focus was on laboratory experiments.

WP 6. Field and pot experiments with biochar in Selangor, Malaysia

A short-term pot experiment was conducted under rain shelter to determine the impact of oil palm empty fruit bunch biochar (EFBB) on recovery of ^{15}N-labelled fertilizer (80 kg N ha^{-1} at 2 % a.e, ammonium sulphate) by maize plant and N leaching at the rate of 0, 5, 10, and 20 t EFBB ha^{-1} in a sandy clay soil. The experimental design was a randomly complete block design (RCBD) with six replications. Each pot was filled with 20 kg soil and EFBB was mixed at the top 20 cm of the soil. Watering was done daily and leachate was collected weekly to determine total volume of leachate and amount of mineral N (NH_4^+-N and NO_3^--N) leached until the harvesting of maize at 56 days after sowing. From the analysis of leachate, it shows that EFBB significantly reduced cumulative leachate volume by 29-52%, 24-51% in NH_4^+-N, and 25-59% in NO_3^--N, when compared to the control. Soils applied with EFBB significantly improved ^{15}N fertilizer recovery by 7-14% in maize and dry matter weight by 32-85%. Other nutrients like K, Ca, and Mg in tissue and in soil also significantly increased in pots added with EFBB. The EFBB was shown to be effective in reducing N leaching and improve N fertilizer recovery at an application rate up to 10 t ha^{-1}. Lower leachate volume and leached mineral N seems to indicate higher retention in the soil with EFBB, attributing to improvement of N fertilizer recovery in the plant.

Another pot experiment was conducted in the open field to determine the effects of EFBB on ^{15}N-labelled fertilizer recovery (60 kg N ha^{-1} at 10% a.e., ammonium sulphate) by maize and N leaching at different EFBB rates (0, 5, 10, 20, and 40 t ha^{-1}) in a clayey soil. The experimental design was a RCBD with five replications. Each pot was filled with 20 kg soil and EFBB was mixed at the top 20 cm of the soil. Leachate samples were collected every time after rain and measured total volume leached, NH_4^+-N, and NO_3^--N content. After 30 days, plant and soil samples were collected for analysis. Findings showed that EFBB application significantly improved ^{15}N fertilizer recovery in maize, up to 8 %, compared to control. However, there was no significant difference in ^{15}N fertilizer recovery in the soil, leachate volume, NH_4^+-N and NO_3^--N leached. As for crop performance, pots treated with EFBB significantly increase maize dry matter weight up to 72%. There were also significant improvements for K, Ca, and Mg uptake in maize. Soil properties also showed significant increment in pH, total C, total N, and exchangeable K, Ca, and Mg, but only after the rate of 10 t EFBB ha^{-1}. Additional EFBB rate do not further significantly increase the soil properties. Conversely, the exchangeable Al was significantly reduced in treated pots compared to control. Application of EFBB was able to improve N fertilizer recovery, however, unlike in the pot experiment above, EFBB do not reduce the leachate volume and loss of NH_4^+-N and NO_3^--N. The EFBB was not effective when there was excessive rain water. The higher maize dry matter weight could be attributed by the improved soil properties by the EFBB.

A field experiment was conducted to determine the effects of different application rates of oil palm empty fruit bunch biochar (0, 5, 10, 20 and 40 t ha^{-1}) on maize yield, N uptake, nitrous oxide (N_2O) emission, and soil properties in an Oxisol. The experimental layout was a RCBD with 5 replicates, each plot measuring 6 m by 4 m. EFBB was distributed evenly before mixing with the top soil. A separate EFBB was weighed and applied in a 1 m by 1 m microplot, bordered with PVC plastic sheet. The microplot was randomly placed around the centre area of each plot for gas, soil, and plant tissue sampling. Maize seeds were sown and two split applications of fertilizers were applied at the rate of 180 kg N ha^{-1} (ammonium sulphate), 60 kg P_2O_5 (triple superphosphate), and 120 kg K_2O (muriate of potash). Gas sampling was done weekly for N_2O flux measurement, collected in a static gas chamber, till harvesting period (80 days after sowing). Maize tissue samples were harvested for dry matter weight and nutrient content analysis (N, P, K, Ca, and Mg), while soil was collected for pH, CEC, total C, total N, and exchangeable cations (K, Ca, and Mg). Results showed that addition of EFBB significantly increased dry matter weight and yield up to 46% and 74% respectively, compared to plots without biochar. The crop uptake of N and K were significantly improved by 38% and 65%, respectively. For soil properties, EFBB increased soil pH, extractable P (up to 34%), and exchangeable K (64%), but no significant difference for other elements were found. There were mixed results in emissions of N_2O, where some treated plots had higher flux rate than the control, while others were lower. As a result, the total N_2O emission for this planting season was insignificantly different among the treated and non-treated plots.

