Production and Use of Biochar from Agricultural Plant Residues

Consequences for climate and soil fertility

Master's thesis in Industrial Ecology

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Abstract

The agricultural sector plays a significant role in contributing to climate change while at the same time being vulnerable to its impacts. With approximately one fifth of the world's total greenhouse gas emissions originating from agriculture, there is a growing interest in developing agricultural practices that combat climate change while simultaneously enhancing soil health and fertility. This thesis aims to address this challenge by developing an agricultural carbon flow model to quantify climate mitigation potentials of producing biochar using agricultural plant residues as feedstock, at various pyrolytic temperatures. Additionally, a comprehensive literature search was conducted on the interactions between biochar and different types of soils. The results from the literature search along with the model was applied to the Swedish agricultural production region Götalands norra slättbygder to analyze and discuss the outcomes in a practical case.

The research findings reveal that biochar soil amendment holds promising potential in enhancing various aspects of soil health and fertility. Through its interactions with soil properties such as crop yield, pH, water retention, nutrient retention, soil organic carbon content and bulk density, biochar can help reduce the reliance on synthetic fertilizers, irrigation, lime, and pesticides while at the same time increasing soil fertility. Furthermore, the study highlights significant possibilities for employing biochar as a climate mitigation technology. The carbon sink potential of biochar was found to depend heavily on pyrolysis temperatures. At the same time biochar production generates surplus heat, and its use as soil amendment can potentially decrease agricultural nitrous oxide emissions. This generates indirect climatic benefits additional to the direct biochar carbon sink. Consideration is however required before implementing biochar soil amendment. For example, biochar has been found to decrease soil albedo when applied to soil and the harvest of pyrolysis feedstock can potentially disrupt a cropland's nutrient cycling.

In conclusion, this thesis contributes to the understanding of agricultural carbon flows in agricultural biochar producing systems, biochar-soil interactions, and the potential of biochar in climate change mitigation. When the biochar production and soil amendment impact potential was assessed in Götalands norra slättbygder, it was concluded that a carbon sink of about 440 000 tons of carbon dioxide equivalents could be produced annually, while at the same time potentially improving the overall soil fertility in the region.

Keywords: biochar, carbon dioxide removal, soil amendment, agricultural residues, carbon sequestration, carbon flow modelling, climate change mitigation.

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Viktor Skans & Hanna Steinum, Gothenburg, May 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

APR	Agricultural Plant Residues
BSA	Biochar Soil Amendment
CEC	Cation Exchange Capacity
DM	Dry Matter
GHG	Greenhouse Gas
GNS	Götalands norra slättbygder
IPCC	Intergovernmental Panel on Climate Change
MRT	Mean Residence Time
NET	Negative Emission Technology
NPP	Net Primary Production
PAH	Polycyclic Aromatic Hydrocarbons
PFA	Per- and Polyflouroalkyl Substances
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SSA	Specific Surface Area

Contents

1

Introduction

The agricultural sector is both a significant contributor to climate change and vulnerable to its effects, accounting for roughly one fifth of the world's total greenhouse gas (GHG) emissions [1]. Consequentially, there is a large interest in developing agricultural practices that not only combat climate change, but simultaneously improve soil health and fertility.

One such practice is the production and use of biochar, deemed by the Intergovernmental Panel of Climate Change (IPCC) as a viable and readily available option for removing carbon dioxide from the atmosphere [2]. Biochar is produced through thermochemical conversion, i.e. pyrolysis, of biomass at high temperatures in an oxygen free environment. This results in a stable, carbon-rich material that in itself aids in climate change mitigation, and when used as a soil amendment has proven potential benefits for soil fertility [3]. Since the feedstock is biogenic, the carbon stored in biochar can be seen as net reduction in atmospheric carbon dioxide.When this organic carbon is used to produce biochar, the organic carbon is stabilized and, depending on use, sequestered.

Although virtually any biomass can be used as feedstock, certain biomasses are more suited than other for biochar production, for several reasons. Waste streams such as agricultural plant residues (APRs) are usually not utilized and are ultimately left to decompose, resulting in the organic carbon being released back into the atmosphere within a short time frame [4]. Such residues are therefore beneficial as feedstock for biochar production, but also because its production does not compete with food production nor contribute to land use change.

This thesis explores the consequences of producing and using biochar from APRs from a Swedish perspective, focusing on climate impact and soil improvement potentials. This is done by conducting a literature review on the outcomes of biochar soil amendment (BSA). Furthermore, the climatic effects of biochar production and use is estimated with a model quantifying the potential carbon sequestered, considering APRs from major crops and different pyrolysis temperatures. Both the literature review and model will then be applied to a case, the agricultural production region Götalands norra slättbygder (GNS) to analyze and discuss the outcomes in a practical case. By exploring these topics, this thesis aims to contribute to a better understanding of the potential of biochar to support sustainable agriculture and mitigate climate change.

1.1 Aim

The objective of this thesis is to produce an agricultural carbon flow model for quantifying climatic consequences from producing biochar using different types of APRs at different pyrolytic temperatures, and to perform a literature study on biochar-soil interactions and on potential uses beyond the agricultural sector. The thesis is aimed to analyze potential carbon dioxide removal (CDR) and climate change mitigation potential from APR-derived biochar, along with the expected impacts on soil fertility from BSA. This study will be performed from a Swedish agricultural perspective, based on the most commonly cultivated annual crops, agricultural management practices and typical soil types. This report aims to investigate the following research questions:

- How does the production and use of biochar from APRs affect carbon sequestration and climate change mitigation?

- What are the consequences and impacts when applying APR biochar to different soil types compared to not utilizing APRs?

1.2 Limitations

This thesis will focus on Sweden, specifically GNS. The analysis will exclude other countries or regions. No other biomasses than APRs will be evaluated, nor differentiating pyrolysis-technologies. Only two common soil types will be included in the evaluation, sand and clay soil, together with a general evaluation.

2

Background

This chapter provides a general understanding of carbon dynamics, soil and biomass with information about requirements for healthy and fertile soils. Further, pyrolysis as a technology and biochar is covered. Lastly a brief section presents application and impacts of biochar use.

2.1 Carbon dioxide removal

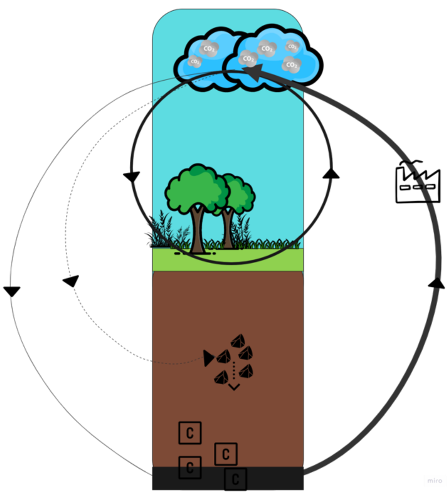

Figure 2.1: Illustration of different carbon cycles

Agriculture accounts for 18 % of the anthropogenic GHG-emissions globally. With a growing population this number is estimated to keep increasing within the coming decades. The increasing demand for food due to a growing population, together with a warming climate, environmental stresses need to be mitigated for a sustainable future [1].

The IPCC indicates that in order to limit global warming significant reductions in GHG-emissions alone may not be enough and recommend the inclusion of negative emission technologies (NETs) or CDR as supplementary strategies [2]. CDR are processes that remove carbon dioxide from the atmosphere and store the carbon over long time periods, either in products or in geological, terrestrial or aquatic sinks [5]. This is illustrated in Figure 2.1, where GHGs are accumulating at a faster pace than they are being naturally removed or absorbed. Therefore, recent research reinforces the conclusion that NETs are crucial for mitigating climate change and decreasing global warming. Among the available negative emission strategies, soil carbon sequestration is being considered as one of the most applicable and cost-effective options for implementation in the near future. Improving soil carbon sequestration is a viable negative emission strategy, which can yield multiple benefits by enhancing soil quality (including chemical, physical, and biological properties) while simultaneously helping to mitigate the impacts of climate change [2], [6].

One of the NETs identified both readily available and economically feasible by the IPCC is biochar-production through pyrolysis with the potential of sequestering 0.3-2 Gt CO2 yr^{-1} globally, depending on feedstock [2]. This technology is not only readily available to be implemented but has the benefit of the possibility to be adapted at small as well as large scales, with differentiating levels of technological solutions [7]. However, the potential for CDR though pyrolysis is largely dependent on the biomass used as feedstock. As seen in Figure 2.1 biochar can be placed in between the long and short term cycling of carbon with potential of being a sink for hundreds to thousands of years.

2.2 Biomass

Biomass is gaining momentum as a way to reduce the use and need for fossil fuels and materials, and at the same time as a means for CDR [8]. In CDR, biomass holds significant ecological value due to its renewable nature and carbon sequestration potential. Through photosynthesis, plants take up atmospheric carbon dioxide and convert it to organic carbon compounds as well as oxygen. This circularity makes biomass an intriguing resource from a sustainable standpoint. However, the utilization of biomass does not come without challenges. The increasing interest in biomass has raised concerns about its unsustainable use. Therefore, it is of importance that associated threats such as land use change, soil erosion, and loss of biodiversity are addressed [4]. To minimize these threats, unavoidable biomass waste streams are of great interest when used in a growing bioeconomy. Currently, there is a significant amount of these wastes, in the form of APRs, resulting from the need to meet food demands. These wastes often lack further utilization, leading to their disposal through methods like incineration, decomposition or landfilling. Instead, using these wastes by, for example, including them as means of CDR, value can be created to a previously unutilized resource. This approach not only minimizes waste but also maximizes the value derived from biomass resources [9].

2.3 Soil fertility

Soil is a critical component of our planet's ecosystem, sustaining life in numerous ways, providing food, fibre, and other types of biomasses. Soils also provide essential ecosystem services, such as storing and purifying water, regulating flows, recharging aquifers, and reducing the impact of droughts and floods. Furthermore, soil is a crucial component in mitigating the impacts of climate change by capturing carbon from the atmosphere and storing it [10]. In fact, more carbon resides in soil than in the atmosphere and all plant life combined [11].

Also known as the top layer of the Earth, soil is an intricate blend of mineral particles, organic matter, microorganisms, air, and water. While the composition and characteristics of soil can differ greatly, it serves an essential function in sustaining life on our planet [12]. As stated, earth's soils hold a significant stock of carbon, with only the top 1 meter containing approximately 1500 Pg. This carbon stock continuously interacts with the atmosphere through photosynthesis, respiration and decomposition, implying that even minor fluctuations can result in a substantial impact on the atmospheric carbon dioxide levels and the global carbon balance [6]. For being such an important resource, it is complex and fragile. It takes many hundreds of years to form, but can be destroyed during one storm. And its properties and characteristics can vary significantly across different locations. Soil types are mainly determined by its physical structure and are usually categorized in three main categories, sand, silt and clay. Sandy soils have a low proportion of fine mineral particles, which makes them less able to retain moisture and nutrients. Silt soils have a high proportion of fine mineral particles than sandy soils, which gives them better water retention and nutrient availability. Clay soils, on the other hand, have an even higher proportion of fine mineral particles, which gives them higher water retention potential and nutrient holding capacity but can also result in poor drainage and compaction inhibiting root-growth.

A healthy and fertile soil is the quality of soil that allows it to provide the necessary chemical, biological and physical properties in appropriate quantities and proportions required for the growth of specific plants [12].

Even though soils are an important part of our planet, industrialization has caused many soils to be degraded, leading to eutrophication, carbon loss, water erosion and compaction. One of the factors contributing to this is the unsustainable management practices in agriculture. Both the IPCC and the European Commission have emphasized the necessity of adopting more sustainable alternatives that promote soil health and fertility [2], [13]. Managing sustainable soil conservation is necessary to enhance biodiversity, carbon cycling, land productivity, food security and mitigate climate change.

2.4 Agriculture in Götalands norra slättbygder

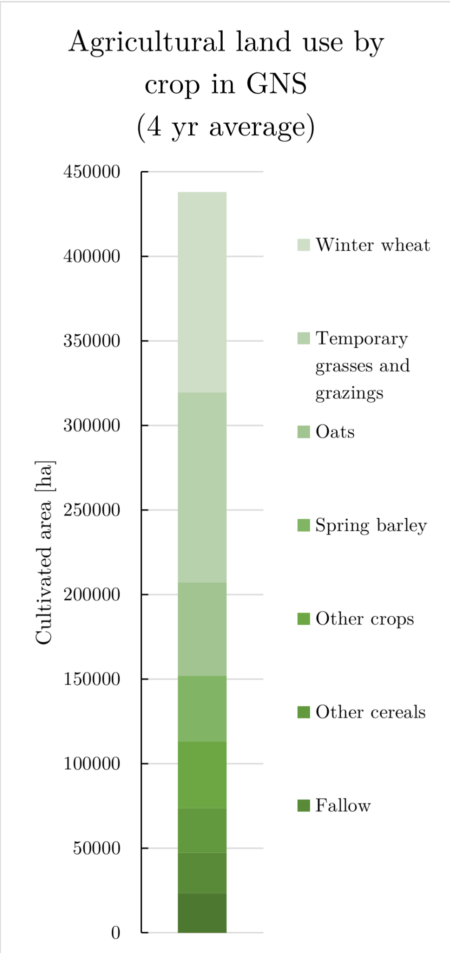

Figure 2.2: Compilation of average arable land use in the Götalands norra slättbygder production region (GNS) over the years 2019-2022

In the production region GNS, about 440 000 ha are cultivated for crop production and the distribution of arable land use is shown in Figure 2.2. The most commonly grown crops in the region, by area grown, are winter wheat, oats, spring barley and winter rapeseed in that order. Winter wheat, oats and spring barley account for 90 % of all cereals grown in GNS, where cereal production accounts for more than half of the arable land (240 000 ha), followed by temporary grasses and grazings (110 000 ha). In Figure 2.2, *Other crops* account for leguminous plants, seed ley and table potatoes, among others. *Other cereals* are comprised of spring wheat, rye and winter triticale, among others [14].

2.5 Agricultural plant residues

Every crop grown will, after the economic part of the crop (product) is harvested, leave a certain amount of plant residue behind. These can be categorized as above-ground and below-ground residues, and the amounts and ratios between the two vary from crop to crop. Above-ground residues are defined as all above-ground-growing biomass apart from the desired harvested product. This includes leaves, stalks, stover and chaff, and is generally called straw. Below-ground residues consist of roots, root hairs and rhizomes [15]. The two residues differ in terms of nutrient content, physical structure and decomposition rate in soil. Below-ground residues generally decompose much slower than above-ground residues and its retention time in soil has been estimated to on average 2.4 times longer than its above-ground counterpart [16]. Due to this, above and below-ground residues have different impacts on soil properties such as physical structure and soil organic carbon (SOC). When left to decompose, about 10 % of the biomass carbon remains in the soil over time, becoming SOC. A majority of this SOC input is derived from below-ground residues due to its higher retention factor; 2.3 times more of the carbon input comes from the decomposing below-ground residues than the above-ground residues [17]. The remaining 90 % is rapidly decomposed into carbon dioxide and returned to the atmosphere within the first few years [18].

In Sweden, cereal and rapeseed production produce several million tons of plant residues each year. After harvest, APRs remain in the field as a by-product and can either be harvested and used for feed or bedding for example, or left to decompose in the soil. The level of residue utilization varies from crop to crop, but a majority of all produced APRs are left to decompose, resulting in the release of biogenic carbon dioxide. Figures 2.3 and 2.4 show the fate of cereal and rapeseed straw, respectively, after harvest based on statistics from 2012 [19]. Additionally, *other* include minor areas (1-4 %) of residue use for direct feeding and bioenergy purposes. Regardless of conventional use and fate of APRs today, a significant majority of the carbon stored in the biomass will most often be released to the atmosphere as carbon dioxide.

