Estimation of soil quality improvement through the use of biochar-based and compost substrates on low-yield soils in Lusatia, Germany

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By Michelle Breezmann
BSc Agricultural Sciences (2020, University of Rostock)

School of Natural Sciences
Bangor University
Gwynedd, LL57 2UW, UK
www.bangor.ac.uk

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Declaration

This dissertation is being submitted in partial fulfilment of the requirements for the degree of Master of Science.

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

This dissertation is the result of my own independent work/investigation except where otherwise stated.

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Ethical Statement

This research was screened under Bangor University Research Ethics Framework, no issues were identified.

Abstract

Biochar is being widely discussed as a soil amendment and a way to sequester carbon for a long time in soils. Especially on low-fertile soils it seems to have a huge potential. This thesis investigates on sandy acidic soils in Lusatia, Germany, whether biochar-based amendments improve soil quality for good agricultural production and, how the carbon sequestration potential is being influenced. In literature, results from previous investigations vary depending on soil type, biochar origin, climate conditions and additional fertilization methods. However, most studies find an increased total organic carbon content. In the framework of the AgroBaLa-project, answering the forementioned questions could contribute to a better understanding of value creation in an agroforestry circular economy and climate change adaption on sandy soils in rural Lusatia, Germany. General agricultural parameters like pH, mineralised nitrogen, double lactate extractable potassium and phosphorus and humus content were investigated for a soil quality assessment, as well as different carbon parameters to estimate carbon stocks and relation between those. No significant differences were found between the soil samples prior and after the substrate application. Anyway, the results hint towards an increased total organic carbon content made of stable carbon compounds, which would maybe have become significant with a bigger sample size.

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ABC	Activated Biochar
BS	Base Saturation
CEC	Cation Exchange Capacity
Cext	Extracted Microbial Carbon
Cmic	Microbial Carbon
DM	Dry Matter
EM	Effective Microorganism
GWC	Green Waste Compost
HWTC	Hot Water Extractable Total Carbon
HWTN	Hot Water Extractable Total Nitrogen
HWTOC	Hot Water Extractable Total Organic Carbon
K	Potassium
M	Mol
Mg	Magnesium
N	Nitrogen
NABC	Non-Activated Biochar
Next	Extracted Microbial Nitrogen
Nmic	Microbial Nitrogen
Nmin	Mineralised Nitrogen
P	Phosphorus
TN	Total Nitrogen
TOC	Total Organic Carbon
TON	Total Organic Nitrogen

1. Introduction

1.1. Literature Context

1.1.1. Biochar as a Soil Amendment

Biochar is the solid, charcoal-like product of a pyrolysis, the process of heating biomass in an oxygen-limited environment (Geoengineering Monitor, 2021; Smith et al., 2019). It is known to be a soil amendment, based on observations of the extremely fertile anthropogenic dark earths, or “terra preta”- soils in the Amazon basin (Glaser and Birk, 2012; Smith et al., 2019). Those started to develop several thousand years ago, so the actual process is not totally understood yet (Glaser and Birk, 2012; Schmidt et al., 2021). This leads to a controversial discussion too, including the questions what impact the use of biochar might have on nutrient cycles, the soil structure and soil microbial communities, or what interactions with pollutants might occur (Agegnehu et al., 2017; Glaser and Birk, 2012; Jeffery et al., 2016; Tammeorg et al., 2013).
While the highest potential of improving soil quality through biochar was found on highly weathered soils in the humid tropics, with rapid turnover of organic matter due to high temperatures and precipitation, there are fewer publications available for the potential of biochar in temperate climates (Crane-Droesch et al., 2013; Glaser et al., 2002).

In 2009, a similar experiment to the one presented in this thesis was conducted by Liu et al. (2012) on infertile, sandy soils in Brandenburg, North-East-Germany. The authors described that often not all components of terra preta are taken into consideration but the biochar only. As the biochar does not offer many nutrients for plants, according to the authors, they decided to investigate compost-based substrates (32,5 Mg dry matter (DM) ha^{-1}) with different percentages of biochar (0, 5, 10 and 20 Mg DM ha^{-1}), and one control (neither compost nor biochar). They found that an application of compost-biochar substrates can increase soil fertility and plant available water-holding capacity but highlighted that mostly, only the variation with the highest amount of biochar showed significant results. To summarize their findings, total organic carbon (TOC), total nitrogen (TN), the C:N-ratio and plant-available K and Mg increased through the application of compost biochar substrates, soil pH, cation exchange capacity (CEC) and base saturation (BS) did not change significantly and soil water content and plant available water-holding capacity increased with biochar application. Compost application increased plant available P, N, CEC, BS, and soil pH but did not show significant differences after an additional biochar application.

Most experiments distinguish between pure biochar application and biochar application in combination with organic or inorganic fertilizers or a composting or fermentation process prior to the application (Abujabhah et al., 2016; Hagemann et al., 2017; Jeffery et al., 2011; Joseph et al., 2013; Kammann et al., 2015; Prost et al., 2013; Schmidt et al., 2015; Schulz et al., 2013; Sohi et al., 2010).

This is seen as a “good way to overcome biochar’s inherent nutrient deficiency” (Schulz et al., 2013). In everyday language, this enrichment of biochar with nutrients prior or during the application to the soil is called “activation”. To generalise this practice, in this thesis, the term “non-activated biochar” will be used for experiments in which the biochar was applied without any treatment or composting. Furthermore, the term “activated biochar” will be used for experiments in which the biochar was enriched with nutrients through one of the described methods.

Many of the forementioned studies found an increase of soil pH and TOC in soil through the application of biochar in general (Abujabhah et al., 2016; Mukherjee et al., 2014; Novak et al., 2014). Some found an increase in TON and of the C/N-ratio (Schulz et al., 2013), while others presented reduced nitrate leaching in soils and composts amended with biochar compared to soil and composts without biochar (Hagemann et al., 2017). A higher nutrient capture and delivery for the crop was found by Kammann et al. (2015), while Sohi et al. (2010) see biochar as a method to capture plant available nitrate and reduce nitrate leaching, and Novak et al. (2014) found that activated biochar treatments showed higher plant-available P- and K-values and a higher N content.

Looking at crop yields, the beneficial potential of biochar was again higher under humid conditions with a much higher increase of crop productivity on sandy soils with acidic pH (Liu et al., 2013). In temperate climates, activated biochar increased positive effects while the application of non-activated biochar sometimes showed negative effects (Jeffery et al., 2011; Joseph et al., 2013; Kammann et al., 2015). While non-activated biochar treatments sometimes even showed a yield reduction of crops, e.g. in *Zea mays L.* (Borchard et al., 2014b), activated biochar often resulted in a yield increase (Schmidt et al., 2015; Sohi et al., 2010). To conclude with the words of Prost et al. (2013): “composting enhances the functionalization of biochar”.