Deviations from the initial plan

The initial plan was to complete this project within three years, however, it exceeded the due date. One of the main reasons was technical issue of troubleshooting and repairing the gas chromatograph (GC). The detector of the GC for N_2O analysis, the electron capture detector (ECD), was aged and needed replacement, which took more time than expected.

WP 7. Welfare analysis

Due to its high carbon stability, the soil incorporation of biochar is increasingly discussed as a promising means to remove carbon dioxide from the atmosphere and, thus, to help mitigate climate change. Against this background, work package 7 has analyzed the greenhouse-gas (GHG) mitigation potential and costs of biochar soil carbon sequestration. In particular, it has studied whether the deployment of slow-pyrolysis biochar in agricultural soils in Germany – combined with the use of the by-products from biochar production (pyrolysis oils and gases) as renewable sources of energy – could be a viable mitigation strategy against Germany's targets for the reduction of its annual GHG emissions.

Focusing on emissions of CO_2, CH_4 and N_2O, the economic assessment of biochar in Germany has been based on the technical GHG mitigation potential of biochar and the associated GHG mitigation costs per ton of CO_2e abated for the years 2015, 2030 and 2050. Evaluating the costs against a given CO_2 price, the economic GHG mitigation potential has been derived in bottom-up marginal abatement cost curves (MACCs). The analysis is scenario-based and has been performed for a wide range of biochar options, i.e. feedstocks used for biochar production. They include cereal straw, forestry residues, open-country biomass residues, industrial wood waste, wood in municipal solid waste, green waste from compensation areas, biomass from habitat-connectivity areas, green waste from extensive grassland, short-rotation coppice from erosion areas, sewage sludge, solid cattle manure, solid swine manure, solid poultry manure, liquid cattle and swine manure, sugar-beet leaf and potato haulm, commercial and industrial waste, organic municipal solid waste, and digestates. Different scenarios have been used for biomass availability, pyrolysis-technology scales, process heat recovery, and future price developments for fossil fuels and GHG emission certificates. Thereby, the calculation of the GHG mitigation potentials and costs has been conducted against the baseline scenario of conventional feedstock management – referring to decomposition on site for cereal straw, forestry residues, green waste from compensation areas as well as sugar-beet leaf and potato haulm, to biomass combustion for industrial wood waste and short-rotation coppice, to conventional manure management plus land spread for the manures, and to composting and subsequent land spread for all the remaining feedstocks. Throughout, the study has accounted for feedstock-specific biochar yields, carbon contents and other biochar properties from an extensive literature survey.

Abstracting from any cost considerations, biochar allows for an annual technical GHG mitigation potential in Germany in the range of 2.1-3.2 million tons (Mt) of carbon dioxide equivalents (CO_2e) in 2015, 2.8-10.2 Mt CO_2e by 2030 and 2.9-10.6 Mt CO_2e by 2050. In 2030 and 2050, this corresponds to approximately 0.4-1.5% and 0.3-1.1% of the respective GHG reduction targets. Thereby, forestry residues are associated with the greatest GHG mitigation potentials of biochar, followed by cereal straw, green waste from extensive grassland, solid cattle manure, and some other solid biomass residues. In terms of the net GHG emissions that can be avoided per dry tonne of feedstock, biochar from biomass with a low water content (e.g., cereal straw) appears superior to biochar from wet feedstocks (e.g., solid cattle manure). Some feedstocks with very high water contents – liquid cattle and swine manure, sugar-beet leaf and potato haulm, sewage sludge, and digestates – are even associated with a negative GHG mitigation balance due to the high amount of energy required to dry the feedstocks and are, thus, considered unsuitable for slow-pyrolysis-biochar carbon sequestration. In many cases, a negative GHG mitigation balance is also obtained for industrial wood waste and short-rotation coppice, the feedstocks that are assumed to be directly combusted in the baseline scenario. Besides the type and available amount of biomass and the choice of the baseline scenario, the net avoided GHG emissions are strongly influenced by the type of fossil fuel considered and by whether process heat is recovered during pyrolysis. In contrast, the size of the pyrolysis plants and, thus, the transport distances for biomass and biochar play only a minor role.