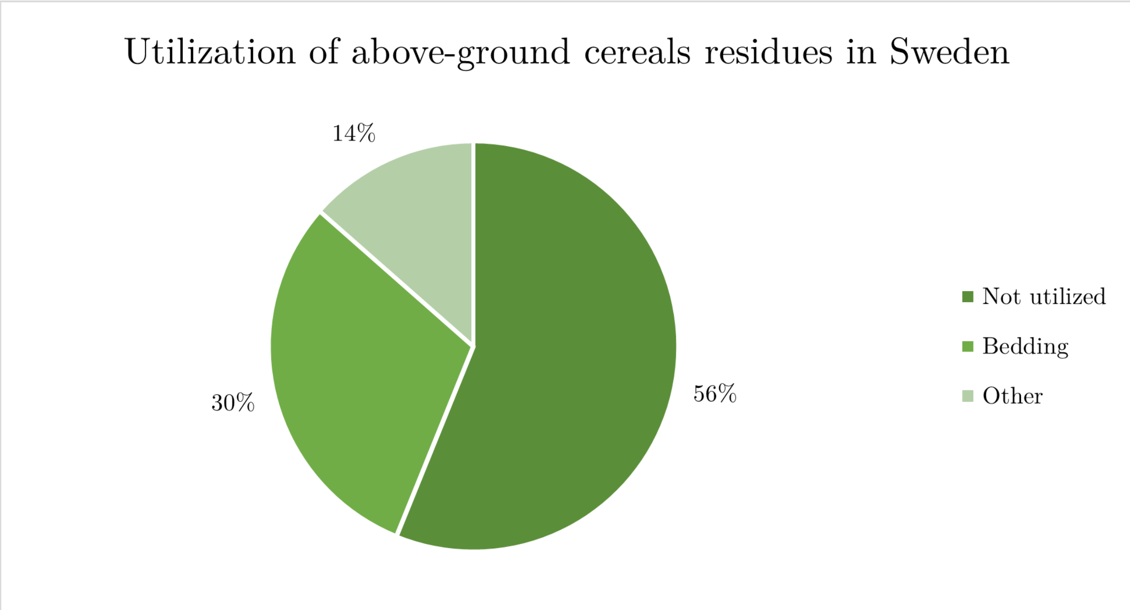

Figure 2.3: Utilization of above-ground plant residues from cereals in Sweden

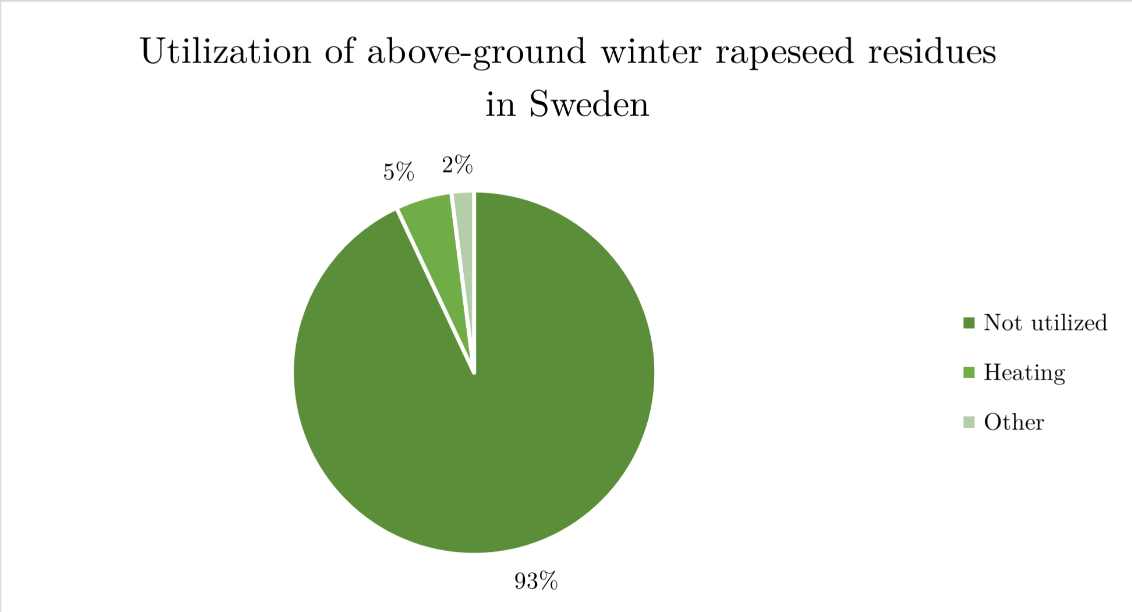

Figure 2.4: Utilization of above-ground plant residues from winter rapeseed in Sweden

The reason for not utilizing the straw is mainly due to the lack of market demand or further need for the farmer. Therefore, it is unnecessary to extract it from the field in the first place, as it would only contribute to additional cost and time required.

2.6 Pyrolysis

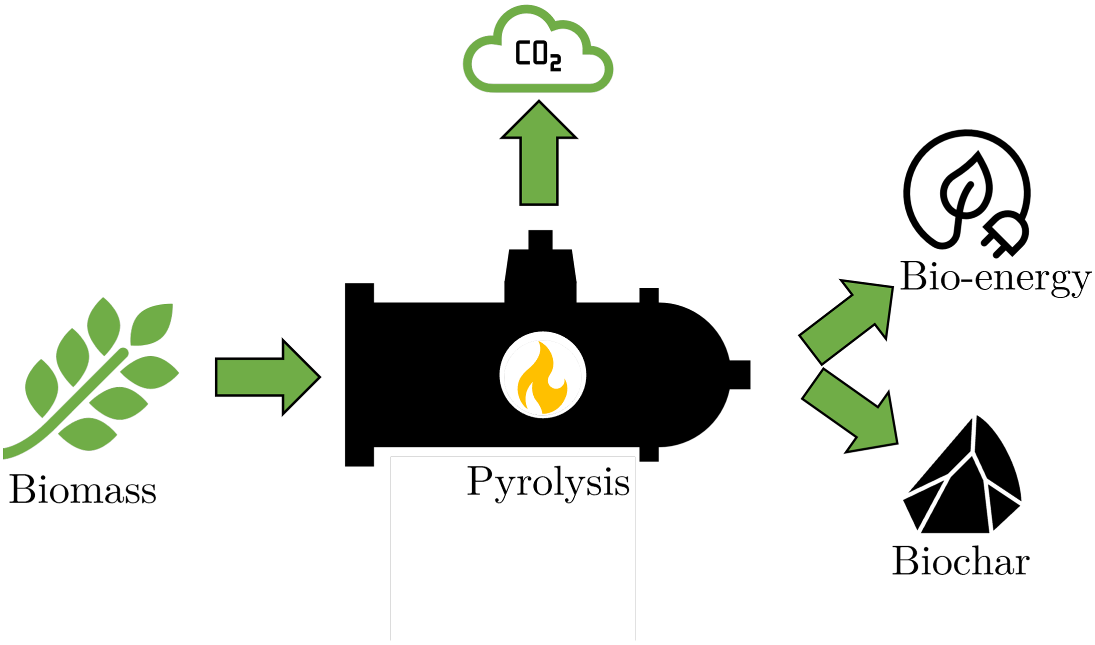

Figure 2.5: Schematic overview of a biochar production system

Pyrolysis is a thermochemical conversion process that converts biomass or other carbonaceous substances into solid, liquid and gaseous products. The process is executed at high temperatures in an inert or oxygen-free environment which allows for a more controlled decomposition of the feedstock compared to conventional combustion. Consequentially, pyrolyzed compounds generally retain more molecular complexity, chemical energy and physical properties than combusted compounds [3]. A schematic visualization of a biochar-producing pyrolysis process is illustrated in Figure 2.5.

As the pyrolysis reaction is exothermic, recoverable heat is also produced. Depending on process parameters and feedstock, the amount of recoverable heat can vary. Generally, the energy content in the biomass feedstock can be categorized into thirds of equal size, illustrated in Figure 2.6. One third of the energy is allocated to the produced biochar, one third remains in the pyrolysis process to keep the reaction going and the last third can be used for heating or electricity. This can be used for heat-demanding on-farm processes such as greenhouse heating or grain drying. Depending on the location, the excess heat could also be connected to a district

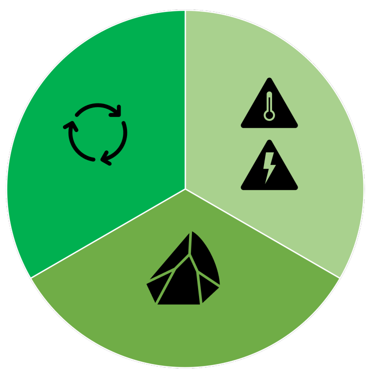

Figure 2.6: Energy distribution of biomass in biochar production

heating system [20], [21]. As the heat is generated from biomass it can be regarded as a net neutral energy source, and has the potential to offset the need for heat produced elsewhere by other means.

2.6.1 Feedstock

Biochar can be produced from virtually any biomass, such as wood, leaves, straw, manure, food waste and sewage sludge. Depending on which biomass is pyrolyzed, the resulting biochar will have varying properties [22]. Dense biomasses such as wood and forestry waste produce a biochar with low porosity, whereas biochar produced from herbaceous feedstocks result in biochar with higher porosity [23]. Since biomass is becoming increasingly attractive for various industries, ranging from fuel to materials, careful consideration is required when choosing biochar feedstock. By choosing feedstocks that are already used within other industries, competition over the feedstock might result in indirect negative impacts. Using, for example, only forestry biomass for biochar production could potentially increase indirect or direct land use change due to the competition of a shared feedstock. Therefore, it is crucial that the feedstocks sourced for biochar production hold no other uses such as APRs [21], [24], [25].

2.6.2 Pre-treatment

Depending on which biomass is used for pyrolysis, pre-treatment of the feedstock might be necessary. If the moisture content of the feedstock is too high, drying is required to ensure that the pyrolysis is operational. Pyrolysis equipment is generally able to process biomass feedstocks with a moisture content up to 20-30 % [26], [27]. However, the amount of recoverable heat is heavily decreased when processing wetter feedstocks. To achieve an adequate pyrolysis in terms of energy efficiency and product yield, it is therefore desirable to dry biomasses to a moisture content of less than 20 % [25], [26].

Feedstocks that are of small particle sizes could also be in need of pre-treatment for the process to run smoothly. Using smaller particles such as stalks, leaves and husks as feedstock could potentially clog the pyrolytic feeding unit, thus halting the process. Furthermore, if small particles are pyrolyzed, the resulting biochar becomes even smaller in size. Dust-like biochar is difficult to use without further treatment and can pose a risk to humans while handling, both in terms of health hazards and the potential risk of dust explosions. In cases where smaller feedstocks are used, pelleting of the feedstock could be necessary to achieve a satisfactory pyrolysis process [25], [28].

Feedstocks of larger particle size could on the other hand be required to be reduced in size to fit the process demands of the pyrolysis. Chunks of biomass too large in size could both jam the feeding unit and produce a biochar that is only partially pyrolyzed. This could be solved by adding a process step where the biomass is chopped or shredded before the pyrolysis [25].

2.6.3 Pyrolysis parameters

Mainly, pyrolytic temperature determines both the yield and properties of the produced biochar. Furthermore, several other parameters such as, retention time, heating rate, feedstock particle size, catalysts, pressure, gas flow and reactor size, also play an important role in biochar production, although less significant compared to pyrolytic temperature [29]. The stability of biochar depends on the ratio of hydrogen and oxygen to carbon in biochar. At higher temperatures (>600 °C), the resulting biochar has a lower ratio of hydrogen to carbon than that of biochar produced at lower temperatures, thus implying a higher molecular stability. At the same time, higher pyrolytic temperatures result in decreased biochar yields due to a faster thermal decomposition and volatilization of the biomass [30].

2.6.4 Biochar

Biochar is a carbon rich material with a variety of characteristics which, in turn, depend mainly on feedstock and pyrolysis parameters. Carbon content, porosity, cation exchange capacity (CEC), pH, specific surface area (SSA), oxygen and hydrogen to carbon ratios and molecular stability are characteristics that are of potential importance when using biochar [31], [32].

2.7 Biochar uses

Due to its many varieties of feedstock, versatile properties and production parameters biochar can be used in many applications. The most common application is within agriculture as soil amendment which is described in Section 2.7.1, but industrial uses across several sectors are increasing in popularity. Due to its porosity, high carbon content and high surface area, biochar has favorable properties that make it promising outside of the agricultural sector as well. These uses are described in Section 2.7.2.

2.7.1 Soil amendment

Biochar's potential as a soil amendment has gained significant attention and experimentation. Its appeal stems from its versatility and potential positive impacts on soil fertility and health. However, the main challenge associated with biochar lies in its inherent variability. The production parameters and feedstock sources can vary greatly, as can the specific soil types and application rates. Consequently, biochar as soil amendment is interesting but complex.

The interesting features using biochar as soil amendment comes from its possibilities for increased yield, plant available nutrient capacity, water holding capacity, alkalinity and porous characteristics making it possible as sorbent [33]. Due to its physiochemical structure, biochar has been proven to also be an efficient means of rendering heavy metals and contaminants less harmful. Amending contaminated soils with biochar can immobilize heavy metals, making them either insoluble or non-reactive to soil organisms and crops [34]. Its porosity and permeability makes biochar play an interesting role as drainage material in soils with high water content, and reduction in soil bulk density for compact soils. It also has potentials for increasing microbial activity, enhancing soil organic matter (SOM) content and at the same time being a carbon sink mitigating climate change. Biochar has also been found to have potential in reducing GHG-emissions through inhibiting the formation of methane and nitrous oxide [35], [36].

2.7.2 Other applications

Biochar has been proven to work well as filtration for groundwater remedy due to its high porosity [37]. It can be a substitute to active carbon filters, being less costly, and possessing several desirable properties such as SSA, porosity, pH, and CEC [38]. Further, biochar can be used as catalyst and activator in bio-diesel production, with promising recyclable potentials [39], [35]. Biochar does not only have possibilities to act as catalyst for bio-fuels such as bio-diesel production but also in production of other bio-fuels such as bio-hydrogen and bio-methane [40], [41]. There is also potential for biochar to act as an anode, cathode, cathode catalyst, and as base for proton exchange membranes in microbial fuel cells, but standardization of the process and cost remain limitations to this application [42].

There is also the potential of biochar as a substitute for materials like sand and concrete in building materials production, thereby contributing to decreasing their emissions [43]. Additionally, biochar could potentially replace the reduction agent in steel production with biogenic carbon, leading to substantial reductions in net GHG-emissions [44], [45].Noteworthy is that most sectors other than the agricultural sector generally requires biochar with specific characteristics, which in turn requires consistency in both feedstock and process parameters [46].

3
Methods

This chapter will explain the methodology of the literature review assessing the consequences and impacts on soil fertility when performing BSA. The parameters listed in the report correspond to the parameters acquired through the analysis of existing literature. The chapter will also cover the method of investigating carbon dynamics by quantifying the net primary production (NPP) for different crops, how much of above-ground residues can be potentially collected and the equations used for estimating the potential carbon sequestration by biochar production. It also covers the potential climate change mitigation from production and using the biochar as soil amendment, with the aim of the model to provide information on the climatic impacts of production and use of biochar from APRs. The last part of the chapter shows the potential and impacts of BSA in a case study, and ends with a sensitivity analysis. The method is illustrated in Figure 3.1.

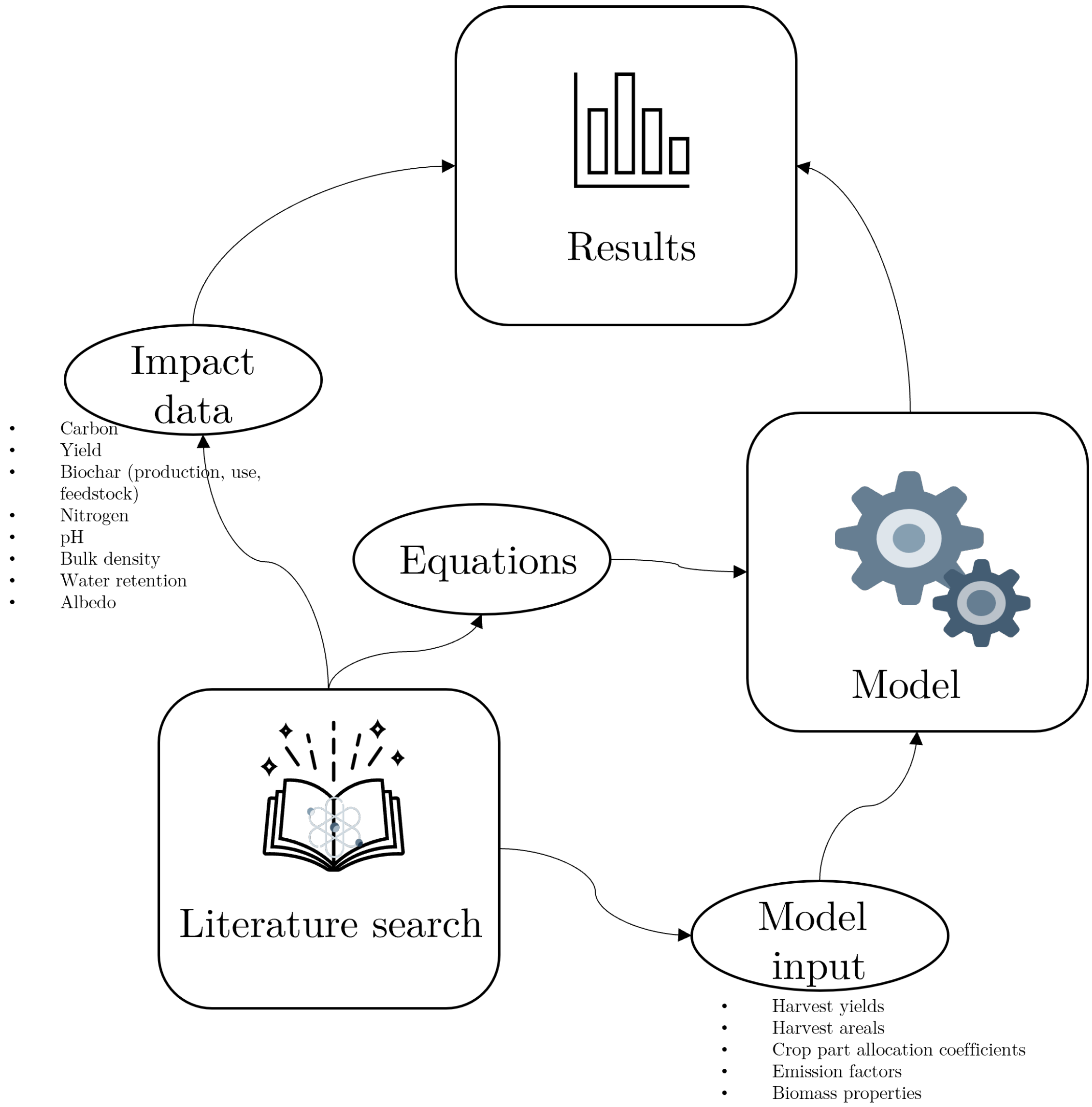

Figure 3.1: Schematic illustration of method

3.1 Literature search

A systematic literature search was conducted by collecting literature on biochar impacts on soils. Because of the complexity of impacts due to biochar type and soil type, we prioritized effects and impacts that have been recorded and discussed in review papers and meta-analyses. When necessary, individual articles covering specific areas were gathered to achieve a more detailed understanding of a topic.

The literature was collected from various databases such as Scopus, Google Scholar and Google during early spring 2023. Search strings were constructed and used to find articles by including keywords, abstract and title in the search. The acquired literature was categorized to cover biochar effects in soil, along with the main topics of this study, feedstock production, biochar production and biochar usages.