1.1.2. Mitigating Climate Change through Carbon Sequestration

Agricultural areas with infertile soils are especially vulnerable to soil degradation and crop losses through extreme weather events like heavy rainfalls or droughts, which are predicted to increase, due to climate change (Giorgi et al., 2004; IPCC, 2019; Lenderink et al., 2007). The aforementioned threats to land use and our living environment should encourage everyone to try to mitigate climate change.

Loss of soil fertility and soil organic matter through agricultural practices are some of the most discussed topics that are strongly influenceable by land users (IPCC, 2019).

It is widely accepted that the application of organic matter improve soil properties and that soil carbon sequestration offers the highest potential to mitigate climate change within the agricultural sector, while having further beneficial effects on, e.g., water quality, food security and the environment (FAO, 2013; Gattinger et al., 2012; Lal, 2004).

Repeated applications of organic matter improved soil carbon in the long term, thereby enhancing soil quality and agronomic productivity (Gattinger et al., 2012; Lal, 2006). Due to their stable carbon composition, biochar soil amendments are being discussed as a tool for long lasting carbon sinks in soils (Glaser et al., 2002, 2001). In temperate climates, biochar applications were found to have long term beneficial effects on the carbon sink potential through the decreased turnover of soil organic matter (Borchard et al., 2014b; Hernandez-Soriano et al., 2016). Furthermore, benefits on crop yields through biochar applications increased over time (Crane-Droesch et al., 2013). It is important to mention that, depending on the study, no further increase of beneficial effects were found at application rates higher than 40 – 50 t per ha (Borchard et al., 2014b; Liu et al., 2013). All these investigations support the statement by Joseph et al. (2013) that the most effective way for sequestering carbon and improve soil properties in the long term is to apply activated biochar in low doses over time.

The forementioned paragraphs present the potential of biochar as a soil amendment for carbon sequestration. On a global scale, a variety of studies discussed whether or not the production of bio char is carbon-emission-negative or, if applying bio char on soils leads to a carbon sink in general or influences other climate relevant greenhouse gases (Agegnehu et al., 2017; Borchard et al., 2019; ETC-Group and Heinrich Böll Stiftung, 2017; Jeffery et al., 2016). Because of its high carbon content, bio char is discussed controversially as a climate geoengineering technique to capture and store carbon in soils (ETC-Group and Heinrich Böll Stiftung, 2017). The debate of the potential of the so-called "pyrogenic carbon capture and storage" as a negative emission technology is being discussed very emotionally, especially regarding the needed area for biomass plantations (ETC-Group and Heinrich Böll Stiftung, 2017; Werner et al., 2018).

As many renowned research institutes and organisations agree, all geoengineering techniques may only serve as "time-buyers" to achieve a reduction of carbon emissions on a sustainable level. Therefore, the transformation of, e.g. more than 280 Mha of natural vegetation for biomass plantations to reach the 1.5°C goal (modest calculation by Werner et al. (2018)) are not seen as a suitable tool for so-called "negative emission technologies", especially, if social issues occur in that context, e.g, discussions about land-grabbing (Ernsting et al., 2010; ETC-Group and Heinrich Böll Stiftung, 2017).

For an estimation of the carbon sequestration potential of biochar, a comprehensive understanding of the details is needed, as (biofuelwatch, 2013) pointed out.

For example, the effects of pyrolysis temperature and the feedstock on biochar yields and the quality of the biochar concerning heavy metals and other contaminants or the effect of biochar application on soils concerning their albedo remain not comprehensively understood (Li et al., 2020; Smolker, 2020; Zhu et al., 2019). For example, biochar from wood and crop residues showed a consistent crop productivity increase, which was more stable compared to biochar from manure or municipal waste (Liu et al., 2013).

Setting aside valuable productive land or transferring natural vegetation to biomass plantations for biochar production would only lead to a trade-off between carbon sequestration goals and food security and natural conservation goals (biofuelwatch, 2013). But in the context of a small-scale farm-based heating system with biochar and heat as products, the plantation of biomass for pyrolysis in, e.g., agroforestry systems becomes interesting. Through the intercropping of trees with agricultural production, no additional natural vegetation would be needed to be destroyed, and the loss of land for food production would be reduced through a higher land efficiency ratio, not only under tropical conditions (Böhm et al., 2020b; Dupraz and Talbot, 2012). In temperate climates too, agroforestry systems offer another benefit: Additionally to the carbon sequestered in the biochar, the trees themselves contribute to a higher carbon sequestration compared to cropland (Mayer et al., 2022). Mayer et al. (2022) analysed the soil organic carbon sequestration potential of agroforestry systems under temperate conditions, comparing hedgerows with alley cropping and silvopastoral systems. They found a mean carbon sequestration rate of 0.24 t/ha/a for 0 – 30 cm soil depth, ranging from 0.09 – 0.46 t/ha/a.

Especially in Germany, carbon certificates as additional payments for farmers on the one hand, and as a tool to offset carbon footprints of companies on the other, are being discussed controversy in politics and science (Häusling, 2020; Hübner et al., 2022). Hübner et al. (2022) describe the chance of carbon certificates as a financial way to support agroforestry, as investments are often an issue among farmers. They state that the responsibility for a good certification lies in the hands of the certification companies, so their programmes are transparent, reliable, fair and well-calculated on the state of art in science, and suggest 10 baselines on which those programmes should build upon. The authors suggest a certification model structured in 4 parts: carbon in a) above-ground biomass, b) below-ground biomass, c) soil and litter, d) upstream and downstream processes (e.g., substitution effect of biomass as fuel instead of fossil fuel, products of further processing like furniture, or management: reduction of agri-chemicals on arable sites through agroforestry). Furthermore, it is crucial that the certification does not endanger any entitlement for agricultural or environmental subsidy schemes of the CAP. They conclude that certainly the woody parts of agroforestry systems sequester significantly more carbon in the long term compared to cropland and pasture (in most cases). The financial reward should consider this additionally to the investment costs of establishing agroforestry (Hübner et al., 2022).

1.1.3. Soil Quality Assessments

According to Bünemann et al. (2018), assessments of soil quality should only be conducted in relation to one or several soil functions, ecosystem services or soil threats and should evaluate management and societal demand (like ecosystem services). It is difficult to detect

changes in soil quality as it reacts slowly to changes in soil management. Therefore, it is important to identify soil attributes that allow interpretations on soil function and can be used as indicators for soil quality. After analysing 62 publications on soil quality, the authors explain that a good soil assessment approach needs four steps:
First, clear objectives must be determined to identify for what a “good soil quality” is needed, as different aims might defer in their definition of what a good soil quality means.
Second, target users of the assessment must be defined to increase adoption.
Third, suitable indicators for soil quality should be set, based on the aimed soil function or ecosystem services.
Finally, references and a suitable interpretation of indicators should be established to provide management advice and improvement of the assessment (Bünemann et al., 2018).