The mitigation potential is reduced if costs are taken into account. Only about 3.1 Mt CO_2e could be maximally abated in 2030 at costs below $€_{2012}$45 per ton of CO_2 – the then assumed maximum price for GHG emission certificates – and nearly 3.8 Mt CO_2e in 2050 at costs below $€_{2012}$75 per ton of CO_2. This translates into about 0.5% and 0.4%, respectively, of the 2030 and 2050 GHG reduction targets and about a third of the maximum technical GHG mitigation potential of 10.2 Mt CO_2e in 2030 and of 10.6 Mt CO_2e in 2050. The feedstocks associated with these economic GHG mitigation potentials mainly refer to green waste from extensive grassland, open-country biomass residues, biomass from habitat-connectivity areas, and wood in municipal solid waste. In 2030, they also include organic municipal solid waste as well as commercial and industrial waste, and, in 2050, cereal straw and green waste from compensation areas.

Deviations from the initial plan:

Originally, it was planned to incorporate the potential agricultural benefits of biochar into the analysis, such as improved crop yields or fertilizer savings. To date, however, the agricultural benefits of biochar soil addition and, thus, the related changes in GHG emissions remain highly uncertain, in particular in the long-term. Moreover, they are expected to be of limited importance in the temperate zone. For these reasons, they were not included in the analysis for Germany.

This procedure has been largely confirmed ex-post by the project output of the other work packages.

A similar analysis of biochar in Malaysia is still work in progress. It will be finalized during a research stay at the University of Putra Malaysia (UPM) scheduled for the second half of 2016.

4 General conclusions

The obtained results of the use of different biochars in Germany and Malaysia showed different effects on crop yields, N fertilizer recovery and soil properties. In Malaysia improved N fertilizer efficiency and pH values, increased total C and N and exchangeable K, Ca, and Mg as well as increased maize yield and dry matter weight on highly weathered soils were found. Biochar use in Germany induced an improved availability of plant nutrients, however, this was apparently not yield limiting in this region because crop yields could not be increased. However, the contrasting biochar-N interactions on different N-related processes when supplied with different amounts of N fertilizer in Germany indicates that biochar can have a greenhouse gas mitigation effect at high levels of N supply and may stimulate nutrient uptake at low levels of N supply. Both regions mostly indicated insignificant differences in N_2O emissions which might be explained by the high variability and low number of replications, a heterogeneous distribution of biochar in the field and potentially due to a comparatively low application rate of biochar. Increasing gas chamber size and more replications may be able to remediate this issue. To investigate impacts of biochars on N cycling including the underlying mechanisms further research is needed. Biochar in soil decreased soil respiration by stabilizing organic substrates in lab experiments. It can be stated that within a few days of investigation, qualitative and semi-quantitative information about CO_2 gas fluxes can already be achieved. Although the exact time scales of long-term physical phenomena cannot be obtained by this way, short-term studies are helpful to compare different treatments and to gain insight into features of the initial decay dynamics. In the case of slowly-decaying substrates like biochar, these studies can facilitate early decisions on appropriate feedstocks, production parameters or post-treatments of chars, which are provided for soil amendment. Findings regarding microbial community and earthworm populations correspond to other reports in international journals. Despite of the high number of publications and increasing details of analyses, the studies from this project are relevant and can be integrated in the recent state of research. Especially the highly integrated, experimental approach was a crucial criterion. Special highlights were to find microbial biomass (C_{mic}), taxon specific qPCR and zoological analyses of earthworms suitable for the analysis of biochar impacts. Based on these parameters, a soil ecological characterization was provided. Furthermore, more specific studies were performed, such as CT analyses of soil structure and earthworm borrows, and a detection of N-cycle specific genes. Studies of the reactions after HTC-biochar application and reactions of microbial taxa are of basic interest and deserve further study. Especially the effects of HTC char on plant growth, as well as on soil microbial activities and microbial community composition led to further research activities concerning the mechanisms behind impacts, such as a joined project of Egamberdieva et al. (2016) in biochar and plant-beneficial rhizobacteria intended to reveal potentials for improved soybean production (supported by the Alexander von Humboldt Foundation, 2015-2016). The stimulation of certain rhizobacteria bacteria by biochar also suggests the possibility of developing combined approaches of biochar treatment and biological control solutions.