Since only a small quantity of the literature that was found from a Swedish, Nordic and European regions, it was not possible to evaluate research data from these pedoclimatic conditions only. Literature findings were therefore categorized as effects due to soil types, biochar types and biochar feedstocks.

After the initial categorization process, a thorough literature search on the use of biochar in agriculture with emphasis on impacts on soil properties and functions was conducted. The parameters that are presented in the report represent the obtained parameters in the literature study.

3.2 Modelling biochar production and use from agricultural plant residues

Here we describe the model developed which 1) quantifies the total (NPP) and its distribution in plant parts in cereals and rapeseed, and estimate how large share of above-ground residues that are possible to harvest and use for pyrolysis; 2) calculates biochar yield in pyrolysis based on biomass input and pyrolysis temperature, and 3) accounts for biochar stability in soils and thus potential for CDR.

The input to the model consists of crop-specific yield data for the four most grown crops in GNS: winter wheat, oats, spring barley and winter rapeseed. Yield data were retrieved from the Swedish board of agriculture (Jordbruksverket) and consist of a four year average over the years 2019-2022 in GNS, shown in Table 3.1. A more detailed data compilation can be seen in Appendix Table A.1.

Table 3.1: Average harvest yield in kg ha^{-1} for the four most grown crops [47]

Crop	**Average yield** [kg ha^{-1}]
Winter wheat	7430
Oats	4760
Spring barley	5368
Winter rapeseed	3525

The yield data were used to calculate total NPP and its distribution on harvested product (grain, rapeseed), above-ground residues and below-ground residues with the use of allometric equations. This was calculated as dry matter (DM) biomass and as carbon based mass, given that 45 % of DM biomass is carbon [15]. The carbon content was estimated to determine the carbon flow and NPP in the system. The DM mass was estimated to fit the equations regarding elemental composition, yield and stability.

To calculate the dry mass of APRs for pyrolysis, crop-specific yield data had to be converted to DM mass. Cereal and rapeseed yields in Table 3.1 are presented with moisture contents of 14 % and 9 % respectively [47]. These were converted to

DM yields. In this model, the moisture content of ingoing APRs was assumed to be between 15-20 %, which is normal for Swedish straw after harvest [48]. The moisture content of APRs were deemed to have little significance on the mass balance of the conversion of DM biomass into biochar. The moisture content does however have an impact on the energy balance over the pyrolysis, and varies with different moisture contents. With the general moisture contents of 15-20 %, the pyrolysis process results in a recoverable amount of heat corresponding to one third of the ingoing biomass' energy content [21], [49].

The model solely uses peak pyrolytic temperature to calculate qualitative and quantitative characteristics of the produced biochar. Other pyrolytic process parameters such as retention time, heating rate and feedstock particle size also influence the pyrolysis process. However, the pyrolytic yield of biochar along with its elemental composition of carbon, hydrogen and oxygen is mainly determined by the pyrolytic temperature. This is however a valid assumption, as previous studies have determined that the temperature is the single most influential process parameter for biochar characteristics [50], [51], [52].

As different pyrolysis feedstocks and biochar uses might demand different pyrolytic temperatures, the model is constructed to assess temperatures between 300 and 700 °C. The same equations could be used for estimations outside the temperature span, but the uncertainties regarding the results would in that case be much greater. Depending on the temperature chosen, the model returns the pyrolytic yield of biochar in kg kg $^{-1}$ dry biomass, and elemental composition of carbon, hydrogen and oxygen in kg kg $^{-1}$ biochar, which can then be used to estimate biochar stability. All pyrolysis gases produced during biochar production are assumed to undergo full combustion.

3.2.1 NPP quantification and distribution in cereals and rapeseed

The NPP is the annual production of biogenic carbon per unit of area and different plant parts have varying contributions to NPP. The annual flow of carbon to soil from each crop part was quantified by the use of allometric equations. In the literature, several models have been constructed to quantify such carbon flows. However, depending on methodology and data availability, some equations are more suitable than others. Based on a review by Keel et al [53], it was determined that Equation 3.4, developed by Bolinder et al [15], most appropriately estimates the distribution of carbon to different parts of the plant, these four fractions are shown in Figure 3.2.

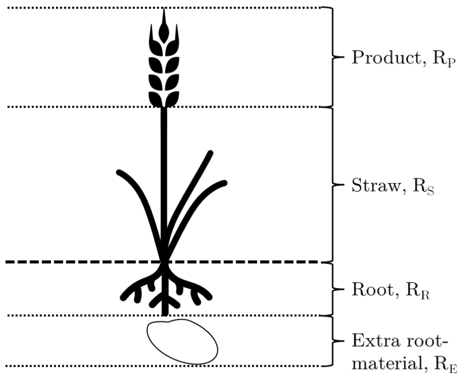

Figure 3.2: Visual representation of different crop parts. The relative size of different crop parts is only illustrative. Adapted from Bolinder et al [15]

The product fraction, R_P accounts for the economic part of the crop that is harvested and removed from the cropland. The product fraction could however be completely or partially part of below-ground plant matter, in the case of crops such as tubers or root vegetables.

R_S is the above-ground crop residue fraction and accounts for all above-ground plant matter excluding the harvested product. This consists of straw, leaves, stalks and other crop remnants that are left after harvest.

R_R accounts for the fraction of all extractable below-ground crop residues, excluding any potential product as in the case of tuber crops.

The last plant fraction, R_E, accounts for all non-extractable below-ground residues, sometimes also referred to as rhizodeposition. This plant part is assumed to always remain in the soil after harvest, regardless of crop, harvesting method or crop management. R-values for winter wheat, spring barley, oats and winter rapeseed are shown in Figure 3.3. Note that all R-values for cereals are retrieved from Bolinder et al [15], whereas the R-values for winter rapeseed is retrieved from Wiesmeier et al [54].

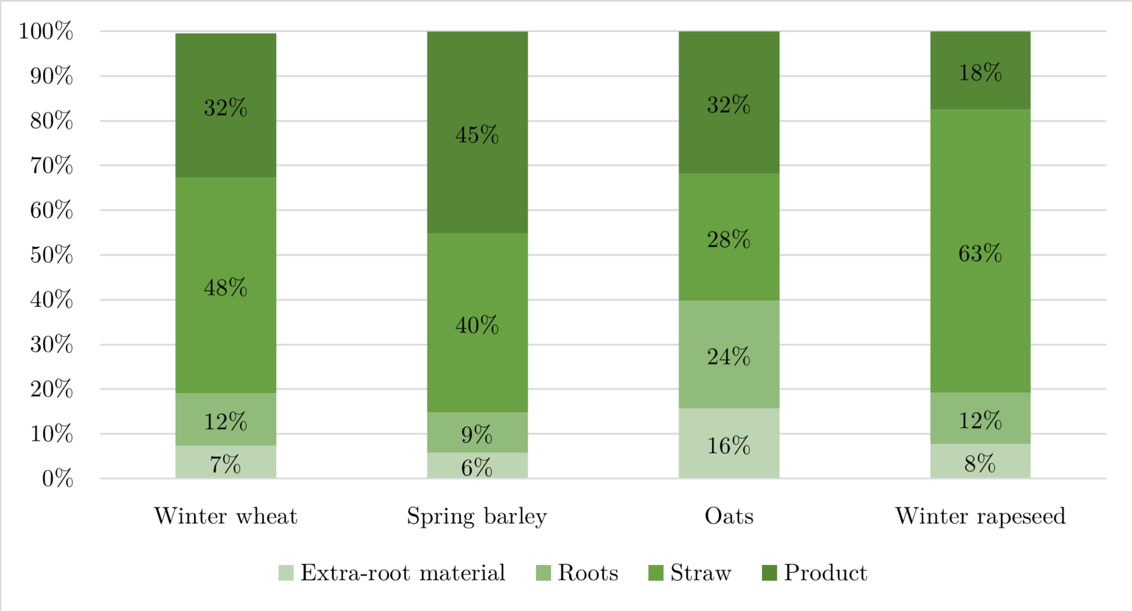

Figure 3.3: Relative crop part mass allocation for winter wheat, spring barley, oats and winter rapeseed

The total mass of the crop was established by the following relationship:

$$Y_{crop} = Y_P + Y_S + Y_R + Y_E \tag{3.1}$$

Where Y_{crop} is the total DM yield of the crop, and Y_P, Y_S, Y_R and Y_E is the DM yield of each plant part. Since the four crop fraction coefficients (R) that determine the mass fraction relative to the entire crop and the product DM yield (Y_P) is generally known, each crop part yield was determined by Equation 3.2.

$$Y_k = R_k * \frac{Y_P}{R_P} \tag{3.2}$$

Where k denotes for which part of the crop the DM yield is being calculated for. For this equation, k denotes S (straw), R (roots) and E (extra root-material). When each crop part DM yield is known, each crop part's carbon mass was determined by Equation 3.3.

$$C_k = Y_k * 0.45 \tag{3.3}$$

C_k denotes the carbon yield for crop part k, and Y denotes the specific crop part DM yield derived in Equation 3.2. All crop parts were assumed to be 0.45 ton C ton^{-1} DM biomass [15]. When all carbon yields were known, the NPP for cereals could be calculated with Bolinder et al's allometric equation, Equation 3.4.

$$NPP = C_P + C_S + C_R + C_E \tag{3.4}$$

Where C_P, C_S, C_R and C_E were calculated with Equation 3.3 and NPP is the annual carbon production per unit of area.

3.2.2 Biochar yield in pyrolysis

The yield of dry, ash free biochar was expressed as a fraction of the biomass input in the pyrolysis process. Neves et al [55] express the char fraction of the pyrolytic products, based on their empirical model, with Equation 3.5.

$$Y_{ch} = 0.106 + 2.43 * e^{\frac{-0.66}{100} * T} \tag{3.5}$$

Where Y_{ch} is the pyrolytic mass yield of biochar produced (kg biochar kg^{-1} dry biomass feedstock) and T (°C) is the peak temperature of the pyrolysis that produced the biochar. The temperature dependence of the pyrolytic biochar mass yield is visualized in Figure 3.4. The mass of biochar (M_{BC}) received after pyrolysis could then be expressed as:

$$M_{BC} = Y_{ch} * I_{BM} \tag{3.6}$$

Where I_{BM} is the input of dry biomass in kg.

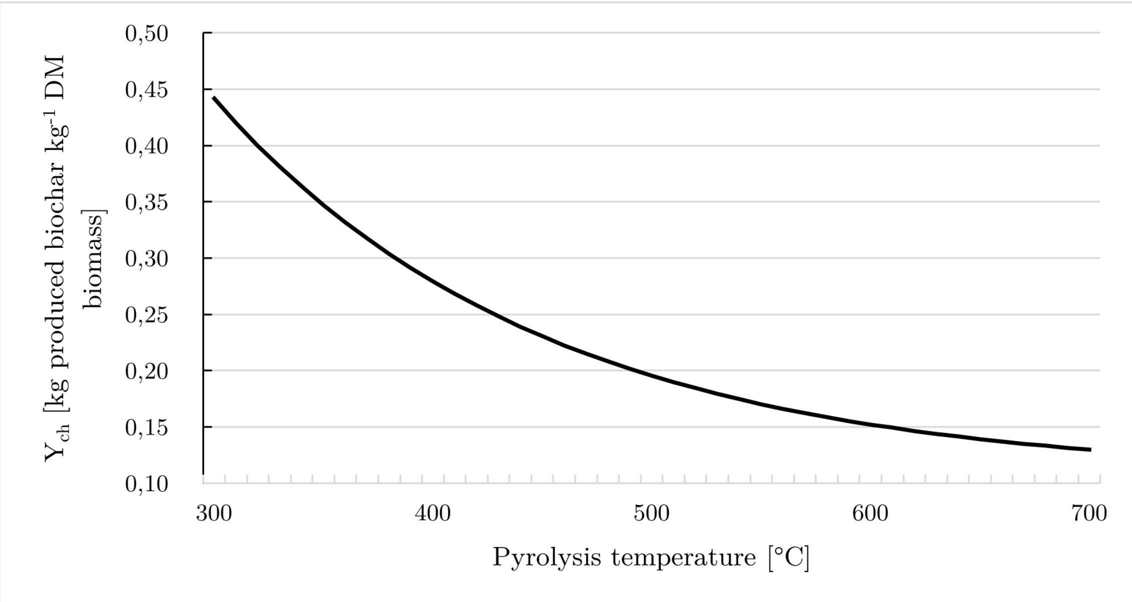

Figure 3.4: Pyrolytic biochar yield with respect to the dry weight of ingoing biomass at different pyrolysis temperatures

3.2.3 Biochar stability in soil

Accounting for the direct climate impacts of biochar as a carbon sink required insight in biochar's persistence in soil, where the stability is strongly correlated with the presence of hydrogen and oxygen in the form of functional groups. Lehmann et al [56] express the mean residence time (MRT) (Equation 3.7) and the fraction of biochar remaining in the soil after 100 years (BC_{+100}) (Equation 3.8) as a function of the atomic ratio of hydrogen to carbon in the biochar. Both equations are valid for an ambient soil temperature of 10 °C.

$$MRT = 4501 * e^{-3.2\left(\frac{Y_{H,a}}{Y_{C,a}}\right)} \tag{3.7}$$

$$BC_{+100} = 1.06 - (0.424\left(\frac{Y_{H,a}}{Y_{C,a}}\right)) \tag{3.8}$$

Where $Y_{H,a}$ and $Y_{C,a}$ are the atomic fractions of hydrogen and carbon, respectively, of the biochar. Further, the mass fractions of hydrogen and carbon, and its dependence on pyrolysis temperature have been expressed by Neves et al [55] with Equations 3.9 and 3.10.

$$Y_{C,m} = 0.93 - 0.92 * e^{\left(\frac{-0.42T}{100}\right)} \tag{3.9}$$

$$Y_{H,m} = \frac{-0.41}{100} + 0.10 * e^{\left(\frac{-0.24T}{100}\right)} \tag{3.10}$$

Where T (°C) is the peak temperature of the pyrolysis that produced the biochar and $Y_{C,m}$ and $Y_{H,m}$ are the mass fractions of carbon and hydrogen, respectively, of the biochar. Biochar carbon and hydrogen content produced at different pyrolytic temperatures are visualized in Figure 3.5.

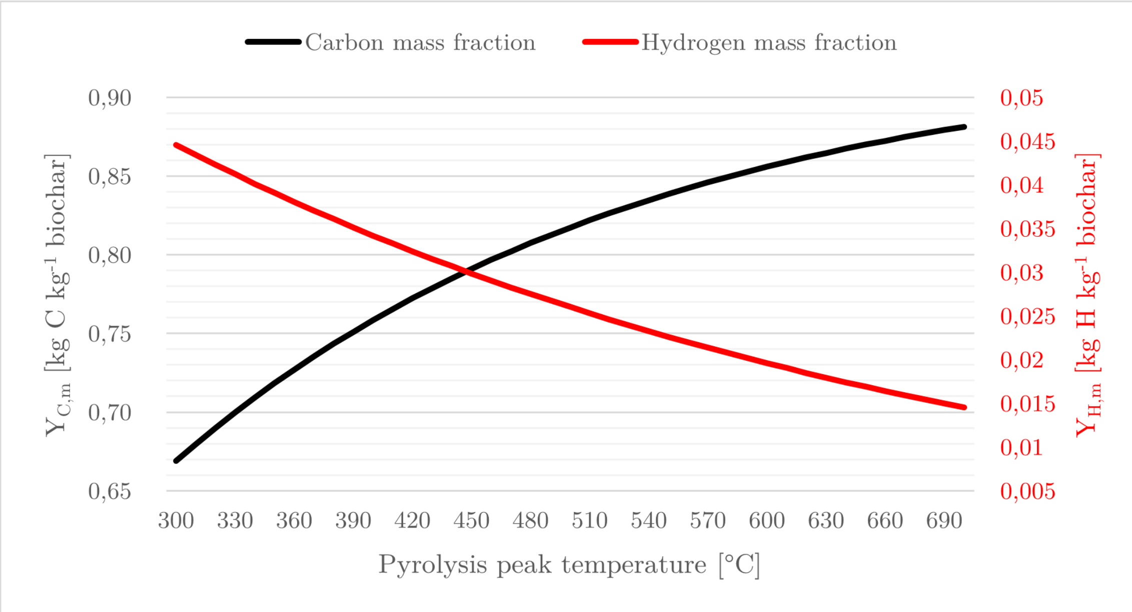

Figure 3.5: Biochar carbon and hydrogen content per mass unit of biochar at 300-700 °C

To fit the required atomic ratio of Equation 3.7 and 3.8, the elemental mass yields from Equation 3.9 and 3.10 were converted according to:

$$Y_{j,a} = \frac{Y_{j,m}}{M_j} \tag{3.11}$$

Where j denotes the element and M denotes the molar mass of element j.

When the fractions from Equation 3.9 and 3.10 were converted from mass to atomic ratio, Neves et al's and Lehmann et al's equations were combined to express biochar MRT and BC_{+100} in soil as a function of pyrolysis peak temperature, resulting in Equations 3.12 and 3.13.

$$MRT = 4501 * e^{-3.2\left(\frac{\frac{-0.41}{100}+0.10*e^{\left(\frac{-0.24T}{100}\right)}}{0.93-0.92*e^{\left(\frac{-0.42T}{100}\right)}}*\frac{M_H}{M_C}\right)} \tag{3.12}$$

$$BC_{+100} = 1.06 - (0.424\left(\frac{\frac{-0.41}{100}+0.10*e^{\left(\frac{-0.24T}{100}\right)}}{0.93-0.92*e^{\left(\frac{-0.42T}{100}\right)}}*\frac{M_H}{M_C}\right) \tag{3.13}$$

Equations 3.12 and 3.13 are visualized in Figure 3.6.