1.2. Aims and Objectives

As described before, very few studies investigated carbon sequestration potential and soil improvement comparing compost, activated and non-activated biochar substrates in temperate climates. The questions framing this study are:

1. Can the study site be improved for agricultural cultivation regarding different soil parameters through the application of different substrates? Will there be differences in the level of improvement comparing the three substrates?
2. How will the carbon sequestration potential be influenced through the application of the different substrates?

This study is conducted on sandy acidic soils in temperate climate. Therefore, it is expected to find the strongest effects here, if any at all, as the highest potential for improving soil quality and sequestering carbon was found on highly weathered, sandy, acidic soils in humid climates, too.
It will be investigated if the application of different substrates leads to an improvement in soil quality regarding a good agricultural value, comparing compost, activated and non-activated biochar. It is expected that all substrates will increase some soil parameters like pH-value, TOC or plant-available nutrients, while the activated biochar has a stronger effect than the non-activated and the compost.

Furthermore, it will be analysed, if carbon is sequestered through a single application of different substrates on infertile sandy soils in Lusatia. Again, it is expected, that the activated biochar will have a stronger effect on the carbon sequestration, but all variants will sequester carbon. Additionally, the long-term carbon sequestration potential through the use of agroforestry-based biochar will be estimated.

2. Materials and Methods

2.1. Site Description and Project Background

The experiment site is located in Peickwitz, Germany, more specific at 51°27'32.41"N, 13°58'31.13"E, as can be seen in Fig. 1. The average annual precipitation is 550 mm, the average annual temperature 9.6 °C (DWD, 2021; Riecken and Böhm, 2017). The experiment was established on sandy soils (brown earth-rigosol with 93 % sand, 5 % silt and 2 % clay) with 20-25 soil points (German standard to estimate soil quality for agricultural production of soils based on, e.g., soil type, climate and slope, developed from and since the "Reichsbodenschätzung" in 1934 (Blume et al., 2010)) on an agroforestry site (arable land intercropped with short-rotation coppice-stripes) which was planted in 2015 to reduce the high exposure to wind and, thereby, reduce erosion. Being 70 m West of an agroforestry stripe planted with *Robinia pseudoacacia* for the extraction of pasture posts, and 80 m East of an agroforestry stripe with *Populus spec.* for wood chip production, it is located in the middle of the field (Hübner et al., 2021). Apart from *Robinia pseudoacacia* and *Populus spec.*, *Alnus glutinosa* is included in other agroforestry systems on the farm. In an initial investigation in August 2021, the overall TOC content was 2.4 %.

After the harvest of rye in July 2021, the arable part was treated with a disc harrow and mustard was sown. The substrates were applied on the residues of the mustard and mixed with the topsoil using a rotary tiller in 5 cm depth in March 2022 right before the sowing of oat. Due to the extreme drought, the oat was abandoned in May 2022 and millet was sown.

Figure 1: Location of the experimental site in Germany

This thesis is embedded in the sub-project 3 of the AgroBaLa project (agroforestry circular economy as a basis for a climate resilient agriculture, rich in structure with a high potential of creating value) funded by the federal ministry of education and research, which aims to increase climate change adaption and value creation of arable sites to strengthen structural development in rural Lusatia. Both aims are depending on the agricultural production which is to be improved by introducing an agroforestry circular economy, experimenting with different crops (herbs, arable crops and trees) but also by increasing soil organic matter content (Land-Innovation-Lausitz, 2019).

2.2. Experimental Design

Four different variations were established in this experiment. To estimate the effects of different substrates that would occur much later with a more often but little amount of applied substrate during this short-term project, this single application aims to increase the TOC content by approximately 1 % to 3.5 %. The amount of TN applied should not exceed the requirements of the Fertiliser Ordinance and should be appropriate to the site conditions.

The German Fertilizer Ordinance ("Düngeverordnung vom 26. Mai 2017 (BGBl. I S. 1305), die zuletzt durch Artikel 97 des Gesetzes vom 10. August 2021 (BGBl. I S. 3436) geändert worden ist") aims to avoid nutrient run off by applying fertilizers at the right time and amount while meeting the nutrient needs of the crops. It is based on a fertilizer requirement calculation including a N-requirement value and increases and reductions for, e.g., the current Nmin, estimated yields, different soil properties and planned fertilizations. The result of the calculation may not be exceeded by more than 50 kg N ha^{-1} in the mean over three years (KTBL, 2018).

The four plots are oriented parallel to each other in an almost North-South direction parallel to the driving lanes of the field, leaving the headlands out. The plots are sized 10 m x 240 m = 2,400 m^2 each.

The four variations were established from West to East as followed: control (C), green waste compost (GWC), non-activated bio char substrate (NABC), activated bio char substrate (ABC). The properties of the unamended soil and the compost, fermentation residue and the activated biochar used in this study can be found in Table 1. The arrangement can be seen in Fig. 2 and the variations are explained in the following:

The control plot was fertilized with 3.7 t fermentation residues (12.35 t ha^{-1}), aiming to apply 100 kg TN/ha/a. This would lead to an application of approximately 1.24 t carbon per hectare, which is assumed to decompose during the year and to not build up stable carbon compounds.

As it is often discussed whether compost or bio char substrates are the better soil amendments, the green waste compost variation was installed to receive a direct comparison. An increase of the TOC content by 1 % through green waste compost would exceed the maximum quantity according to the fertiliser ordinance and, therefore, would not be practical relevant. To obtain the practical relevance, the treatment aims to apply 100 kg TN per ha and year instead, so in total 300 kg TN ha^{-1}, as compost treatments are regularly applied every three years. Taking the total nitrogen contents of the compost into account, 11.25 t compost per plot were applied, which results in an application of 4.23 t carbon per hectare.

As presented earlier, differences were found between activated and non-activated substrates by other studies. To investigate these findings under temperate conditions on sandy, acidic soils, a non-activated biochar application was included in this experiment.
In the activated bio char compost variation, 80 % bio char, 10 % rock flour and 10 % grain bran were fermented with 3.7 t fermentation residues, an effective microorganism (EM)-solution and water (1:10 to 1:50 ratio) over six weeks, starting in January 2022. To raise the carbon content to 3.5 %, 41 t carbon per hectare were needed. With a carbon content of 80 %, 51.25 t biochar per ha were needed, resulting in 15.38 t per plot.
The non-activated bio char compost variation was not fermented, but the ingredients (without the EM-solution) were mixed together directly before the application to the plot, in the same ratio like in the activated variation.
It is to mention, that the non-activated biochar differs from the definition in the introduction, as both biochar substrates were amended with fermentation residues to achieve a practical comparison to the control plot. In this specific case, the difference between activated and non-activated substrates is related to the addition of EM's and the fermentation process.