To the best of our knowledge, this project includes the first study providing a comprehensive analysis of the GHG mitigation potentials and associated GHG mitigation costs of biochar soil incorporation in Germany. So far, most of the related studies on biochar have been conducted outside Germany and focused exclusively on one of the following aspects: the GHG emissions that can be avoided per ton of biomass turned into biochar – without providing an estimate of the biomass potentials that could be available for biochar production; the GHG mitigation potentials,

or the mitigation costs. Moreover, biochar is not included in the numerous MACC studies analyzing GHG mitigation in agriculture. Likewise, the only bottom-up MACC for Germany covers the agricultural sector only very broadly and does not contain any biochar. While the amount of biochar carbon sequestered in soil is an important factor for the technical GHG mitigation potentials of biochar, the study has revealed that the contribution of the pyrolysis by-products offsetting GHG emissions from fossil fuels might often be equally or even more important than that of biochar soil incorporation. This indicates that other conclusions about the technical and economic GHG mitigation potentials of biochar might be obtained when focusing on the use of biochar for energetic purposes or on the extraction of pyrolysis oils and gases (rather than biochar) for energy generation. These alternative uses and the general trade-offs between the choice of feedstock, conversion process, highest heating temperature, biochar (carbon) yield, and biochar carbon stability call for more research on the optimal feedstock-specific GHG mitigation strategies with biochar.
In May 2015 ATB organized an international biochar symposium “Biochar Contribution to Sustainable Agriculture“ in Potsdam, where results of this project were presented and discussed with more than 100 scientists from more than 20 countries world-wide. The result showed promising perspectives as well as limitations of biochar use in agriculture in the tropics and the temperate zones. All abstracts of the international biochar symposium are online available under the following link: http://www.atb-potsdam.de/fileadmin/docs/BABs/BAB_Heft89_k.pdf. In June 2016 a consortium of biochar scientists from Germany traveled to Shenyang, China to participate at the Sino-German Symposium „Biochar for Sustainable Agriculture: Opportunity and Challenge” which was initiated by ATB and Shenyang University. We aimed to build up a strong cooperation on biochar projects by a) strengthen bilateral understanding on advancement of biochar research in China and Germany; b) discuss the role of biochar in sustainable agriculture and potential challenges; c) confirm the cooperation methods with respect to the key theories and techniques collaboration; d) create an initial plan for future cooperation and joint projects to be prepared. Further, we want to build up bilateral cooperation in future including sharing equipment, and exchanging scholars.

5 Qualification work arising from the project

Teichmann, Isabel. 2016. *Three topics in agriculture: Private quality standards, marketing channels, and biochar*. Doctoral thesis. Humboldt University Berlin.

Reibe, Katharina. 2015. *Wirkungen von Biokohlen im System Boden-Pflanze*. Doctoral thesis. Humboldt University Berlin.

Christiane Dicke (Accompanying studies). 2015. *Effects of biochar application on the emissions of CO_2 and N_2O from sandy soils*. Doctoral thesis. Technical University Berlin.

Medick, Jakob. 2014. *Hydrothermal carbonization of green wastes: A techno-economic assessment of sustainable organic waste management in the metropolitan region of Berlin*. Master thesis. Humboldt University Berlin.