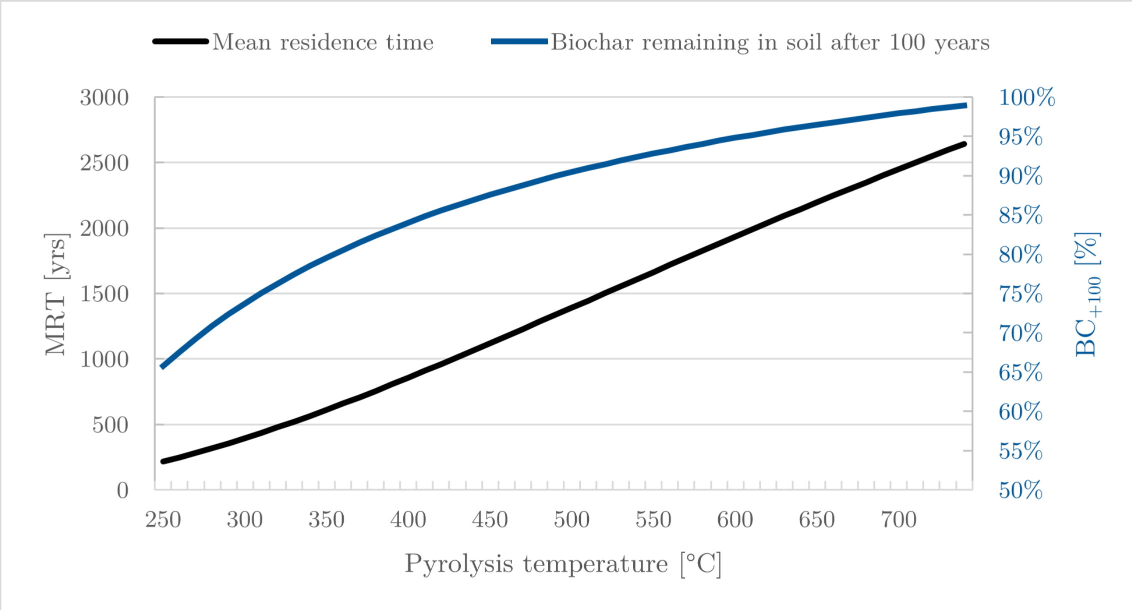

Figure 3.6: Biochar stability properties at different pyrolytic highest heating temperatures °C

3.2.4 CDR potential of biochar in soil

To determine the direct climate impact of applying biochar in soil, the total amount of sequestered carbon dioxide was predicted by Equation 3.14, using the same methodology as the IPCC when estimating the changes in SOC stocks from BSA [57].

$$Seq_{CO_2} = M_{BC} * Y_{C,m} * BC_{+100} * (M_{CO_2}/M_C) \tag{3.14}$$

Seq_{CO_2} denotes the mass of directly sequestered carbon dioxide equivalents in the form of the carbon remaining in biochar applied to soil, after 100 years. M_{BC}, $\mathrm{Y}_{C,m}$ and BC_{+100} were derived from Equations 3.6, 3.9 and 3.13, respectively. Since the pyrolysis input is biogenic it is safe to assume that every carbon atom in the resulting biochar has sequestered one molecule of carbon dioxide. Thus, the carbon share of biochar remaining after 100 years was multiplied by 3.67 (i.e. the ratio between the molecular mass of carbon dioxide and the atomic mass of carbon) to account for the total amount of carbon dioxide sequestered.

The CDR potential in other end-uses is covered briefly in Appendix B.

3.2.5 Substitutional effects of biochar soil amendment

Biochar production and BSA can have indirect climatic impacts, in this thesis mainly identified as the offsetting of heat or electricity, or through the reduction of nitrous oxide emissions from fertilized croplands. The substitutional effects do not only occur from the use of biochar as soil amendment, but also occur during the generation of heat from biochar production.

The climatic benefit from offsetting energy was determined by estimating the GHG emissions that would be emitted when producing an equal amount of heat or electricity. The Swedish average emissions for producing 1 GJ of electricity and heat for district heating are 25 kg CO_2eq and 15 kg CO_2eq, respectively [58]. If the surplus pyrolysis heat is used for electricity generation in, for example, a small-scale steam turbine, a thermal efficiency of 35 % was assumed.

The reduced nitrous oxide emissions have been generalized, since they depend on several factors that can be difficult to establish, such as fertilizer use, moisture, pH and temperature. Instead, a crop-specific annual nitrous oxide emission per hectare was used to first estimate the total emissions per crop grown. These emissions were then multiplied by a biochar-induced nitrous oxide emission reduction factor found in the literature search. The general annual nitrous oxide emissions from a Swedish cropland are shown below in Table 3.2.

Table 3.2: Crop-specific Nitrous Oxide (N_2O) and Carbon Dioxide Equivalent (CO_2eq) Emissions [59]

Crop	N_2O Emissions [kg N_2O yr^{-1} ha^{-1}]	CO_2eq Emissions [kg CO_2eq yr^{-1} ha^{-1}]
Winter wheat	3	795
Spring barley	2	530
Oats	2	530
Winter rapeseed	3.12	826.8

Nitrous oxide emissions were assumed to have a carbon dioxide equivalence of 265 [60].

3.2.6 Cooling effect of biochar soil amendment

The climatic impacts of producing and using biochar for soil amendment was also estimated in terms of potential global mean temperature change. To do this, a climate model revised by Persson & Johansson [61] was used to calculate the GHG emission-induced temperature change 100 years after a specific mass of carbon dioxide equivalence emission. In this case, the carbon dioxide input was equal to the direct sequestered carbon dioxide calculated using Equation 3.14, along with indirect potential substitutional effects.

3.3 Potential for biochar production and CDR from APRs in an agricultural region - case study GNS

GNS soil types are generally clayey, consisting of on average 29 % clay [62]. Further, GNS soils have an average pH of 6.3 and a SOC content of 3.8 % [63]. The region's most cultivated crops along with their utilization can be seen in Appendix Table A.1 and A.2, respectively. In GNS, the *Maximum theoretical harvest* is in this case defined as the amount of almost all above-ground residues, leaving only a fraction, maximum 15 %, of these on the field in the form of stubble [15]. This implies that there is no wasted above-ground residue, and that all husk, chaff, etc. is harvested.

The model however, was tested by quantifying the *practical harvestable* amount of APRs in the Swedish production region GNS. *Practical harvestable* was in this case defined as 60 % of the entire above-ground residue production for cereals. For rapeseed, the practical harvestable amount is even lower, 30 % of the entire above-ground residue production. Further, the mass and stability of biochar from the practical harvestable amount of APRs was calculated, along with the potential climate impacts from the biochar's production and use as soil amendment. When producing biochar, the agricultural management of APRs differs from the case where residues remain on the field after harvest. If not utilized, straw is chopped by the harvester and incorporated in soil. As the extra process step of chopping straw occurs simultaneously during crop harvest, the small extra amount of emissions were thus viewed as negligible.

Figure 3.7 illustrates the agricultural process steps of harvesting, preparing and storing APRs for biochar production. When harvesting APRs for biochar production, the first steps are common practice when producing large rectangular straw or hay bales for animal feed and bedding. Further, pelleting is added to make the feedstock more easily handled and reduce the risks when using a fine-particle feedstock such as APRs.

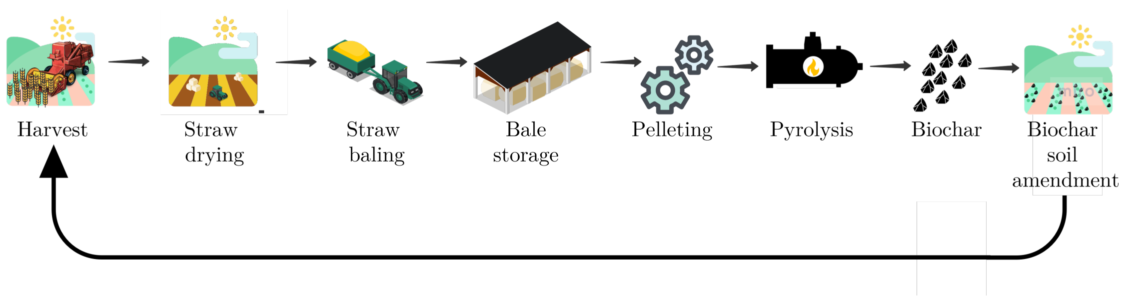

Figure 3.7: Process flowchart illustrating the sequential steps from crop harvest to biochar production and use as going back to the fields as soil amendment

All related energy requirements and emission factors related to harvesting, transporting and pre-treating APRs are shown in Appendix Table A.3.

3.4 Sensitivity analysis

This study is focusing on the maximal theoretic possibility for utilization of APRs. It is however not reasonable to assume that this amount of biomass will be utilized in practice. Therefore, when applied to GNS, it was assumed that 60 % of the available straw could be harvested for cereals, and 30 % for rapeseed, a more reasonable and realistic assumption. These fractions are validated by Bolinder et al [15] and Wiesmier et al [54], respectively.

Another important observation is that soil and biochar interactions are complex processes with varying results. Not only are the interactions between the two complex, academia is using inconsistent vocabulary and nomenclature making the process of finding patterns more difficult. There was also often a lack of detailed information about biochar type, application rate and climatic conditions in the reviewed literature. Therefore the data presented in BSA are general assumptions with varying uncertainties. A more detailed illustration of these uncertainties is presented in Figure 4.4.

4

Results

The start of this chapter will include impacts of BSA both in terms of functions that are general and then more specific functions for soil type. This is followed by the model results of specific crop carbon flows and case model results.

4.1 Impacts on soil from BSA

Soil properties play an important role in trying to understand what biochar will alter in terms of physical, chemical or biological functions when used as soil amendment. This section presents the impacts on water retention, bulk density, nitrogen and carbon cycling, pH and yields from using biochar as a soil amendment. First, general impacts observed regardless of soil type are presented in section 4.1.1. As biochar has differing impacts in different soils, BSA in two different soil types are also assessed with sandy soils in section 4.1.2 and clayey soils in section 4.1.3 with an overview of all soil types in section 4.1.4.

4.1.1 General

This section covers BSA impacts generally observed, regardless of soil type. The effects of BSA in general have been qualitatively assessed in a matrix in Figure 4.1.

	Water retention	Bulk density	Nitrogen cycle	pH	Carbon cycle	Yield	Albedo	Heavy metal and toxin remidation
General	Increase/ Decrease	Decrease	Increase/ Decrease/No alteration	Increase	Increase/No alteration	Increase/ Decrease	Decrease	Increase

Figure 4.1: Overview of general results on biochar soil amendment (BSA). Green indicates a higher certainty and yellow indicates lower certainty

4.1.1.1 Water retention

A meta-analysis by Enell et al [33] found that many studies demonstrate a decrease in moisture stress and soil loss, as well as an increase in plant drought-resilience, due to the increased water holding capacity of soil through biochar application. Omondi et al [23] identified that biochar's effects on soil water retention could be both beneficial and adverse, depending on feedstock and pyrolysis parameters. Biochars derived from APR were found to have a higher porosity and therefore proved beneficial for soil water retention compared to woody and other high-density biomass feedstocks such as nut husks. Biochar application can also increase available water-content. Increases of on average 10 % were observed with application rates of <20 tons ha^{-1}. Increases of on average 25 % were observed at application rates of >80 tons ha^{-1}. Water-permeability also increased with biochar application, but did conversely not have any significant correlation with application rates. Instead, pyrolysis parameters and soil type seem more significant to the change in water permeability. Edeh et al [64] reported that water content could both decrease and increase depending on the soil type with typical increase of saturated hydraulic conductivity in fine textured soils, and decrease in coarse textured soils. Fischer et al [65] observed that plant available water increases through biochar application and Cayuela et al [66] noted that biochar can retain water in soil.

4.1.1.2 Bulk density

Biochar application is associated with a decrease in soil bulk density and lower soil compaction, as shown in studies by Cayuela et al [66] and Razzaghi et al [67]. The extent of the decrease in bulk density may vary depending on soil type, as noted by Razzaghi et al [67]. It is however generally observed across different studies that biochars produced at higher temperatures have a greater impact on bulk density reduction compared to biochars produced at lower pyrolytic temperatures, according to Omondi et al [23]. Additionally, the pyrolysis feedstock used can also affect the extent of the bulk density decrease, with high-porosity biochars derived from plant residues having a greater impact compared to lower porosity chars derived from woody feedstocks, also reported by Omondi et al [23].

4.1.1.3 Nitrogen cycle

According to studies by Almaraz et al [68], biochar application can lead to an, on average, 11 % increase in plant nitrogen uptake despite a decrease of nitrogen in soil. Biochar application in grasslands or perennial croplands has shown no alteration of nitrous oxide emissions. Individual studies show that biochar application could lead to increases, decreases or no changes at all to nitrate emissions. However, where nitrous oxide emissions have been seen to decrease, NOx emissions could also be assumed to decrease. Furthermore, 95 % of the studies assessed showed that there was a 10.5 % decrease of ammonium and nitrate emissions within one year of biochar application. A 13 % decrease of nitrate emissions during the first 30 days was observed and after 30 days the nitrate emissions had decreased further to 26 %. A decrease in nitrous oxide emissions of 54 % was observed in laboratory and field experiments. Kammann et al [69] states that biochar application generally reduces nitrous oxide emissions, primarily due to pH increase and changes in microbial activity. Biochar applied in combination with fertilizer can potentially lead to an increased efficiency in the soil's nitrogen cycle. Cayuela et al [66] argue that biochar-induced nitrous oxide reductions depend on the oxidative state of nitrogen present in soil, which in turn is influenced by the fertilizer's application. Ogura et al [70] suggests that higher pyrolytic temperature leads to higher SSA and micropores, thus making it a better sorbent for fertilizers.

4.1.1.4 pH

Acidic soil can potentially decrease nutrient availability which hinders plant growth. Therefore, it is a common practice in agriculture to increase pH in acidic soils by liming. Liming does not only increase nutrient availability but also hinders toxic heavy metal mobility [71].

Ye et al [72] reported that biochar increases the pH of soil, therefore improves nutrient availability and decrease potential toxins. This can be explained by acidic soils being more prone to leaching due to a low CEC [71]. However, it was also stated that caution should be taken when applying biochar to neutral and alkaline soils, as it can further increase the pH and lead to adverse effect. Furthermore, both Azzi et al [73] and Yang et al [51] highlighted that biochar is strongly correlated with increasing the pH of acidic soils. When produced, biochar is in most cases alkaline, or very rarely neutral to slightly acidic [66] which explains the alteration in pH when biochar is added to soils. And it is important to note that the liming effect of biochar is time-dependent, and the pH-increasing effect will decrease over time if more biochar is not applied [73], [51].

4.1.1.5 Carbon cycle

Understanding the dynamics between biochar and soil requires distinguishing between carbon in SOC and carbon in SOM. SOC refers to the carbon stored in the organic components of soil, such as plant residues, decomposed organic matter, and microbial biomass. SOM, on the other hand, encompasses the entire organic component of soil, including SOC. It consists of both living organisms, such as microbes, fungi, and earthworms, as well as decaying plant and animal materials at various stages of decomposition [74].

According to Yang et al [51] and Lehmann et al [56], biochar produced at higher temperatures are more resistant to mineralization in soil compared to those produced at lower temperatures. In other words a more stable biochar in terms of carbon sequestration is produced at high temperatures than at low, illustrated in Figure 3.6.

Mierzwa-Hersztek et al [75] found that biochar application leads to an increase in microbial activity, together with a long-term carbon retention in soil. Azzi et al [73] suggests that the long-term changes in SOM depend on agricultural practices and management. Further, Ren et al [76] show that the surface layer of biochar undergoes relatively rapid mineralization during the first years in soil, attributed to either the adsorption of SOM or that the biochar surface undergoes oxidation, which can occur through either living organisms or non-living processes. This mineralization is however deemed to have a negligible impact on global warming according to Azzi et al [73]. Chagas et al [77] states that biochar not only boosts SOC levels indirectly but also enhances soil nutrient content due to its porosity, with nutrients being able to reside within its pores. Biochar is therefore indirectly promoting the increase of SOM by increasing plant growth from providing plant available nutrients. This in turn increases the decomposition of APRs and rhizodeposition, leading to the increase of microbial activity. This favorable environment encourages the growth of microbial biomass and subsequently benefits crop productivity and enhances SOM.

4.1.1.6 Yield

Several studies have demonstrated the potential benefits of using biochar to improve soil fertility and crop yields. Liu et al [78] found that applying 5-10 ton biochar ha^{-1} can lead to greater yield increases compared to application rates greater than 10 ton ha^{-1}. However, the type of feedstock used to produce biochar may also have an impact on yield potential. Biochar made from plant residues such as wheat straw, as demonstrated by Mierzwa-Hersztek et al [75], has the potential to increase yield by 2-14 %. Biochar has also been shown to improve shoot and root mass, as observed by Hamidzadeh et al [79].

Woolf et al [80] found that on average, biochar can increase yields by 10 % on average, but revised studies show that the mean could in reality be as high as 18 %. However, the effect on yield can vary greatly depending on the type of soil and the properties of the biochar used. Negative yield impacts may occur when an alkaline biochar is added to an already neutral to alkaline soil. The highest yield increases have been observed in soils that are already poor in quality, such as acidic or degraded soils.

Biochar also has positive effects on soil microbial activity and water and nutrient retention capacity due to an increase in CEC, according to Enell et al [33]. Fischer et al [65] found that biochar has a positive impact on plant-available water and yield response under most climatic settings, although its effectiveness decreases at northern latitudes. Moreover, both Ye et al [72] and Azzi et al [73] concluded that the beneficial effects of biochar are generally greater in tropical regions than in temperate regions, and that the application of biochar alone does not have any effect on yield; the biochar needs to be mixed with some kind of fertilizer.