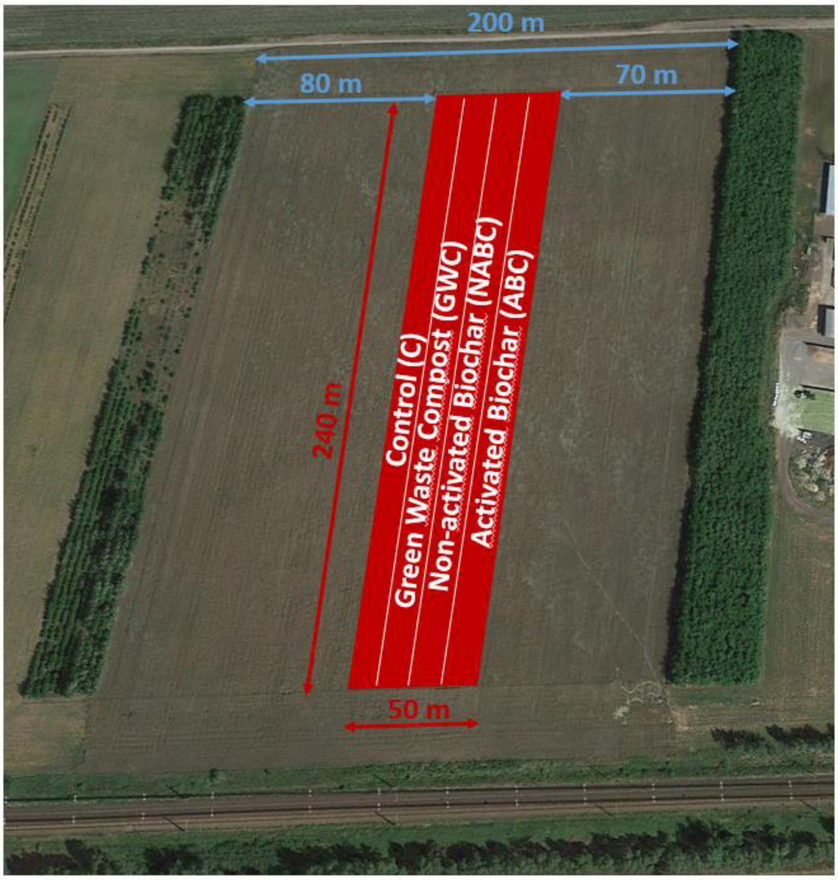

Figure 2: Arrangement of the variations at the experimental site in Peickwitz, Germany

2.3. Soil Quality Assessment

Keeping the baselines explained by Bünemann et al. (2018) in mind, the objectives of the soil assessment of this study are clearly stated in section 1.2..

The target users of this assessment are scientists and project related farmers of AgroBaLa, so the results should be transformable for scientists to the public and should allow easy drawn management advice for the farmer.

Therefore, indicators with a standard method and high availability of reference and interpretation material were very attractive for this study. Furthermore, due to the relatively short-term lab phase of the project (March 2022 – July 2022), methods that do not take a lot of time are suitable.

Bünemann et al. (2018) report an average indicator number of eleven with a minimum number of six to eight investigated parameters. Furthermore, they suggest a diversity of methods, not to use indicators that focus on either inherent or manageable attributes, but cover both. Also, chemical, as well as biological and physical attributes should be investigated.

As the main aim was to investigate how the application of different substrates influence soil carbon sequestration and agricultural related soil quality (availability of nutrients, pH-value etc.), investigations in 0.30 cm soil depth were most suitable. Taking the other requirements mentioned earlier into account, TOC, pH, plant-available P and K, TN and Nmin as most frequently used chemical indicators were investigated in this study. Soil water content and bulk density as often used physical parameters were analysed, as well as microbial biomass as a regular biological attribute. The last mentioned also supports a better indication for soil organic matter processes together with analyses of the labile C-pool through hot-water extraction. Another biological indicator like earthworm density (which would have indicated changes in water and nutrient cycling too) could have been interesting too but we expected major changes due to seasonal differences in soil quality and moist than changes due to different variations, why this method was excluded. Other physical investigations on water storage parameters, e.g. water retention curves would have been of immense interest regarding the climate adaption potential through fertilization with different substrates on the dry soils in Lusatia but, unfortunately, those investigation would have taken too much time.

The analysed parameters were chosen because of their practical relevance (e.g. pH, P, K, Nmin) and their comparability with other studies (e.g., pH, TN, TOC in Liu et al. (2012)).

2.4. Soil and Substrate Sampling

The soil and substrates were sampled on 10th March 2022 prior the substrate application and on 15th June 2022, 13 weeks after the application of the different substrates. Every variation plot was divided into four sub-plots from South to North (A, B, C and D). For the mixed disturbed soil samples, every sub-plot was sampled every 10m from North to South, so six samples formed one disturbed sample. In total, 4 mixed disturbed samples were taken per variation (one of each sub-plot). A soil auger was used to produces soil samples from 0 cm - 30 cm depth.

Three 100 cm^3 undisturbed soils samples were taken per sub-plot (so 12 per variation), always at the third position of the mixed sampling counting from South. They were taken in 15- 20 cm depth.

2.5. Lab Investigations

2.5.1. Preparation of Soil Samples

Right after taking the mixed soil samples, each sample was homogenised and a part of the sample was separated for fresh soil investigations (Nmin, water content and Nmic), while the rest of the bag was opened and placed at 40 °C in a drying cabinet for dry soil analyses. Afterwards, they were sieved to 2 mm to determine the coarse soil content.
Two of the three undisturbed samples were placed in the drying cabinet at 105 °C until weight consistency to calculate the bulk density (Blume et al., 2011, p. 87).

2.5.2. Analysis of Soil Samples

To measure the gravimetric soil water content, 10 g of fresh soil were given into a weighted crucible, dried at 105 °C until weight consistency and, after cooling in the desiccator, reweighted.
To determine the soil organic matter content, afterwards, the samples were annealed in a muffle stove at 450 °C for 2-4 h and reweighted after cooling in a desiccator, following DIN 19 684-3.
The soil water content and soil organic matter content were calculated according to (Blume et al., 2011, p. 132).