Expected completion of dissertations in 2016 by Giacomo Lanza, Philip Rebensburg and Frederick Büks

6 List of publications from the project

Agacayak, T., Larsen, O., Büks, F., Kaupenjohann, M., Rotter, V.S. (in prep.) *Benefits of Compost Application Regarding Mitigation of Greenhouse Gas Emissions in Arid Climates.*

Büks, F., Reger, P., Richter, A., Rueß, L., Kaupenjohann, M. (in prep.) *Nematode feeding and motion of Acrobeloides buetschlii in a sandy agricultural soil neither affects aggregate stability nor basic markers of biofilm composition.*

Büks, F., Kaupenjohann, M. (under review) *Enzymatic biofilm detachment causes a loss of aggregate stability in a sandy soil.* Soil.

Büks, F., von Müller, G., Kaupenjohann, M. (in prep.) *Influence of pyrogene biochar application on manganese cycling and heavy metal mobilization.*

Büks, F., Rebensburg, P., Lentzsch, P., Kaupenjohann, M. (in rev.) *Relation of aggregate stability and microbial diversity in an incubated sandy soil*. Soil.

Dicke, C., Andert, J., Ammon, C., Kern, J., Meyer-Aurich, A., Kaupenjohann, M. (2015) *Effects of different biochars and digestate on N_2O fluxes under field conditions*. Sci Total Environ. 524, 310-318. http://dx.doi.org/10.1016/j.scitotenv.2015.04.005

Egamberdieva, D., Wirth, S., Behrendt, U., Abd-Allah, E.F., Berg, G. (2016) *Biochar treatment resulted in a combined effect on soybean growth promotion and a shift in plant growth promoting rhizobacteria*. Front. Microbiol. 7, Article 209.

Graf-Rosenfellner, M., Kayser, G., Guggenberger, G., Kaiser, K., Büks, F., Kaiser, M., Müller, C.W., Schrumpf, M., Rennert, T., Welp, G., Lang, F. (in prep.) *Round robin test on the soil disaggregation efficiency of ultrasound*. J. Plant Nutr. Soil Sci.

Joschko, M., Reinhold, J., Lentzsch, P., Franko, U. (in prep.) *Neue Ansätze für die Bewertung von organischen Materialien zur Humusreproduktion*. J. Plant Nutr. Soil Sci.

Lanza, G., Wirth, S., Gessler, A. Kern, J. (2015) *Short-term response of soil respiration to addition of chars: impact of fermentation post-processing and mineral nitrogen*. Pedosphere 25, 761-769. http://dx.doi.org/10.1016/S1002-0160(15)30057-6

Lanza, G., Rebensburg, P., Kern, J., Lentzsch, P., Wirth, S. (2016) *Impact of chars and readily available carbon on soil microbial respiration and microbial community composition in a dynamic incubation experiment*. Soil Till. Res. http://dx.doi.org/10.1016/j.still.2016.01.005

Lanza G., Kern, J. , Geßler, A., Wirth, S., Meyer-Aurich, A. (in prep.) *Effects of postprocessing and environmental conditions onto the stability of chars in field.*

Meyer-Aurich A., Sänger A. (2015) *International Biochar Symposium: Biochar - Contribution to Sustainable Agriculture*. Bornimer Agrartechnische Berichte, Band 89.

Rebensburg, P., Büks, F., Kaupenjohann, M., Lentzsch, P. (in rev.) *Biochar impact on established and augmenting soil microbial populations.* Pedobiologia.

Reibe, K., Götz, K.-P., Roß, C.-L., Döring, T.F., Ellmer, F., Ruess, L. (2015) *Impact of quality and quantity of biochar and hydrochar on soil Collembola and growth of spring wheat.* Soil Biol Biochem. 85:84-87. http://dx.doi.org/10.1016/j.soilbio.2015.01.014

Reibe, K., Götz, K.-P., Döring, T.F., Roß, C.-L., Ellmer, F. (2014) *Impact of hydro-/biochars on root morphology of spring wheat.* Arch. Agron. Soil Sci. 61: 1041-1054. http://dx.doi.org/10.1080/03650340.2014.983090

Reibe, K., Roß, C.-L., Ellmer, F. (2014) *Hydro-/Biochar application to sandy soils: impact on yield components and nutrients of spring wheat in pots.* Arch. Agron. Soil Sci. 61:1055-1060. http://dx.doi.org/10.1080/03650340.2014.977786

Reibe, K., Ellmer ,F. (2013) *Einfluss von Biokohle und deren Behandlung auf die Ertragsbildung von Kulturpflanzen*. Mitt. Ges. Pflanzenbauwissenschaften Band 25, 315-316.