Furthermore, Azzi et al [73] also found that the pyrolysis feedstock and process parameters also have a significant impact on the properties of biochar and its effectiveness as a soil amendment. Greatest yield increases are generally observed when biochar is applied to low-to-neutral pH soils.

4.1.1.7 Albedo

The findings indicate that the incorporation of biochar into soil can lead to a substantial reduction in albedo. Biochar is known to have a dark color, and as noted by Smith, the addition of biochar in large quantities to soil can result in the top soil becoming darker, potentially causing a decrease in albedo [81]. Meyer et al [82] found that the degree of reduction in albedo varied between 13-22%, depending on the crop that is cultivated on the soil and biomass utilized for producing biochar, with a smaller reduction of albedo observed in soils that already had dense vegetation and a darker color. Usowicz et al [83] also observed a decrease in albedo as more biochar was added to the soil. Similarly, Agegnehu et al [84] found a 37% reduction in albedo when charcoal was incorporated into the soil, which is similar to biochar. Genesio et al [85] demonstrated that the reduction in albedo with biochar addition could reach up to 40% over the growing season, with the greatest reduction occurring before the soil was covered by vegetation and concluded that there was no evidence of a difference in albedo reduction between different amounts of biochar application.

4.1.1.8 Heavy metal and toxin remediation

Several studies have shown that BSA can aid in rendering several toxic metals and per- and polyfluoroalkyl substances (PFASs) less harmful. Omondi et al [23] argue that over time, biochar could help sequester and immobilize harmful heavy metals, leading to a decreased soil contamination. Enell et al [33] show that the pyrolysis of herbaceous feedstocks at low temperatures could be effective in remediating PAH and heavy metal-polluted soils. It is worth noting that the effect of biochar on heavy metals in soil depends on the charge of the heavy metal ions, with anionic heavy metals being unaffected or even increased in mobilization and cationic heavy metals generally immobilized. Additionally, Dalahmeh et al [86] found that biochar with high SSA could be highly efficient in removing certain PFASs from soil, with removal rates reaching up to 90-99 % for PFAS molecules with longer carbon chains. This has also been confirmed by studies by Hale et al and Sørmo et al who both present PFAS removal rates above 90 % in contaminated soils. The removal efficiency has been proven to depend on SOC concentrations, with the highest removals observed in soils with low SOC concentrations [87], [88] together with rate of application of biochar according to Ogura et al [70].

4.1.2 Sandy soils

This section covers BSA impacts in sandy soils. The effects of BSA in general have been qualitatively assessed in a matrix in Figure 4.2.

	Water retention	Bulk density	Nitrogen cycle	pH	Carbon cycle	Yield	Albedo	Heavy metal and toxin remidation
Sandy soil	Increase	Decrease	Increase/ Decrease	Increase	Increase	Increase	Decrease	n/a

Figure 4.2: Overview of results on biochar soil amendment (BSA) functions in sandy soils. Green indicates a higher certainty and yellow indicates lower certainty

4.1.2.1 Water retention

Biochar application is known to enhance soil water retention, improving its water holding ability and bio-availability. The addition of biochar to sandy silt soils leads to an increased water retention, as demonstrated in studies by Enell et al [33] and Woolf et al [80], where the latter found increases in water holding capacity up to 84 %, with the highest increases observed in sandy soils. According to Yang et al [51] and Mierzwa-Hersztek et al [75], biochar application can improve soil water holding ability and increase water bio-availability due to its surface and pore structure. Razzaghi et al [67] reported a significant correlation between biochar application and available water, with coarse textured soils exhibiting the greatest increase in available water, on average by 45 %, and an average increase of 51 % in field capacity of water with application rates of 2.5 %. Edeh et al [64] noted that sandy soils are most suited for biochar application in terms of soil water properties due to SSA, which can increase when biochar is applied. This increases the absorption factor which therefore also increases the available water content in the soil. Omondi et al [23] showed that available water content and water-permeability increased by, on average, 36 % and 24 % in coarse textured soils.

4.1.2.2 Bulk Density

Razzaghi et al [67] observed a decrease of soil bulk density of 11 % on average in sandy soils, while Omondi et al [23] found an average decrease of 7 %, regardless of pyrolytic feedstock and temperature. This is because biochar application can alter the physical structure of the soil, leading to improved soil porosity and decreased compaction. Coarse textured soils generally receive greater benefits from biochar application compared to fine textured soils, as noted by Azzi et al [73].

4.1.2.3 Nitrogen cycle

Almaraz et al [68] found that sandy soils experienced the highest reduction in N_2O emissions from biochar application. On the other hand, Cayuela et al [66] found that the effect of biochar on N_2O emissions varied depending on moisture content, with sandy soils generally emitting more N_2O but also having the highest uncertainty in results. In contrast, dry coarse textured soils had the highest N_2O reduction with high certainty. Borchard et al [89] also found that sandy soils leached less NH_3 and had decreased N_2O emissions when biochar was applied. Liu et al [90] reported that biochar amendment in sandy soils increased plant N uptake by 10 % and decreased soil N_2O emissions by 25 %, while increasing NH_3 volatilization by roughly 25 %. Biochar application in sandy soils also led to an average 25 % decrease in soil N leaching.

4.1.2.4 Carbon cycle

Sandy soils are more susceptible to carbon erosion in terms of leaching compared to clay soils [91]. Therefore it is possible that carbon increases in sandy soils are not only attributed to chemical processes but also physical protection.

Yang et al [51] found that mineralization of biochar occurs faster in sandy loam soils than in sandy clay loam soils, which may be due to the lower content of reactive iron and aluminum in sandier soils. Additionally, mineralization rates tend to be higher in sandier soils compared to finer textured soils. Akmal et al [92] reported that applying biochar to sandy loam soils results in the growth of microbial populations, leading to higher SOM. Mierzwa-Hersztek et al [75] observed beneficial effects of biochar application on microbial activity in loamy sand, with field trials conducted over 6 months. Chai et al [93] found enhanced microbial activity and biomass due to biochar application, with field trials conducted over 13 months. Harun et al [94] reported an increase in microbial biomass when biochar was co-applied with phosphorus, leading to an increase in SOM with field trials conducted over 60 months. Xiang et al [95] conducted a meta-analysis that showed biochar application can enhance root growth, with the highest growth improvements observed when biochar was applied to sandy soils. Chagas et al [77] found that total carbon increase in sandy soils could be as high as 53 %. This high increase is however due to biochar having high carbon content, and is dependent on application rate and soil carbon content at application.

All these studies collectively suggest that biochar application can have beneficial effects on soil health in terms of SOM due to higher microbial biomass and crop growth.

4.1.2.5 Yield

Ye et al [72] compared the yield impacts of biochar application in different soil types and found that sandy soils exhibited the greatest increase when biochar was applied in combination with fertilizers. This is attributed to the low CEC of sandy soils. Liu et al [78] reported an average yield increase of 30 % within the first year of application in sandy soils due to biochar application. Additionally, Xiang et al [95] observed that the largest increase in root biomass occurred in sandy soils. This could be due to the low water and nutrient content, as well as low pH, of sandy soils. These findings suggest that biochar application can be a valuable tool for improving crop yields in sandy soils.

4.1.3 Clay soils

This section covers BSA impacts in clay soils. The effects of BSA in general have been qualitatively assessed in a matrix in Figure 4.3.

	Water retention	Bulk density	Nitrogen cycle	pH	Carbon cycle	Yield	Albedo	Heavy metal and toxin remidation
Clay soil	Increase/ Decrease	Decrease	Increase/ Decrease	Increase	Increase	Increase	Decrease	n/a

Figure 4.3: Overview of results on biochar soil amendment (BSA) functions in clayey soils. Green indicates a higher certainty and yellow indicates lower certainty

4.1.3.1 Water retention

Zhang et al [96] found that on average, plant available water content was increased by 18 % in clayey soils following biochar application. Razzaghi et al [67] found that on average, there was a 14 % increase of available water content in clayey and fine textured soils due to the porosity of biochar. However, the field water capacity in fine textured soils were generally unaffected by the addition of biochar to soil. Castellini et al [97] noted that excessive application rates of biochar to clay soils can result in decreases in available water content and field water capacity. However, different application rates of biochar, due to its low density relative to clay soils, can result in varying increases in soil water retention. Edeh et al [64] found that available water content is increased when applying biochar to soil, indirectly due to the decrease of bulk density in soil. Finally, Omondi et al [23] showed that water-permeability increased by, on average, 18 % in fine textured soils.

4.1.3.2 Bulk Density

Castellini et al [97] noted that there is limited knowledge on the long-term impacts of biochar application on soil bulk density in clayey soils, but several studies have shown a short term decrease in bulk density. Zhang et al [96] observed a 13-15 % reduction in bulk density in clayey soils with a 2 % application rate of biochar, with particle size being a factor. Razzaghi et al [67] reported an 11 % reduction in bulk density in fine textured soils. Omondi et al [23] found that the effects of biochar on bulk density were more pronounced in fine textured soils than in coarse, with an average decrease of 9 %.

4.1.3.3 Nitrogen Cycle

Cayuela et al [66] found that N_2O emissions were generally decreased in fine textured soils with the application of biochar. Conversely, Almaraz et al [68] observed that biochar increased NH_3 volatilization by 19 % in clayey soils, particularly when the pH of the biochar was high or the application rate was greater than 40 ton ha^{-1}. Liu et al [90] reported that biochar amendment in clayey soils increased plant N uptake by 15-20 %, while also increasing soil NH_3 volatilization by an average of roughly 110 %. The same study also found that soil N_2O emissions were on average decreased by 20 %, with a range of 10-30 % decrease, and soil N leaching was decreased by an average of 35 %, although with relatively high uncertainty ranging between 15 and 50 %.

4.1.3.4 Carbon cycle

Yang et al [51] found that biochar carbon is more stable in clayey soils than in sandy soils partly due to clay mineral composition. Chagas et al [77] found that the impact of texture on the effectiveness of biochar in increasing total carbon content varies depending on soil properties. In soils with a fine texture, the increase in total carbon was more significant than in sandier soils, reaching 81 %. This high increase, as stated before, is due to the high carbon content of biochar and will vary with application rate and soil carbon content at application.

Clay minerals play a crucial role in this context by facilitating both chemical interactions and physical protection of SOM. They contribute to the stability of soil aggregates, preventing the breakdown of organic matter. Additionally, clay minerals aid in the carbon cycle by adsorbing and blocking enzymes involved in the decomposition process. These mechanisms ensure the preservation and stability of SOM in various ways.

4.1.3.5 Yield

Biochar application to clayey soils has been shown to result in an increase in yield. Liu et al [78] reported an average increase of 16 % in yield within the first year of biochar application to clayey soils. Castellini et al [97] found that applying less than 10 grams of biochar per kilogram of soil resulted in a potential increase of 5-10 % in durum wheat yields in clayey soil, although the results need further verification in field studies. Additionally, Xiang et al [95] observed that root biomass increased by an average of 30 % in clayey soils when biochar was applied. These findings suggest that biochar application to clayey soils can have positive effects on crop yields and plant growth.

The effects of BSA in general, and in sandy and clayey soils have been qualitatively assessed in a matrix in Figure 4.4.

4.1.4 Overview of results on BSA

The effects of BSA in general, and in sandy and clayey soils have been qualitatively assessed in a matrix in Figure 4.4.

	Water retention	Bulk density	Nitrogen cycle	pH	Carbon cycle	Yield	Albedo	Heavy metal and toxin remidation
General	Increase/ Decrease	Decrease	Increase/ Decrease/No alteration	Increase	Increase/No alteration	Increase/ Decrease	Decrease	Increase
Sandy soil	Increase	Decrease	Increase/ Decrease	Increase	Increase	Increase	Decrease	n/a
Clay soil	Increase/ Decrease	Decrease	Increase/ Decrease	Increase	Increase	Increase	Decrease	n/a

Figure 4.4: Overview of results on biochar soil amendment (BSA) on different soil types and functions. Green indicates a higher certainty and yellow indicates lower certainty

4.2 Pyrolysis effect on carbon flows from APRs

This section assesses the model results of biochar production and its climate impact, and covers NPP distribution in cereals and rapeseed, biochar yield and stability, and the maximum CDR potential achieved through pyrolysis.

4.2.1 NPP and its distribution in cereals and rapeseed

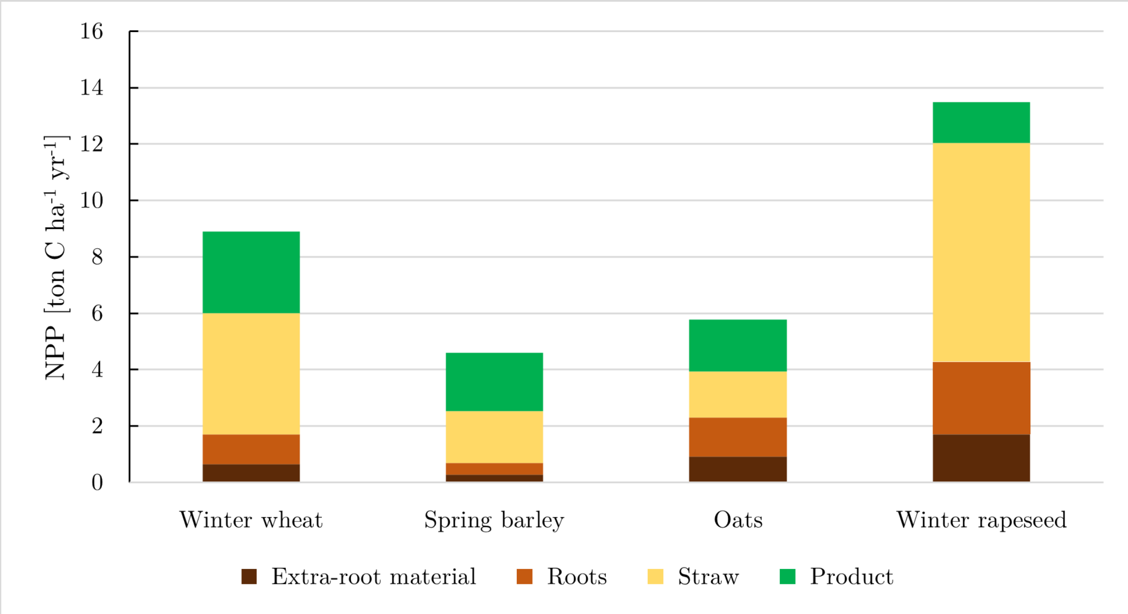

Figure 4.5: Net primary production (NPP) for cereals and rapeseed, given harvest yields in Götalands norra slättbygder (GNS) presented in Table 3.1, in ton C ha^{-1} yr^{-1}

Figure 4.5 shows the NPP for winter wheat, spring barley, oats and winter rapeseed. The NPPs were calculated using data from the 4 year-average yields in GNS, shown in Table 3.1. The NPPs for cereals and rapeseed were calculated using Equation 3.4.

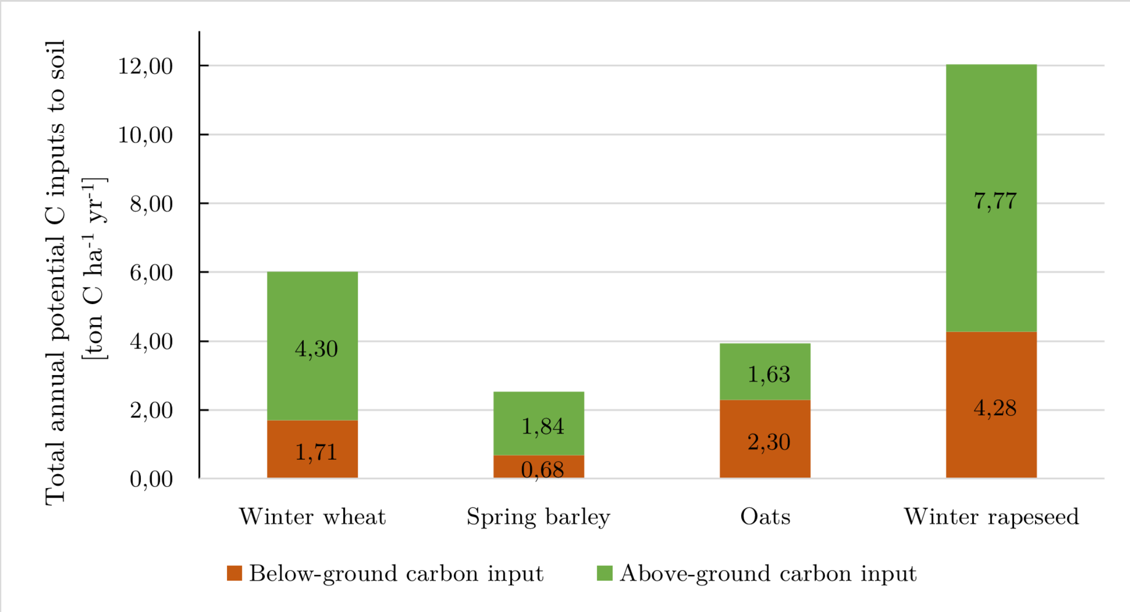

Figure 4.6: Annual carbon inputs to soil when all above-ground residues remain on the field after harvest, in ton C ha^{-1} yr^{-1}

The model was used to calculate the carbon input to soil for the four crops using Equation 3.3, comparing no harvest of APR and the maximum theoretical harvest of APR. Figure 4.6 illustrates the carbon input to soil when all above-ground residues are left to remain on the field after harvest.