For analysing Nmin, 100 ml of 0.01 M $CaCl_2$-solution was added to 25 g of fresh soil. After shaking for 30 min., the solution was filtered using *sartorius filters 292a* and Nmin measured photometrically in a *FIA compact* module. The values were calculated according to the following formula:

$$Nmin\ \left[\frac{mg}{kg}DM\right] = \left(\frac{NH_4^+ - N \times V \times 100}{fS \times DM}\right) + \left(\frac{NO_3^- - N \times V \times 100}{fS \times DM}\right)$$

Formula 1: Calculation of mineralised nitrogen (Nmin)

With:

NH_4^+ - N = *FIA compact* - measured ammonium in mg L^{-1}

NO_3^- - N = *FIA compact* - measured nitrate in mg L^{-1}

DM = dry matter content in %

V = volume of solution in ml

fS = amount of fresh soil in g

To measure the soil microbial biomass, the samples were treated according to (Vance et al., 1987) and analysed in a *Shimadzu TOC-VCPH*. Following the methods according to Böhm (2005), the extracted C (Cext) and N (Next) were calculated with the following formula:

$$Cext\ or\ Next\ \left[\frac{mg}{kg}\right] = \frac{(E_F - E_{NF}) \times V \times 100}{fS \times DM}$$

Formula 2: Calculation of Cext and Next according to Böhm (2005)

With:

E_F = TOC or TN of the fumigated sample in mg L^{-1}

E_{NF} = TOC or TN of the non-fumigated sample in mg L^{-1}

DM = dry matter content in %

V = volume of solution in ml

fS = amount of fresh soil in g

Using the k_{EC}-factor 0.45 and the k_{EN}-factor 0.54 according to Jörgensen (1995), the microbial C (Cmic) and N (Nmic) were calculated as followed:

$$Cmic\ \left[\frac{mg}{kg}\right] = \frac{Cext}{k_{EC}}$$

Formula 3: Calculation of Cmic using the k_{EC}-factor (and the k_{EN}-factor to calculate Nmic) according to Böhm (2005)

For the investigation of hot water extractable C and N, 10 g of dry soil were boiled with reflux cooling for 1 h after 50 ml distilled water was added. The flasks were closed with a rubber plug directly afterwards and placed into a cold-water bath for cooling. After decanting the solution into a centrifuge tube, two drops of 2 M $MgSO_4$-solution were inserted and the samples centrifugated with 4000 rotations per minute for 10 minutes in a *Beckman Coulter Allegra X-12R Centrifuge.* Decanted into flasks, the sample solution was kept refrigerated until measured in a *Shimadzu TOC-VCPH*. Calculation accomplished according to (Blume et al., 2011, p. 149).

To investigate the TOC and TN, dry soil was ground to a fine dust and analysed in an *elementar vario MICROCUBE* following the producer's instructions.
For determining double lactate extractable P and K methods according to VDLUFA (1991) were used. After following the methods by (Blume et al., 2011, p. 132), the solution was measured in *Thermo Fisher Scientific iCAP 6000 Series*. Calculation was done using the following formula:

$$P_{DL}\ \left[\frac{mg}{kg}\right] = \frac{P \times V \times 1000}{dS}$$

Formula 4: Calculation of P_{DL}

With:
P = *ICP* – measured P in mg L^{-1}
V = volume of solution in ml
dS = amount of dry soil in g
This formular was followed equally for the calculation of K_{DL}.

For the analysis of the pH-value, 10 g of dry soil were infused with 25 ml 0.01 M $CaCl_2$-solution, shaked, left to rest for 15 min., shaked again and left to rest for another hour. After calibrating the system, the pH-value was measured using a *WTW Multilab 540.*

The carbon stock (TOCstock) was calculated using the formula according to (LfL Bayern, n.d.):

$$TOCstock = TOC \times BD \times \frac{100 - CSC}{100} \times\ SD\ \times\ 0.1$$

Formula 5: Calculation of carbon stock according to LfL Bayern (n.d.)

With:

TOC = measured organic carbon in mg g^{-1}

BD = bulk density in g cm^{-3}

CSC = coarse soil content in %

SD = soil depth in cm

2.6. Statistical Analysis

All statistical analyses were accomplished using the software RStudio Version 4.1.2. (2021, the R Foundation of Statistical Computing) including the packages "GGally", "ggplot2", "agricolae", "gplots", "tidyverse", "rstatix" and "ggpubr".

Correlation between parameters were identificated using Spearman's rank correlation coefficient.

Using the Shapiro test, all parameters were considered to be normally distributed if the significance level was less than 0.05. If the bartlett test indicated equal variances through a p-value higher than 0.05, an ANOVA followed to determine significant differences between the variations, which were then grouped, using a HSD-Tukey test.

To investigate differences between the first sampling period in March and the second in June, a Wilcoxon signed-rank test was used.

3. Results

The results of the laboratory investigations from March 2022 can be found in Table 1. The mean dry matter of the soil was 90.00 ± 0.962 % in March and 95.29 ± 0.75 % in June. The overall bulk density is 1.40 ± 0.051 g cm^{-3} and the mean coarse soil content was 2.02 ± 0.645 % in March and 1.73 ± 0.375 % in June. The hot water extractable organic carbon made up 83 % of the total hot water extractable carbon.

The TOC was linked with the other Carbon parameters (hot water extractable total organic carbon (HWTOC), hot water extractable total carbon (HWTC) and Cmic), that raised or declined with an increase or decrease of TOC, as well as the humus content. TN and Nmic also changed in relation to TOC. Furthermore, more double-lactate extractable K (K_{DL})

became plant-available with an increasing TOC. The humus content followed the same positive correlations.

Close to this relation were the values of TN: It increased with higher values of HWTOC, HWTC, HWTN, Cmic, Nmic and K_{DL}.

Even though no significant differences between March and June were found using the Wilcoxon signed-rank test, the variations differed significantly regarding Cmic and Nmic, as can be seen in Figure 3 and 4. The ANOVA showed that the ABC treatment was significantly higher compared to C and GWC concerning the Cmic and Nmic (p-value = 0.02145 and 0.02302, respectively), while only slightly compared to the NABC-variation. Furthermore, Nmin showed a positive correlation to HWTOC and HWTC.

The humus content and all carbon and nitrogen parameters decreased with a higher pH-value and vice versa.