Reinhold, J. (2015) *Biokohle als potenzieller Bestandteil der organischen Bodensubstanz*. Gutachten.

Sänger A., Reibe K., Mumme J., Kaupenjohann M., Ellmer F., Roß C.-L., Meyer-Aurich A. (2016) *Biochar application to sandy soil: effects of different biochars and N fertilization on crop yields in a three-year field experiment.* Arch. Agron. Soil Sci. http://dx.doi.org/10.1080/03650340.2016.1223289

Sun, Z., Meyer-Aurich, A., Sänger, A., Rebensburg, P., Lentzsch, P., Wirth, S., Kaupenjohann, M. (in rev.) *Contrasting effects of biochar on N2O emission and nitrogen uptake at different nitrogen fertilizer levels*. Sci Total Environ.

Teichmann, I. (2014). *Technical greenhouse-gas mitigation potentials of biochar soil incorporation in Germany*. DIW Discussion Paper 1406. → will be submitted to journal

Teichmann, I. (2014). *Technical greenhouse-gas mitigation potentials of biochar soil incorporation in Germany: Data documentation*. DIW Data Documentation 73.

Teichmann, I. (2015). *An economic assessment of soil carbon sequestration with biochar in Germany*. DIW Discussion Paper 1476. → will be submitted to journal

Teichmann, I. (2015). *An economic assessment of soil carbon sequestration with biochar in Germany: Data documentation*. DIW Data Documentation 78.

7 Policy reports

Teichmann, I. (2014) *Klimaschutz durch Biokohle in der deutschen Landwirtschaft: Potentiale und Kosten.* DIW Wochenbericht 1+2/2014: 3-13.

Sechs Fragen an Isabel Teichmann. *Biokohle in der Landwirtschaft: Möglicher Nutzen für Klima, Böden und Pflanzen.* Interview im DIW Wochenbericht 1+2/2014: 14.

Teichmann, I. (2014) *Climate protection through biochar in German agriculture: Potentials and costs*. DIW Economic Bulletin 4/2014: 17-26.

Teichmann, I., Kemfert, C. (2014) *Biokohle in der Landwirtschaft als Klimaretter?* DIW Roundup 47.

Haubold-Rosar, M., Heinkele, T., Rademacher, A., Kern, J., Dicke, C., Funke, A., Germer, S., Karagöz, Y., Lanza, G., Libra, J., Meyer-Aurich, A., Mumme, J., Theobald, A., Reinhold, J., Neubauer, Y., Medick, J., Teichmann I. (2016) *Chancen und Risiken des Einsatzes von Biokohle und anderer „veränderter" Biomasse als Bodenhilfsstoffe oder für die C-Sequestrierung in Böden*. Texte 04/2016. Dessau-Roßlau: Umweltbundesamt.

8 List of press releases and media reports

Industrie, Leibnitz-Institute forschen zu Biokohle, Kohlegeneration 2.0, Auch Gärreste aus Biogasanlagen könnten Rohstoff sein (2011)

Wunderkohle auf dem Seziertisch Potenzial der Biokohle wird am ATB erforscht (2011)

IBI: Biochar at Leibniz Institute for Agricultural Engineering (ATB) in Potsdam, Germany (2012)

Deutschlandreise: Biokohle für Malaysia (2012)

In den Fokus genommen: Biokohle – Gewinn für Boden und Klima? (2012)

Biokohle – Gewinn für Boden und Klima? - Leibniz-Institut für Agrartechnik in Potsdam lotet die Potenziale aus (2012)

Agrarforscher im Land der Ideen (2014)

Wenn Kohle gut fürs Klima ist (2014)

Optimierte Biokohle aus agrarischen Reststoffen, Preisträger Land der Ideen (2014)

Biokohle-Forscher tagen in Potsdam (2015)

Wunder mit Abstrichen (2015)