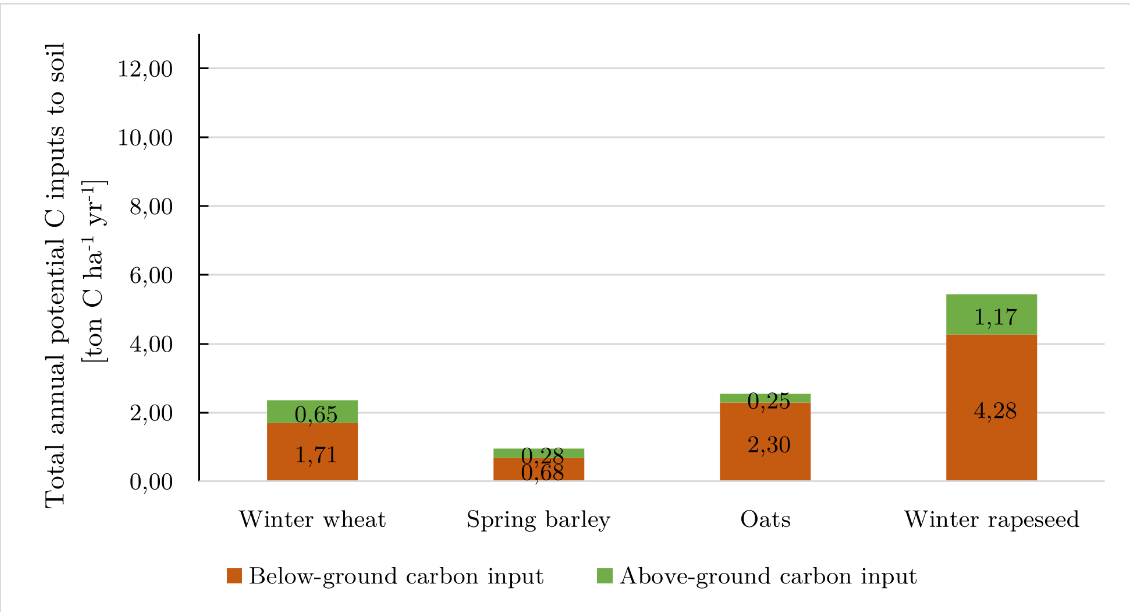

Figure 4.7: Annual carbon inputs to soil when the maximum theoretic above-ground residues are removed after harvest, in ton C ha^{-1} yr^{-1}

Figure 4.7 illustrates the carbon input to soil when the theoretic maximum amount of above-ground residues are removed from the field after harvest. Note that the carbon input to soil from above-ground residues comes from the stubble left after harvesting straw, generally 15 % of the total above-ground residues. Thus, the maximal theoretic harvestable straw carbon is equal to the difference in above-ground residues between Figure 4.6 and 4.7, presented in Table 4.1.

Table 4.1: Maximal theoretic harvestable yield of straw carbon

Crop	Winter wheat	Spring barley	Oat	Winter rapeseed
Yield [ton C ha^{-1}]	3.66	1.57	1.39	6.60

4.2.2 Biochar yield and stability

The biochar yield and stability over 100 years were calculated using Equations 3.6, 3.8 and 3.9, given the crop-specific yields of straw C from Table 4.1 above.

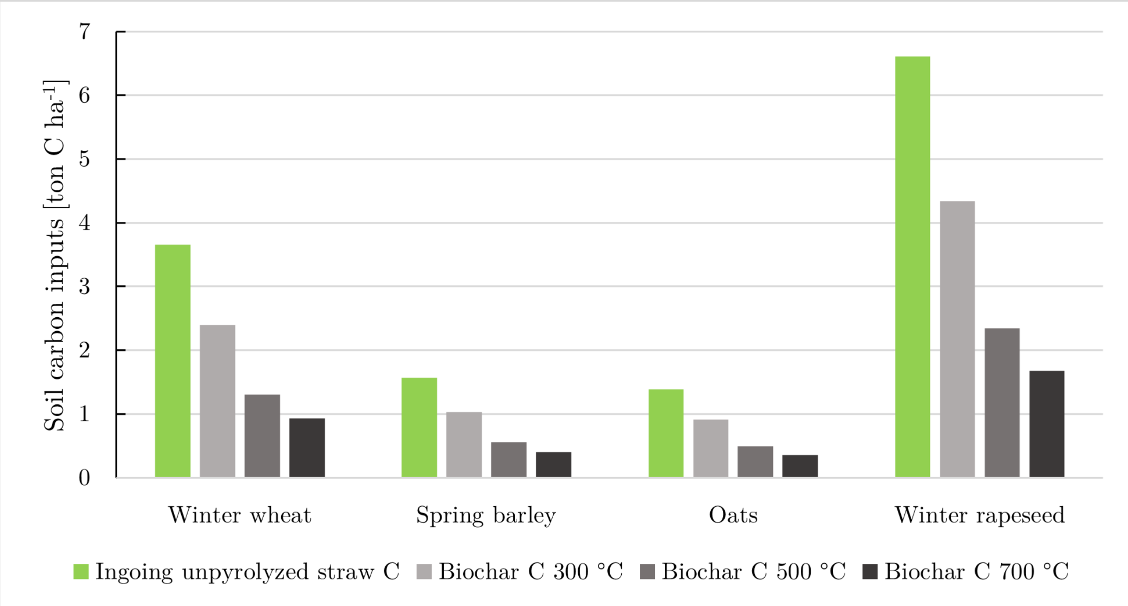

Figure 4.8: Comparison of crop-specific biochar carbon amounts applied to soil, produced at different pyrolytic temperatures from the maximum theoretical harvestable amount of straw compared to ingoing unpyrolyzed straw carbon, in ton C ha^{-1}

Figure 4.8 illustrates the potential carbon content in biochars produced at three pyrolytic temperatures, 300 °C, 500 °C and 700 °C, compared to the corresponding amount of DM straw C. It can be seen that roughly two thirds of the ingoing straw carbon remains in the biochar produced at 300 °C, compared to only about one quarter remaining in biochar produced at 700 °C. Due to higher carbon losses during pyrolysis performed at high temperatures (>700 °C), about half as much carbon is retained compared to biochar produced at lower temperatures (<300 °C).

Further, biochar produced at different pyrolytic temperatures hold different ratios of hydrogen to carbon, and thus different stabilities in soil as calculated in Equations 3.8 and 3.7. Taking both pyrolytic biochar yields and stability into account when estimating the crop-specific areal amount of carbon remaining in soil 100 years after application is illustrated in Figure 4.9.

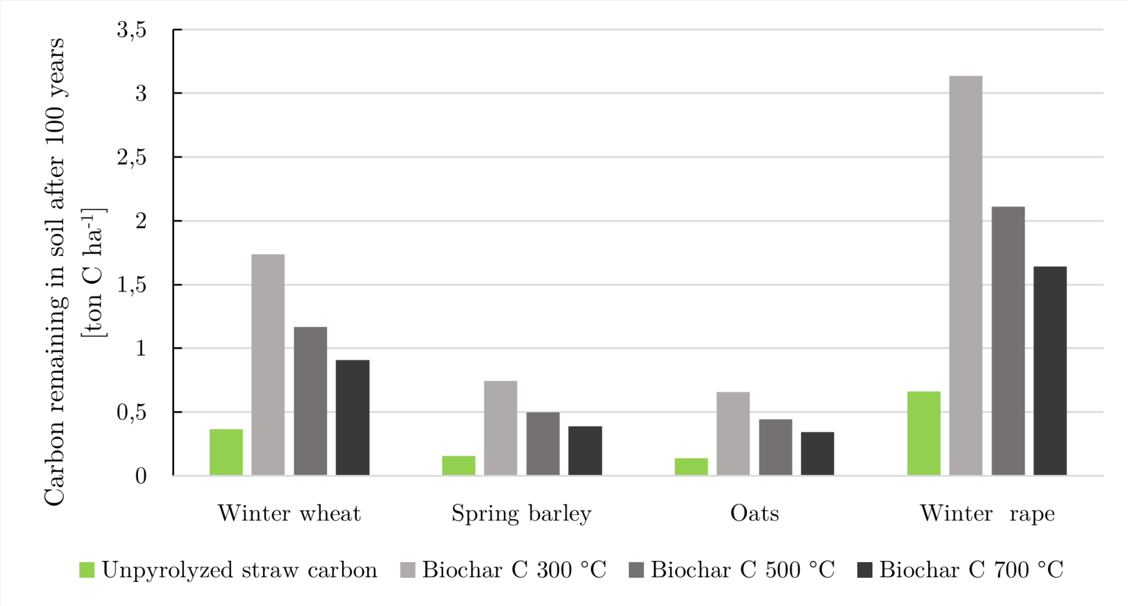

Figure 4.9: Comparison of maximum theoretical harvestable crop-specific carbon amounts remaining in soil after 100 years from biochar produced at different pyrolytic temperatures and unpyrolyzed straw in ton C ha^{-1}

When considering biochar stability over time, the pyrolytic temperature becomes less significant. The carbon input to soil from the unpyrolyzed straw after 100 years is assumed to be 10 % of the initial total carbon input.

4.2.3 Climate impact - maximal CDR for APRs from cereals and rapeseed after pyrolysis

The climatic effects of biochar application to soils are both direct and indirect, and is illustrated in Figure 4.10. A majority of the climate impact comes from the direct sequestration of carbon in biochar. As biochar is stable, its carbon content can be treated as a negative GHG-emission when added to soils. The emissions from transport and pre-treatment in Figure 4.10 was calculated using the emission factors in Appendix Table A.3.

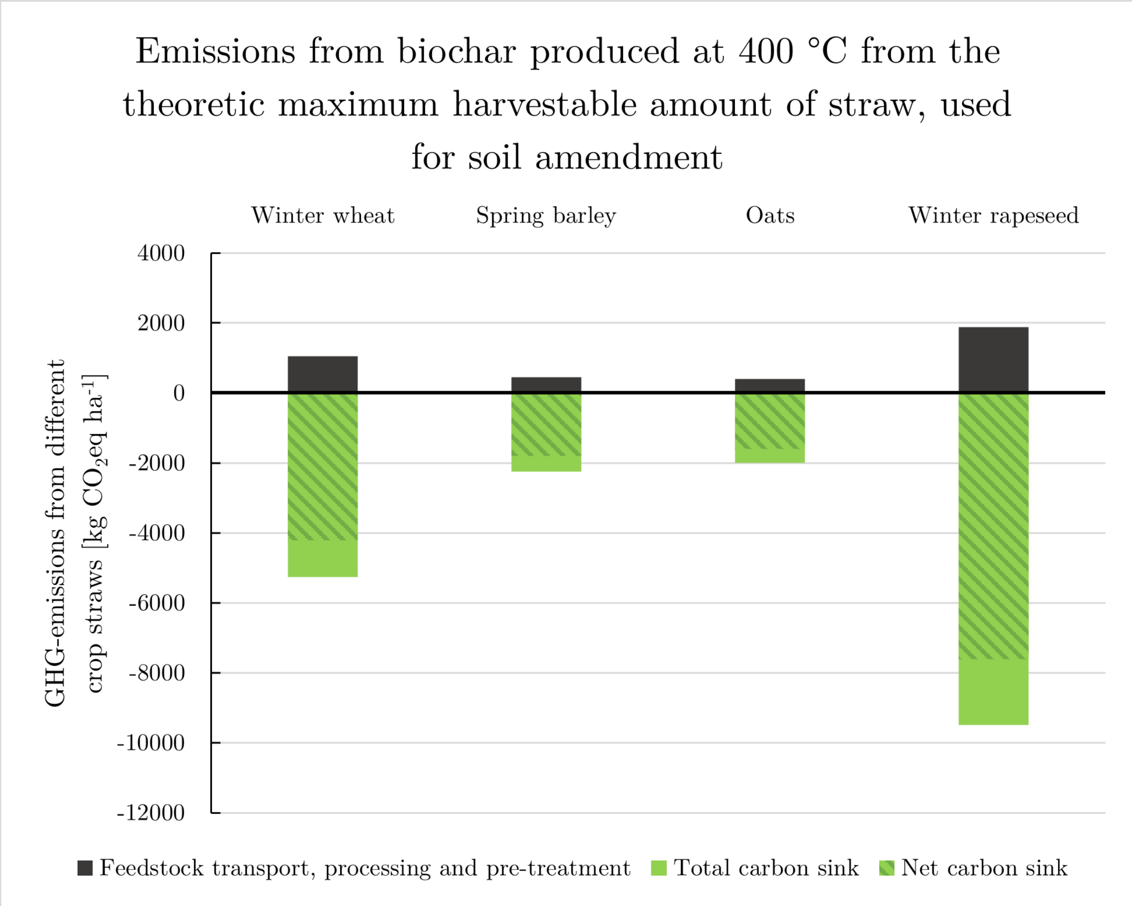

Figure 4.10: Carbon dioxide equivalent emissions from producing and applying biochar to soil at 400 °C

Figure 4.10 illustrates the produced crop-specific biochar carbon sink, compared to the inherent fossil emissions required to produce it. Depending on crop, a potential carbon sink between 2 - 10 ton CO_2eq ha^{-1} can be produced, given the theoretical maximum harvested amount of straw and a pyrolysis temperature of 400 °C. The net carbon sink is however slightly lower, about 80 % of the total carbon sink, when taking emissions from transporting, processing and pre-treating the feedstock into account.

4.3 Potential for CDR from APR-derived BSA - Case GNS

The model was evaluated using the results retrieved in Section 4.2 paired with agricultural statistics from GNS (Table A.1 and Table A.2). In this case, the practical harvestable amount of straw was assessed with the ambition to showcase feasible impacts of BSA in GNS. Taking both the degree of straw utilization and practical harvestability into consideration, the total amount of straw available for pyrolysis in GNS is shown below in Table 4.2.

Table 4.2: Mass of practical harvestable DM straw available for each crop in tons in Götalands norra slättbygder (GNS)

Crop	Mass of straw available [ton]
Winter wheat	429 288
Spring barley	61 482
Oats	81 894
Winter rapeseed	112 940
Total	685 604

Winter wheat accounts for a majority of the available straw as it is both a high straw-yielding crop and the single most cultivated crop by area in GNS. Spring barley and oats provide relatively low amounts of straw due to a smaller cultivated area along with low straw-yields. Winter rapeseed accounts for the second largest carbon sequestration potential in GNS primarily due to its high straw-yield, despite it covering the least cultivated area of the four crops assessed.

Illustrated in Figure 4.11, crop specific biochar carbon sinks are presented when pyrolyzing all available straw in GNS at 400 °C. It should be noted that any temperature between 300-700 °C could be modelled, and that the illustrated 400 °C was chosen due to it being a common temperature for producing APR-derived biochar. Other temperatures would have an impact on the size of the carbon sink, as implied by the temperature dependent carbon yield and biochar stability presented in Sections 3.2.2 and 3.2.3, respectively.

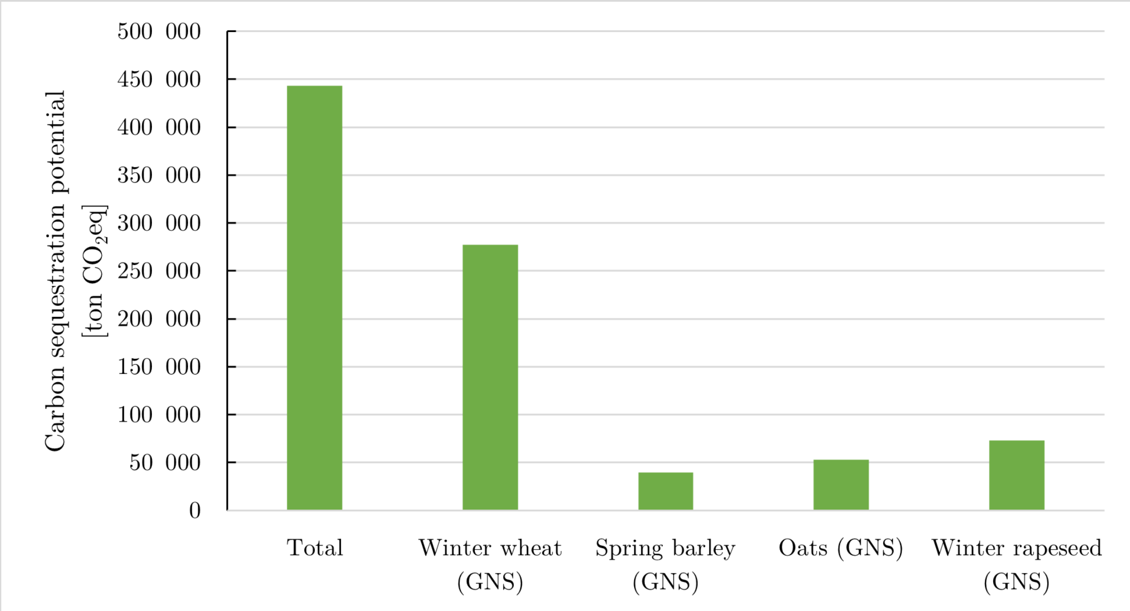

Figure 4.11: Crop-specific carbon sequestration potential when producing biochar at 400 °C of all practical harvestable straw in Götalands norra slättbygder (GNS) in ton CO_2eq

Apart from the direct carbon sequestration stemming from the biochar's inherent carbon sink, substitutional effects from generated surplus heat, along with potential reductions of agricultural nitrous oxide emissions have been estimated and shown in Figure 4.12 below. The figure also illustrates the direct carbon sink and emissions from transportation, processes and pre-treatment for comparison. The substitutional effects depend on what type of energy source that is being substituted, hence the variation in potential avoided GHG-emissions. The lowest amount of avoided GHG-emissions occur when all surplus heat is being converted to electricity, given a thermal conversion efficiency of 0.35 from heat to electricity. The highest amount of avoided GHG-emissions occurs when all surplus heat is being substituted for district heating. The variation in avoided nitrous oxide emissions depend on the literature uncertainties from Liu et al [90], stating that nitrous oxide emission reductions vary between 10-30 %, with an average reduction of 20 %. The net carbon emission amounts to -443 000 tons of CO_2 equivalents.