Table 1: Properties of Fermentation Residue, Compost, Activated Biochar Substrate and the Soil in August 2021 and March 2022

	TOC (%)	TN [%]	TOC/TN	HWTOC [mg/kg DM]	HWTN [mg/kg DM]	HWTOC: HWTN	Nmin [mg/kg DM]	pH-value (CaCl2)	DL-P [mg/kg DM]	DL-K [mg/kg DM]	Humus Content [%]
Soil August 2021	2.4	-	-	-	-	-	-	-	-	-	-
March 2022	1.92	0.14	14.10	905.15	42.88	21.13	4.16	5.96	221.97	141.18	3.71
Fermentation Residue	42.97	1.40	30.69	77,530.62	3,331.47	23.27	5,256.24	9.46	2,269.59	16,958.79	84.34
Compost	11.27	1.17	9.63	14,390.62	1,161.47	12.39	554.74	7.02	1,181.59	4,439.79	22.15
Activated Biochar Substrate	64.32	0.55	1,16.95	11,720.62	508.57	23.05	0.91	6.71	311.99	2,870.79	79.24

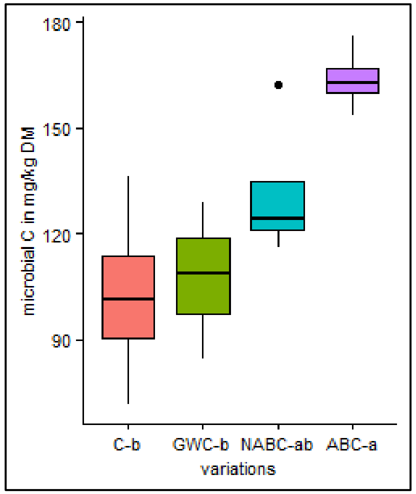

Figure 3:Differences of substrates (Control (C), green waste compost (GWC), non-activated biochar (NABC) and activated biochar (ABC)) regarding the microbial carbon

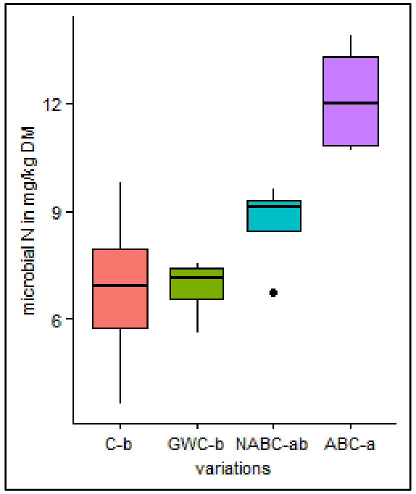

Figure 4: Differences of substrates (Control (C), green waste compost (GWC), non-activated biochar (NABC) and activated biochar (ABC)) regarding the microbial nitrogen

3.1. Soil Carbon and Soil Nitrogen Parameters

The aim of the application was to increase the TOC content by 1 % to 3.5 %. As can be seen in Figure 5, in March 2022 the TOC content was 1.92 ± 0.28 %, which was similar to the TOC content in August 2021 of 2.5 %. From March to June, the TOC content increased to 2.14 ± 0.24. This is not exactly an increase of 1 %, but still an increase. Anyway, no significant differences were found between March and June. Taking the number of soil samples per variation into account, even small outliers would lead to no significant results. Comparing the medians of the parameters between March and June with each other, tendencies were found: As mentioned, from March to June, the TOC of the soil increased, as can be seen in Figure 5. Similarly, TN and Nmin increased between the two sampling dates.

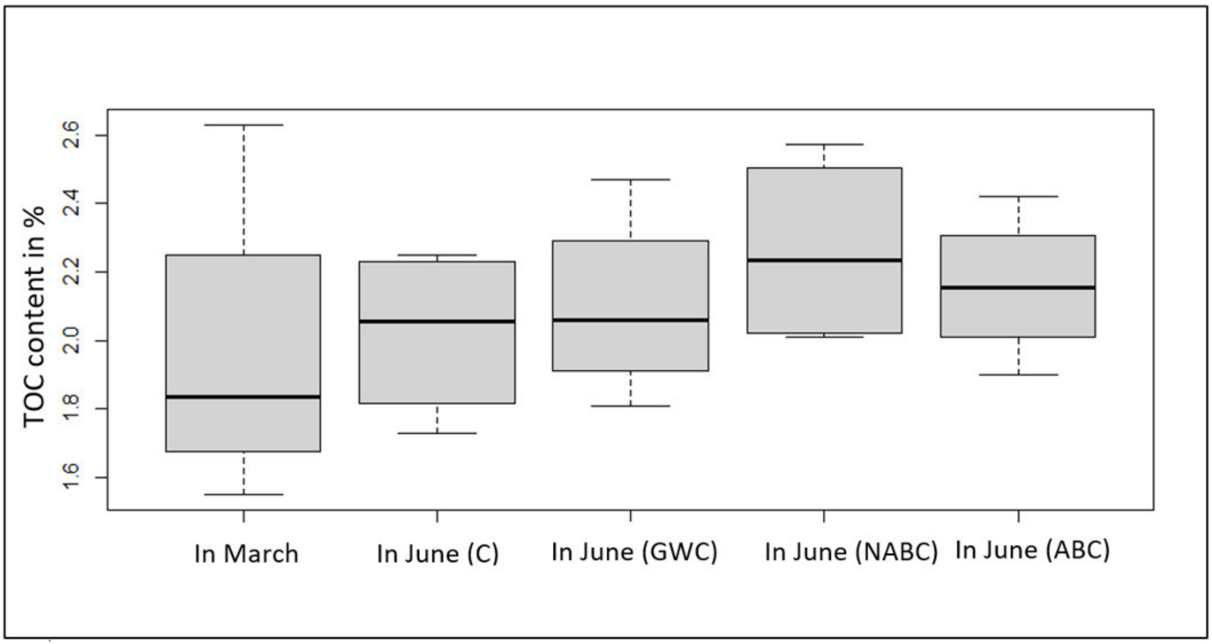

Figure 5: Development of total organic carbon content between March 2022 and June 2022 with C = control; GWC = green waste compost; NABC = non-activated biochar; ABC = activated biochar

In March 2022, the carbon stock was 78.87 t TOC ha^{-1}. After the application of the substrates, no significant difference was detected. The carbon stocks in June were 80.98 t TOC ha^{-1}, 78.3 t TOC ha^{-1}, 77.88 t TOC ha^{-1} and 79.41 t TOC ha^{-1} for C, GWC, NABC and ABC, respectively.

The ratio of TOC to hot water extractable organic carbon increased from 20.55 in March to 26.87 in June, and the ratio of TOC to Cmic from 144.27 to 169.93. The ratio of HWTOC to Cmic was similar from March to June with 7.02 and 6.32, respectively.

3.2. Soil pH value

There were no significant differences found between the pH-values from March to June, but all parameters showed normality and equal variances, while significant differences between variations were found regarding the pH-value. As can be seen in Figure 4, the pH-value of ABC was significantly higher than those of C, GWC and NABC. Relations were also found with other parameters: A decreasing pH-value was followed by higher TOC- and TN-contents, HWTOC and HWTC, HWTN, Cmic, Nmic, Nmin, K_{DL} and a higher humus content.

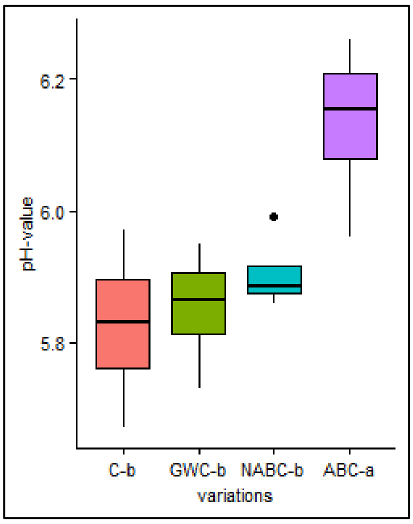

Figure 6: Differences of substrates (control (C), green waste compost (GWC), non-activated (NABC) and activated biochar (ABC)) regarding the pH-value

3.3. Double Lactate extractable Nutrients

P_{DL} was not significantly influenced by any other measured parameter, any substrate or time. The K_{DL} raised with higher amounts of TOC, TN, HWTOC, HWTC, HWTN and Cmic and decreased, as mentioned, with a higher pH and vice versa.

4. Discussion

4.1. Comparison of Initial Laboratory Analysis to previous Investigations

Compared to a Vega in North Germany, the bulk density in this study site is average (Blume et al., 2010).

4.1.1. pH-value

According to Blume et al. (2011, 2010), the optimal pH-value for soils with a humus content lower than 4 % and less than 5 % clay range between 5.0 and 5.5. The lower the pH, the lower the CEC. Compared to the forementioned literature, the measured pH-value on the study site indicates a moderate to slightly acidic soil, which is a little above the optimum, but in relation to average soil pH-values on arable sites in a good condition for agricultural production (Blume et al., 2011, 2010).

4.1.2. Double Lactate extractable Nutrients

According to Blume et al. (2010), average P_{DL}-values on sandy soils are less than 100 mg kg^{-1}. Also compared to fertilizer guidelines by Brod (2004), the here measured P_{DL}-values are twice as high as the maximum value for oversupplied soils. In a conversation with the farmer, the assumption was confirmed: Historically, the farm was a large pig producer, the proximity of the field to the farm led to a regular application with pig slurry. As a monogastric animal, pigs excrete higher P contents compared to ruminants (Sommer et al., 2013).

Regarding the K_{DL}, the soils are well supplied for agricultural production with no need for further fertilization (Brod, 2004).

4.1.3. Soil Carbon and Nitrogen Parameters

Depending on the carbon content of the soil organic matter, humus contents normally range between 1.724 and 2.00 times the TOC, like in our investigation, too (Blume et al., 2010). On sandy soils in Bavaria, the mean TOC content was 1.16 % with maximum contents of 1.69 % (Capriel, 2010). An extensive world-wide meta-analysis of different studies (n=1762) found mean TOC contents of 1.3 % on sandy soils with 30 % of the experiments had higher contents, especially in temperate, colder climates (Yost and Hartemink, 2019). Compared to a Vega in Northern Germany, the TOC content in this experiment is quite similar, but for a sandy soil, it is somewhat above average (Blume et al., 2010). This could be explained by the fact that the site lies in a former coal mining area, so coal dust might contribute to higher carbon contents without having the positive effects on soil quality.

Blume et al. (2010) found for temperate climates on cropland mean TN between 0.7 and 2 g kg^{-1}. Also, our values were confirmed as average by Capriel (2010), who found a mean TN content of 0.095 % with maximum measurements of 0.154 % on sandy soils in Bavaria. The ratio of TOC and TN followed those of other studies in average heights (Blume et al., 2010; Glisczynski et al., 2016; Greenberg et al., 2019) which indicates a moderate humus turnover (Hoth and Meisel, 2004).

Regarding the HWTC, our measurements were twice as high as on comparable soils, more aligning with intensively fertilized pastures than with infertile cropland (Bankó et al., 2021; Böhm, 2005). Also, experiments on pasture very close to our experimental site showed lower HWTC levels (Böhm et al., 2020a). In Ghani et al. (2003), an experiment on soils with similar pH-values, a possible reason was described: "Long-term application of P had a positive influence on the amounts of HWC levels in the soils". The regular and high pig slurry applications in the past resulted in high P applications, and thereby, might have led to extremely high HWTC. HWTN was comparable high to a fertilized cropland in Bankó et al. (2021).

The microbial biomass (Cmic, Nmic, ratio Cmic:Nmic) in March was average compared to Böhm (2005).

Mineralised N is known to be a highly variable soil parameter, strongly influenced by temperature and soil moisture (Blume et al., 2010). With 17.47 kg ha^{-1}, the findings were very similar to multiple measurements on the pasture nearby by Böhm et al. (2020a).

4.1.4. Substrate Parameters

Comparing with other studies, the parameters of the fermentation residues, green waste compost and activated biochar substrate did not show significant high or low values, the values in literature also differed greatly (Glisczynski et al., 2016; Greenberg et al., 2019; Mukherjee et al., 2014; Schulz et al., 2013).

4.2. Comparison of Statistical Results

Overall, the literature suggested an increase of TOC through the application of organic substrates in general, which was not confirmed significantly in this study but tendencies revealed (Glisczynski et al., 2016; Sánchez-Monedero et al., 2019; Tan et al., 2017). The linkage between all carbon parameters seem naturally, as HWTC and Cmic are compartments of TOC, and TOC is a large part of the humus content (Blume et al., 2010). This was confirmed by Sparling et al. (1998), who found a linear relationship between HWTC and Cmic. No significant differences in Nmin did not confirm results of (Hagemann et al., 2017; Sohi et al., 2010), where reduced nitrate leaching in soils amended with biochar was found. But our results suggest similar tendencies, which might be confirmed with a higher sample number per variation.

Jeffery et al. (2011) pointed out that significant results differed a lot between different studies, so the results in this study should be interpreted carefully as well. E.g., Glisczynski et al. (2016) did not find as clear results regarding the pH-value as in our investigation, while Mukherjee et al. (2014); Novak et al. (2014;) Tan et al. (2017) found clearly increased pH-values through the application of different organic substrates.

Similarly, a direct interpretation of the differences of increased Cmic and Nmic regarding the variations might be misleading. The results hint towards a higher microbial biomass through biochar soil amendments that do not only originate from the addition off an EM-solution, but from the biochar itself as the NABC also show differences to the C and GWC. But in literature, results regarding microbial biomass differ strongly: While a decrease of microbial biomass through biochar addition as rarely found, Pokharel et al. (2020) pointed out that the level of increase varied strongly among different experiment types. Xu et al. (2016) found an increase of Cmic and Nmic only under the highest biochar application, while Zhang et al. (2014) found no increase at all through biochar, but through other organic amendments. The variety of significant results in literature is based on the extremely difficult comparability due to the variation of different biochar experiments (Jeffery et al., 2011; Pokharel et al., 2020). Additionally, the effects of biochar on soil properties depend strongly on feedstock, pyrolysis temperature, but also on site specific parameters, so the variation of results among biochar studies differ even more (Li et al., 2020).