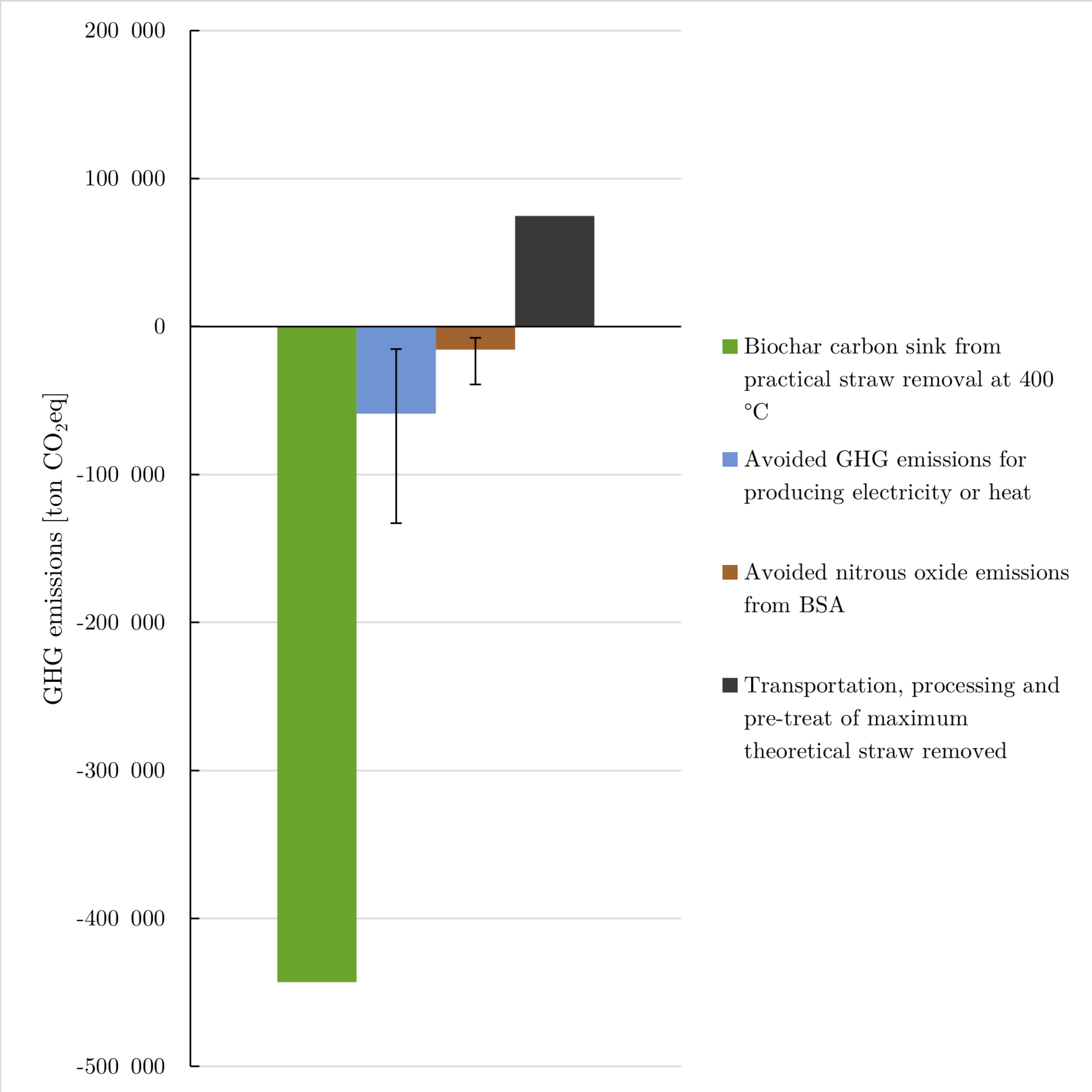

Figure 4.12: Carbon sink and fossil emissions from producing and using biochar for soil amendment in GNS, from the practical harvestable amount of straw pyrolyzed at 400 °C, along with substitutional effects from energy production and nitrous oxide emission reductions, in ton CO_2eq

The potential global temperature change of producing biochar and using it for soil amendment from the practical harvestable amount of APR from cereals and rapeseed in GNS is shown in Figure 4.13, calculated using Persson & Johansson's climate model [61]. The results show a global net cooling effect of roughly 175 nK.

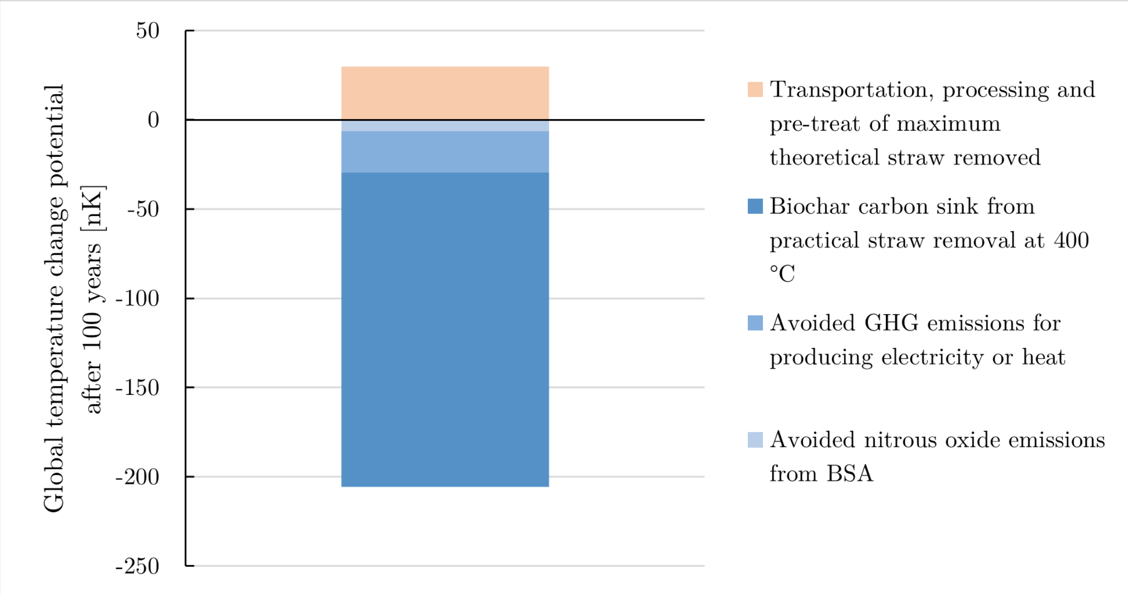

Figure 4.13: Heating and cooling effects resulting from direct and indirect impacts of biochar soil amendment (BSA) in Götalands norra slättbygder (GNS) when producing biochar from the practical harvestable amount of straw at a pyrolytic temperature of 400 °C

5

Discussion

The aim of this thesis was to investigate how the production and use of biochar from APRs affect carbon sequestration and climate change mitigation, together with the impacts on soils when applying APR biochar to different soil types. This chapter covers the discussion on the results and methodological choices. First, uncertainties in this thesis are covered. Second, the potential impacts from BSA in the soils of GNS are assessed. This is followed by a general discussion on the environmental, societal and economic aspects of producing and using biochar. Further, assumptions and decisions made regarding model structure and equation uses are covered. Lastly, future potential research is discussed.

5.1 Uncertainties

The uncertainties relate to the temporal and spatial resolution of the data gathered. Where data from recent years was unavailable, older and available data had to be used in its place with common risks of using data not representative of today. Regarding the spatial aspect of data, the uncertainties are two-fold. First, when local data was unavailable it had to be replaced with more generalized, regional or national averages and thus increasing the uncertainties of the results. Second, data developed for a specific country or region might not necessarily be directly applicable to Sweden, but was still used due to lacking availability of similar data. A challenge with the equations used in the model are that some are for specific conditions and situations, and some are general. Both of these create a potentially uncertain result for the case used in the analysis. With this said, the temporal and spatial resolution of data is not deemed to add a significant uncertainty to the results.

Other uncertainties are connected to the long-term BSA-effects on both climate and soil. Given the novelty of biochar research, it is difficult to establish how soils will interact with biochar. It is also not clear which interactions are coupled or decoupled from each other. For example, yield increase from BSA seen in most soils could possibly be a combination of water and nutrient holding capacity, pH-increase, etc. Therefore, there is a risk that the data presented is being more or less favourable to biochar than is true in practice. Further, given a warmer future climate and increased risks of crop fires, the biochar carbon sink in soil over time is therefore difficult to estimate with certainty.

5.2 Biochar in GNS

This section covers the assumed soil and climatic impacts from BSA in GNS, based on the results in 4.1 and the assessment matrix in Figure 4.4, and the results in Section 4.3. Due to the complexity of soil and biochar interactions the following information should mainly be viewed as recommendations. Specific field experiments need to be done to fully assess the BSA impact on soils in GNS.

Due to the dominance of clay soils in GNS and an average pH of 6.3 we can assume that BSA could potentially have positive impacts. One reason is the possibility of yield increase, up to 16 % within the first year after application, according to Liu et al in clay soils [78]. However, these findings needs to be addressed with caution. GNS has a close to neutral pH and with biochar being alkaline, and with several studies showing with certainty that BSA has a liming effect it might not be beneficial to add biochar to soils in GNS from a pH-perspective. This however depends on the management practice of GNS farming, with a possibility to offset the need of liming.

Further, clay soils are prone to compaction resulting in inhibited root growth, nutrient retention and water retention. Biochar can enhance bulk density and therefore reduce the effects of soil degradation in all soil types, especially in clay soils, specifically with high pyrolytic temperature biochars.

It is evident that biochar in sandy soil has a positive impact on water retention, but the impact in clay soils is not as certain. Clay soils may need drainage to enhance soil fertility, and at the same time increase plant available water. We are cautiously positive to water impact with BSA in clay soils. We believe that BSA have the potential of enhance drainage and at the same time increase plant available water due to the physical structure of biochar. The porous material will decrease the soil compaction and therefore let water get drained, while at the same time keep water in its pores for plants.

We do not recommend to add more than 20 ton biochar ha^{-1} yr^{-1}. This is due to the liming effect of biochar and that we have not found any indications that application of more than 20 t ha^{-1} yr^{-1} is beneficial. This is however not true when it comes to bulk density. Depending on the how compact the soil is, adding more biochar might be needed to enhance the soil. In the case of GNS this will not be of importance due to the yield of biochar will never be of that size but it is still noteworthy.

Annually, the Swedish agricultural sector emits roughly 7 million tons of carbon dioxide equivalents. The agricultural production region of GNS has the potential of sequestering a practical maximum of roughly 450 000 tons of carbon dioxide equivalents.Consequentially, the practical amount of produced and use of biochar for soil amendment in GNS could potentially offset 6.5 % of Sweden's entire agricultural GHG-emissions [98].

Lastly, producing biochar provides surplus heat which can be used for heating or electricity generation. In an agricultural setting, this heat could be used for greenhouse heating or grain drying, or possibly be connected to a local district heating system. This is something that can be seen as further incentive for implementing biochar production in local farming communities.

In summary, BSA has the possibility of having predominantly positive effects in GNS. We believe that biochar from APRs can enhance soil fertility and health, and therefore increase yields and buffer for degradation, thus adding value to a resource not utilized today. It can at the same time act as a carbon sink, mitigating climate change and possibly offset up to 6.5 % of Sweden's agricultural emissions and possibly provide locally produced bioenergy. In other words, there are multiple positive effects with biochar production in GNS that makes it interesting to further evaluate the implementation possibilities.

5.3 Biochar impacts

This section covers a discussion on the general impacts of biochar in terms of climate, soil fertility and economy.

5.3.1 Climate

The climate impacts of biochar production and its use as a soil amendment are multifaceted and extend beyond its direct role as a carbon sink. First, a majority of the CDR potential from BSA is derived from the direct biochar carbon sink. Second, BSA can contribute to climate mitigation indirectly by reducing the emissions of potent GHGs like nitrous oxide, as seen in Section 4.1.1.3 and Figure 4.12, and, to a lesser extent, methane. While the detailed discussion of methane emissions is beyond the scope of this thesis, it is important to acknowledge that BSA can have a positive impact on reducing these emissions, especially in paddy soils.

Another climate benefit associated with biochar production is the generation of surplus heat. The excess heat produced during the pyrolysis process can be utilized to offset the use of electricity or heat generated by other means. By utilizing this surplus heat, biochar production can help avoid potential climate impacts associated with conventional energy production methods.

The temperature at which biochar is produced also plays a crucial role in its climate impact. Although biochar stability decreases with lower production temperatures, the equations used in the model express that producing biochar at lower temperatures results in an even higher mass yield. Consequently, when considering the net carbon sink, which takes both yield and stability over time into account, producing biochar at lower temperatures leads to a greater overall carbon sequestration potential. Further, taking BSA into account, a greater mass yield of biochar is beneficial as there is more biochar available for application.

It is important to note that while BSA has several benefits, solely focusing on the climatic impacts may lead to alternative CDR technologies like Bioenergy with Carbon Capture and Storage (BECCS) appearing more favorable. However, it is essential to consider that opting for BECCS alone would omit the additional positive impacts that BSA brings, even though BECCS has a theoretically higher CDR potential per ton of biomass used. Another important aspect when assessing CDR technologies is the current technological availability. Biochar production is readily available today, where for example BECCS still lacks infrastructure solutions for transport and geological storage of carbon dioxide.

There are however potentially adverse climatic effects of using biochar for soil amendment as well. Making the soil darker with biochar contributes to an increased heat absorption, leading to a higher surface temperature. The magnitude of the impact on albedo varies with application rate, soil type and agricultural management, and these should all be considered before implementing BSA, so that the climatic benefits of the biochar itself are not equalized. Further, albedo decreases when straw is removed from a field after harvest, as plant residues generally are lighter in color compared to the soil beneath. There are however methods to potentially mitigate the decrease in albedo from BSA and extracting APRs. After harvest, cover crops can be planted to minimize the decrease in albedo so that the dark soils remain covered for as long as possible. For BSA, the darkening of the soil surface can be minimized by incorporating the biochar deeper below the surface, directly after application.

A potentially significant threat to the climatic benefits of biochar production on a small scale is the release of uncombusted pyrolysis gases. The gases produced during pyrolysis can consist of methane, polycyclic aromatic hydrocarbons (PAHs) along with other hydrocarbons, many of which have a multiple fold higher global warming impact than carbon dioxide. If these were to be released into the atmosphere, the benefit of the carbon sink in biochar would quickly be lost. Difficulties with reaching complete combustion of pyrolysis gases is mainly a result of having a too wet feedstock. The problem of potentially releasing strong GHGs can easily be solved by the use of modern pyrolysis technology, equipped with exhaust combusters to ensure full combustion of pyrolysis gases. Further, biochar certification organizations such as the International Biochar Initiative (IBI) or the European Biochar Certificate (EBC) emit certificates that ensure a net negative carbon sink from the production of biochar [21].

5.3.2 Soil fertility

BSA has promising potential in enhancing various aspects of soil health and fertility. By interacting with soil pH, CEC, water and nutrient retention, among others, biochar can help reduce the dependence on synthetic fertilizers, irrigation, lime, and pesticides. By reducing the need for these inputs, biochar can potentially generate indirect benefits such as minimizing nutrient runoff and groundwater contamination, and thus eutrophication and acidification. Reducing the need for these commodities can both decrease farmers' costs and the dependence on external supply chains.

Furthermore, the application of biochar has demonstrated a positive impact on crop yields, with some variation depending on soil conditions. The potential improvements in soil pH, water retention, bulk density reduction, root growth, and enhanced nutrient availability are among the key impacts in soils contributing to increased crop yields. This not only benefits farmers by increasing their agricultural productivity but also has broader implications for food security and mitigating climate change.

However, there are potential risks associated with certain practices related to BSA. Removing APRs from a field for biochar production can have negative consequences such as increased soil erosion, as the residues play a role in protecting the soil surface from wind and water. Further, the presence of straw contributes to maintaining short-term SOM and biodiversity.

Other potential risks are the impacts of not returning the produced biochar to the field from which the feedstock was sourced, especially from fields with poor soil quality. By removing carbon and nutrients and not recycling them to the field will reduce a field's resilience to further degradation. Therefore, proper management practices should be implemented to ensure a responsible use of biochar, including considering the appropriate rates and frequency of application, and monitoring soil fertility. However, the risks of not returning biochar to soils can vary depending on the initial condition and health of the soil.

In fields that are already in good quality, with favorable soil properties, the additional benefits of biochar may be limited compared to fields with lower quality. Applying biochar to already fertile soils may result in marginal or negligible improvements in soil health and crop productivity.

Instead, it should be recommended to prioritize the application of biochar in fields with low SOM, bulk density, low pH, nutrient deficiencies or poor water retention. In these situations, the addition of biochar can significantly enhance soil quality, leading to improved crop yield. From a larger systems perspective, targeting fields that are most in need of soil amendment could increase the efficiency of the resources used and efforts associated with BSA.

5.3.3 Economy

There are several economic aspects to assess when producing and using biochar. Although this thesis is more focused on the environmental aspects of biochar production and use, it is seen as an important part when assessing the consequences and impacts of biochar production. The economic analysis of biochar production involves assessing potential sources of income and comparing them with the costs associated with its production. A qualitative discussion regarding the bio-economy correlated to biochar production and its utilization is provided below, and is illustrated in Figure 5.1.

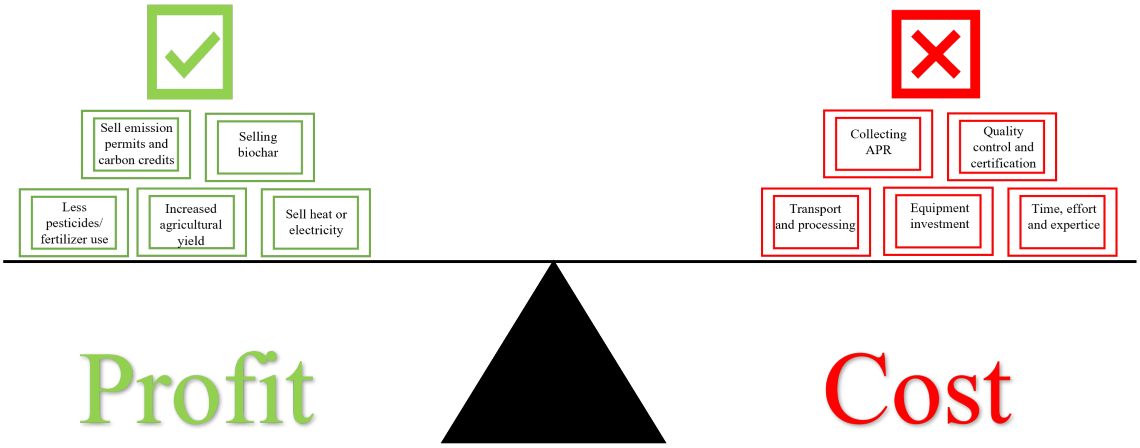

Figure 5.1: Illustration of potential profits or costs associated with biochar production and utilization

Several revenue streams can be considered, including selling emissions permits, either on the potential future European Emissions Trading System, or on contemporary voluntary carbon markets such as Puro or CarbonFuture [99]. Further, increased revenue can come from selling the biochar itself, from potentially increased agricultural yields and by selling heat or electricity generated during pyrolysis. However, it is crucial to carefully evaluate these income sources against the costs involved in a biochar-producing system.

One potential revenue stream is the sale of emission permits or carbon credits. As biochar production has the potential to sequester carbon dioxide from the atmosphere, the produced sink can be quantified and sold through emissions trading schemes. However, the financial gains from selling emissions permits may vary depending on current market prices and regulations. Furthermore, the ownership of the actual carbon sink can be difficult to determine. Depending on if the carbon sink owner is the biochar producer, the actor who applies it to soil, or both, will result in different economic outcomes for all actors involved.

Additionally, the biochar itself can be sold as a product for various applications. The market demand and the area of application of biochar will have an impact on its price. For example, biochar intended for use within the steel or concrete industry is required to hold specific characteristics that will have an impact on both its price and production cost.

Another source of income stems from the potential increase in agricultural yields from BSA. Not only are product yields expected to increase with BSA, the overall biomass production increases as well. Thus, more APR is produced which can in turn be used as feedstock for pyrolysis, consequentially creating a positive feedback loop. This correlation is illustrated in Figure 5.2. Note that this correlation is not studied in detail over time periods longer than a few years.

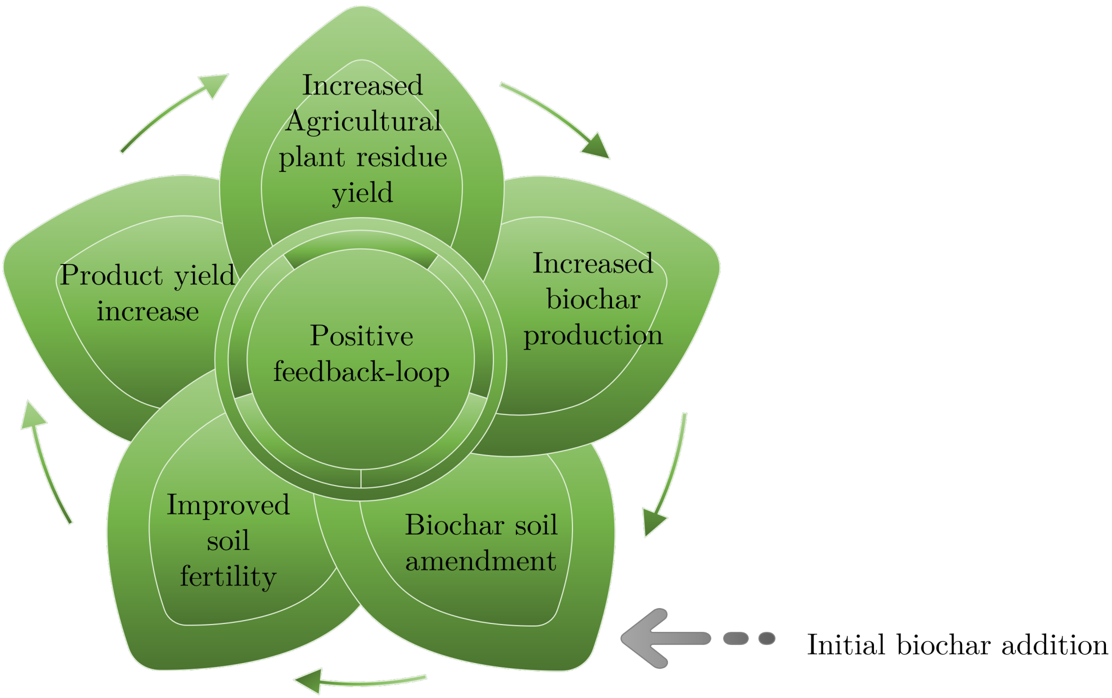

Figure 5.2: Visualization of potential positive feedbacks of producing and using biochar for soil amendment

Further, the generation and sale of heat or electricity during pyrolysis can provide additional revenue opportunities. The heat generated from the pyrolysis process can be utilized for on-site heating or electricity generation, thus reducing energy costs. If surplus energy is produced, it could potentially be sold to the electricity or central heating grid for increased profit. It is worth mentioning that from a Swedish perspective, on-site heating demands depend on season. Therefore, being able to convert heat to electricity is important when the need for heating is low during summer months.

On the cost side, factors such as APR collection, transport and processing, pyrolysis equipment investments, and process efficiency should be taken into account. These factors influence the overall production costs of biochar. Additionally, the time, effort, and expertise required for biochar production, including monitoring and quality control, should also be considered as part of the cost assessment. Lastly, acquiring a certification for sustainably produced biochar from organizations such as the EBC, can be costly and time consuming. This might still be profitable due to the certified biochar being more suitable for inclusion in the market of emission permits or carbon credits.

Lastly, the removal of crop straw, especially rapeseed straw, entails the removal of plant nutrients such as nitrogen and potassium. If residues are removed, these nutrients might have to be compensated for in the form of additional fertilizing, implying a potential additional cost for a farmer [100].

In conclusion, the economic viability of biochar production depends on careful analysis of potential income sources and associated costs. While revenue streams such as selling emissions permits, increased agricultural yields, selling heat or electricity, and selling biochar offer potential financial gains, the costs of production, including transport, storage, processes, pyrolysis investments, and additional time and efforts, must be evaluated. Further, it is essential to assess market conditions, regulatory frameworks, and specific contexts to determine the profitability of biochar production.

To get an overview of how much biochar a small-scale farm could produce, an example is provided in Appendix C. Since biochar price and production cost vary heavily from case to case, this is mainly provided to gain an understanding of roughly how large any potential costs and profits, given that production costs and selling prices per ton biochar are known. Further, surplus energy is shown in the example to give an estimate of how much heat the biochar production could generate.

5.4 Model discussion

The allometric equation used to estimate the carbon inputs from different crop parts of cereals and rapeseed, Equation 3.4, uses coefficients that are old and not necessarily corresponding to Swedish crop production. The coefficients used, in this case the R-values, might however not be entirely representative for Swedish cereals and rapeseed. In reality, the relative fraction of harvestable straw is presumably lower today, given recent advances in plant breeding that promote a higher yield of product relative to the other crop parts [48]. The allometric equation was still used as its methodology is deemed suitable for estimating carbon content of cereals and rapeseed and its carbon inputs to soils [53].

Lehmann et al's equations used for calculating the MRT and mass fraction of biochar remaining after 100 years in soil BC_{+100}, Equations 3.7 and 3.8 respectively, are valid at an ambient soil temperature of 10 °C. In reality, the annual mean temperature in GNS is lower, around 7 °C [101]. Due to this, the values for MRT and BC_{+100} should in reality be higher, meaning that the direct carbon sink of biochar in soil could be larger over time than shown in the results.

Soil type can play a significant role in the stability of biochar where, for example, biochar added to clay soils have a higher residence time than biochar in sandy soils [51], [77]. This implies that the carbon sink in soils with a higher fraction of fine mineral particles would remain more stable over time, compared to in coarse soils. However, to remain more generalized, the model is solely constructed to calculate carbon sequestered in biochar regardless of soil type.

6

Conclusion

In summary, BSA has the possibility of providing predominantly positive effects. We believe that biochar from APRs has great potential to enhance soil fertility and health, and therefore increase yields and soil resilience, while adding value to a resource not utilized today. By reducing the reliance on synthetic inputs and enhancing nutrient retention, biochar can contribute to more sustainable agricultural practices. To maximize the benefits of BSA and mitigate potential inefficient resource use, it is recommended to prioritize amending soils of low quality. Applying biochar to already fertile soils may have marginal or negligible effects on soil health and crop productivity. Biochar can at the same time act as a stable carbon sink, where its production and use also create indirect climatic benefits from energy production and GHG-emission reductions. Hence, it is indicated that biochar has potentials to couple climate change mitigation efforts with increasing soil fertility and therefore agricultural production.

Applying the results to the case of GNS shows the potential of offsetting up to 5 % of Sweden's agricultural emissions, possibly providing locally produced bio-energy and improving the region's soil fertility in general.

However, before implementing biochar production from APR, at any scale, the environmental, economic, technical, climatic and regulatory aspects have to be evaluated. The complexity in trade-offs between technological feasibility, agricultural management practices, climatic impacts, investment and production cost, to name a few, should be evaluated on a case-by-case-basis before implementation.

6.1 Future research

Further studies are crucial to deepen the understanding of the consequences from producing and using biochar. Advancing knowledge in the following areas will enhance the potential of biochar for improved agricultural systems and for climate change mitigation.

- Long-term effects: Further investigation is needed to assess the long-term impacts of biochar application on soil health, fertility, and carbon sequestration in different climates and soil types.

- Upscaled biochar production impacts: More research is required to assess the potential environmental impacts of large-scale biochar production and application. This should include evaluating the carbon footprint and energy balance of a biochar-producing system. Further assessment is needed to evaluate cascading effects that biochar might pose on other value chains. Also trade-offs and impact comparisons should be analyzed to maximize environmental benefits.

- Economic viability: Further studies should assess quantitative economic feasibility of biochar production and application at different scales. This includes evaluating the costs associated with feedstock and biochar production, transportation, and application, and comparing them to the potential known and unknown economic benefits.

- Exploring other feedstocks: Further research should explore the potential of using APRs derived from other crops beyond winter wheat, spring barley, oats and winter rapeseed. Further, diverse feedstocks beyond APR should also be evaluated for biochar production. Assessing the carbon sequestration potential, biochar properties, and application effects of other feedstocks can diversify the scope of biochar utilization and contribute to the development of sustainable and resource-efficient biochar production systems.

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A

Appendix A

This appendix provides a collection of supplementary materials that support and complement the main content of this thesis. It includes additional data and tables that were instrumental in conducting the research and arriving at the conclusions presented in the main text, as well as a small calculation example.

Table A.1: Harvest yield, total cultivated area and total harvest for winter wheat, spring barley, oats and winter rape in Götalands norra slättbygder (GNS) over the years 2019-2022 [47]

	Year				
Crop	2019	2020	2021	2022	Average
Winter wheat					
Harvest yield [kg ha^{-1}]	8 040	7 370	6 800	7 510	7 430
Area cultivated [ha]	123 100	117 280	125 200	117 020	120 650
Total harvest [kg]	989 900	864 900	851 000	879 100	896 225
Oats					
Harvest yield [kg ha^{-1}]	5 260	4 790	3 740	5 250	4 760
Area cultivated [ha]	48 090	58 320	54 660	50 670	52 935
Total harvest [kg]	252 700	279 100	204 200	266 000	250 500
Spring barley					
Harvest yield [kg ha^{-1}]	5 930	5 390	4 360	5 790	5 367.5
Area cultivated [ha]	40 160	38 040	33 950	39 540	37 922.5
Total harvest [kg]	238 100	204 900	148 000	229 000	205 000
Winter rape					
Harvest yield [kg ha^{-1}]	3 570	3 610	3 620	3 300	3 525
Area cultivated [ha]	23 500	21 370	22 310	26 590	23 442.5
Total harvest [kg]	83 900	77 100	80 700	87 800	82 375

Note that harvest yields and total harvest are expressed with a 14 % and 9 % moisture content for cereals and oilseeds respectively.

The values in table A.2 are expressed as estimates on a 95 % confidence interval and might therefore not sum to 100 %. The real value might, at the most, vary with ±6%.

Table A.2: Crop residue utilization in Götalands norra slättbygder (GNS) [19]

Crop	**Not utilized [%]**	**Utilized [%]**
Winter wheat	62	36
Spring barley	66	31
Oats	71	26
Winter rape	93	7

Table A.3: Energy required for processing straw, making large rectangular bales and pelleting along with resulting emissions [48]

Process	Energy required [MJ ton^{-1} DS straw]	CO2eq emissions [kg ton^{-1} DS straw]
Straw raking	37.33	2.8
Pressing/chopping	150.00	11.25
Gathering/loading	25.00	1.875
Transport	17.00	1.275
Unloading/Storing	5.33	0.4
Pelleting	1220	91.5
Total	1454.67	109.10

All energy required for each process is assumed to come from diesel, with an emission factor of 75 g CO2eq MJ $^{-1}$ upon combustion [102].

B

Appendix B

This section covers explanations of the equations and methodology used to estimate the climate impact of substituting fossil counterparts to biochar, or through the inclusion of biochar as an additive in materials such as concrete or composites.

If biochar is to be used industrially to replace fossil feedstocks, it is of importance that the biochar has equal properties to its fossil counterpart. In steelmaking, a high carbon content and low traces of ash and interfering compounds are coveted attributes of the reducing agent [103]. To achieve the carbon content of fossil coal sources (>85%), the required pyrolysis peak temperature can be derived from rearranging Equation 3.9:

$$Y_{C,m} = 0.93 - 0.92 * e^{\left(\frac{-0.42T}{100}\right)} \Leftrightarrow T = \frac{ln(\frac{0.93 - Y_{C,m}}{0.92}) * 100}{-0.42} \tag{B.1}$$

By letting $Y_{C,m} = 0.85$, we get T ≈ 580 °C, which is in line with previous studies stating that pyrolysis peak temperatures above 500 °C are favorable for production of biochars used in metallurgical applications [104], [105].

If the biochar is used in process that consumes it, the climate impact is equal to the amount of fossil carbon that the biochar carbon offsets. If the biochar is used in applications where it is stored, as an additive to concrete for example, the biochar carbon can be regarded as a negative emission for as long as the biochar is stored.

C

Appendix C

Calculation example for a small farm

A farm cultivates 100 ha of land, half the land produces straw that lacks utilization and can be used for biochar production. On these 50 ha, winter rapeseed is grown on 15 ha and winter wheat is grown on 35 ha. Assuming a product yield of $Y_{P,WW}$ = 7 ton ha^{-1} for winter wheat (14 % moisture content) and a product yield of $Y_{P,WR}$ = 3.5 ton ha^{-1} (9 % moisture content) for winter rapeseed. The dry matter (DM) product yield for winter wheat and winter rapeseed is thus:

$$Y_{P,WW,DM} = Y_{P,WW} * (1 - 0.14) \tag{C.1}$$

and

$$Y_{P,WR,DM} = Y_{P,WR} * (1 - 0.09) \tag{C.2}$$

Which gives the DM product yields for winter wheat and winter rapeseed of $Y_{P,WW,DM}$ = 6.02 ton DM ha^{-1} and $Y_{P,WR,DM}$ = 3.19 ton DM ha^{-1}, respectively.

This is used to calculate the DM straw yield with the use of plant-part mass coefficients shown in Figure 3.3 for winter wheat and winter rapeseed. Thus, the DM straw yield for winter wheat and winter rapeseed can be expressed as:

$$Y_{S,WW,DM} = R_{S,WW} * (Y_{P,WW,DM}/R_{P,WW}) \tag{C.3}$$

and

$$Y_{S,WR,DM} = R_{S,WR} * (Y_{P,WR,DM}/R_{P,WR}) \tag{C.4}$$

Which gives a DM straw yield of $Y_{S,WW,DM}$ = 9.01 ton DM ha^{-1} for winter wheat and $Y_{S,WR,DM}$ = 17.15 ton DM ha^{-1} for winter rapeseed.

Given a practical harvestability of 60 % and 30 % of the entire DM straw yield for winter wheat and winter rapeseed respectively, the practical DM straw yield is:

$$Y_{S,WW,DM,P} = Y_{S,WW,DM} * 0.60 \tag{C.5}$$

and

$$Y_{S,WR,DM,P} = Y_{S,WR,DM} * 0.30 \tag{C.6}$$

Which gives a practical harvestable DM straw yield of $Y_{S,WW,DM,P}$ = 5.41 ton DM ha^{-1} and $Y_{S,WR,DM,P}$ = 5.14 ton DM ha^{-1} Given 35 ha and 15 ha of winter wheat and winter rapeseed cultivation, respectively, the total amount of wheat straw produced is 35 * 5.41 = 189.24 ton DM and a winter rapeseed straw production of 15 * 5.14 = 77.15 ton DM. I.e., a total of 266.39 ton DM straw. Pyrolyzing this amount of straw at a pyrolysis temperature of 400 °C, using Equation 3.5, gives a pyrolytic biochar yield of 74.43 ton biochar.

Further, assuming that straw has a heating value of 18.6 GJ ton^{-1} [106] and that one third of the biomass' heating value becomes surplus heat generated during pyrolysis, the pyrolysis generated 6.2 GJ per ton of ingoing straw. Given an ingoing mass of 266.39 ton of straw, the pyrolysis should produce roughly 15 TJ of surplus heat that can be used elsewhere.

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