4.3. Outcome regarding the Improvement of Soil Quality

Regarding the pH-value, the ABC was significantly higher than the other substrates, even though no significant differences were found between March and June.
Maybe, with a larger number of soil samples per variation, a significant difference would have been detected and the tendency of an increased TOC confirmed, too. K_{DL} was positively related to TOC, so there could have been a significant increase with a bigger sample size, as well. As explained before, those results would have to be interpreted carefully, due to the high variability in different experimental setups and biochar.
In summary, the hypothesis of improved soil quality through different substrates and especially through ABC could not be confirmed, although tendencies occurred.

Increasing the soil carbon by 1 % led to an application of more than 50 t biochar ha^{-1}, which, according to Borchard et al. (2014a); Liu et al. (2013) would not result in a higher improvement of soil parameters compared to slightly lower amounts. This high application rate had no practical relation and did not achieve its' aim to increase the TOC by 1 % either, but was chosen, because of the short time period of the project, that would not have covered the costs of a long-term experiment.
As the compost variation would have exceeded the fertilization ordinance, less C was applied compared to the other variations. From a practical point of view, mixing the ABC and NABC with fermentation residues was senseful, as the biochar itself offers little nutrients. But, as already sketched in the Materials and Methods, the non-activated biochar did not meet the definition of most other studies. This and the forementioned arguments made a comparison of the experiment with others difficult.

Many studies investigated the substrates effect on crop yields (Schmidt et al., 2015; Sohi et al., 2010). Due to the time frame of this master thesis, this was unfortunately not possible. For further project investigations, measurements of crop yields are interesting and planned but might become tricky due to the extreme draught in Lusatia this year.
Furthermore, a regular investigation of TOC would be interesting, as Schulz et al. (2013) found it decreasing during the growing season, especially on sandy soils.

4.4. Carbon Stocks and Carbon Sequestration in the existing Context

The carbon stocks did not change significantly between March and June and were in an average level for agricultural soils (Blume et al., 2010; Mayer et al., 2022). This might support the statement that regular applications of organic fertilizers increase carbon stocks in the long-term, not a single application in a short timeframe (Gattinger et al., 2012; Lal, 2006). To confirm this, regular investigations of the carbon stocks are crucial.

To estimate the carbon sequestration potential of the whole site, carbon stocks under the agroforestry stripes should be analysed as well, as they might be higher than in the arable part (Mayer et al., 2022).

The increase of carbon ratios suggests an increase of stable carbon compounds in June compared to March. This would support the indication of increased TOC through substrate applications. Furthermore, these compartments could contribute to a long-term carbon stock, as only the more stable parts increased, while the ratio of instable carbon compartments (Cmic and HWTOC) stayed level.

Regarding the project context, AgroBaLa aims to investigate the potential of a circular economy through agroforestry for a rural structural development, climate change adaption and value creation in agriculture (Land-Innovation-Lausitz, 2019). Naming agroforestry wood for fossil fuel substitution and biochar for soil amendments as examples, their potential to support circular bioeconomy was highlighted in Rois et al. (2019). Using agricultural land for food production for biomass production instead is not a sustainable way to sequester carbon (Werner et al., 2018), but Woolf et al. (2010) highlighted the huge potential of decentralised small-scale biochar production for a sustainable carbon sequestration. In the context of the experiment farm where agroforestry wood chips for heat production are produced, the biochar is a valuable side-product, especially compared to buying biochar for soil amendments. On a farm with livestock partly kept in stables, the biochar activation could be accomplished using organic fertilizers, e.g., pig slurry or cows' manure for composting or fermentation processes.

Furthermore, production costs can be reduced through the own heat and energy production, which is planned to be used most efficient by installing a drying engine for feed and wood. This even offers the potential to generate value if surpluses can be sold to local energy suppliers and, thereby, cover some parts of the of the high investments for agroforestry plantations discussed before. With the appropriate communication methods, even the common people can be reached and connected to agriculture, if, e.g., the benefits of agroforestry are transferred to them by their energy suppliers.

In the timeframe of this thesis, the pyrolysis plant was not completely installed, yet. Therefore, unfortunately, site related evaluations of wood yield, heating efficiency and value and biochar yields were not possible. These parameters would have allowed calculations of the substituted fossil fuels by biomass heating, too.

In the long-term, these parameters can be analysed and, together with data about crop yields and water holding capacity allow more detailed answers about the carbon sequestration potential and soil improvement potential of the site.

The public has a rising interest in carbon certificates, especially for local compensation mechanisms (Mayer et al., 2022). The current available certification systems vary immensely regarding their calculation basis. This is mainly because scientific publications are very diverse and the sequestered carbon is difficult to determine, as can be seen in this study, too. The forementioned investigations will be crucial to reach the project aims of AgroBaLa and to allow statements about carbon certification systems.

5. Conclusion

This thesis investigated if soil quality for agricultural production can be improved through the use of different compost and biochar substrates on low-fertile, sandy soils in Lusatia, Germany. Due to the small sample size, no significant results were found comparing soil analyses prior and after the substrate application. Anyway, the results indicated an increase of TOC from March to June through all variations. Hot water extractable carbon was found to be very high compared to data in literature, which was related to high P-fertilizations in the past. The pH-value rose in the ABC treatment and both biochar substrates seemed to increase Cmic and Nmic. But regarding the microbial biomass, the literature research rose very differing findings, so the results should be interpreted carefully.

Furthermore, the influence of those substrates on the carbon sequestration potential of the site was analysed. It became clear that some important parameters were missing to evaluate the potential of the site. E.g., many publications suggested long-term measurements. Also, the carbon stock of the tree stripes would have been interesting to determine.

Especially in the context of carbon certificates or assessing biochar as a geoengineering technique, data like wood yield in agroforestry systems, heating efficiency and value, biochar yields and associated substitution effects of fossil fuels would have been interesting to calculate. Regarding soil improvement on sandy soils in Lusatia, investigations of water holding capacity and crop yields would be valuable parameters for further research.
Overall, the soil quality did not show significant improvements, nor were significant differences in the carbon stocks (and thereby in the sequestered carbon) found, even though the results indicated increased TOC. The results encourage investigations with a higher sample size and clearly structured variations that accompany other literature to work towards a better overall understanding of biochar as a soil amendment.

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