Biochar in Swedish agriculture – straw pyrolysis as a first step towards net-zero

Elias S. Azzi, Louise Jungefeldt, Shivesh Karan and Cecilia Sundberg

Mistra Food Futures Report #4
2022

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Biochar in Swedish agriculture – Straw pyrolysis as a first step towards net-zero
Biokol i svenskt jordbruk – pyrolys av halm som ett första steg mot netto-noll

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The overarching vision of the programme Mistra Food Futures is to create a science-based platform to enable transformation of the Swedish food system into one that is sustainable (in all three dimensions: environmental, economic and social), resilient and delivers healthy diets. By taking a holistic perspective and addressing issues related to agriculture and food production, as well as processing, consumption and retail, Mistra Food Futures aims to play a key role in initiating an evidence based sustainability (including environmental, economic and social dimensions) and resilience transformation of the Swedish food system. This report is a part of Mistra Food Future's work to identify agricultural systems with potential to make agriculture net-zero, one of the central issues within Mistra Food Futures.

Mistra Food Futures is a transdisciplinary consortium where key scientific perspectives are combined and integrated, and where the scientific process is developed in close collaboration with non-academic partners from all parts of the food system. Core consortium partners are Swedish University of Agricultural Sciences (SLU), Stockholm Resilience Centre at Stockholm University and Research Institute of Sweden (RISE).

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Publication: Mistra Food Futures Report #4
Year of publication: 2022
Publisher: SLU
Cover photo: Pixabay
Print: SLU Repro, Uppsala
ISBN: 978-91-8046-758-2 (electronic), 978-91-8046-759-9 (print)

FUNDED BY
MISTRA
The Swedish Foundation for Strategic Environmental Research

Abstract

Biochar is a method for carbon dioxide removal through long-term storage of biogenic carbon in soil. Quantifying biochar impacts on agricultural greenhouse gas emissions requires a systems perspective since biochar can be produced from various agricultural feedstocks, and will have various effects when applied on cropland. In this report, climate impacts are quantified in a life cycle assessment of wheat production in Sweden using biochar produced from straw. When comparing wheat production with biochar to either ploughing straw back into soil, or using straw for heat production, the climate impact of wheat is reduced by about 45%. Some factors that have large influence on the result are the assumptions on the energy system, long-term biochar stability, and effects of biochar on crop yield. Biochar sustainability, potential and implementation are also discussed in the report. In total, the prospects for biochar as a climate solution for Swedish food and agriculture are complex but also diverse and promising.

.*Keywords:* barriers, biochar, opportunities, life cycle assessment, potential, wheat

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1. Introduction

Biochar is a carbon-rich biomaterial produced by biomass combustion in a controlled process called pyrolysis. Although it resembles regular charcoal, biochar is created using a method to reduce contamination and properly retain carbon. In pyrolysis, organic materials like straw or garden waste are burnt with limited oxygen. The organic material is transformed into biochar, a stable form of carbon. Pyrolysis also produces gases that can be burnt to produce heat or other forms of energy, thereby providing renewable energy.

By retaining biogenic carbon in biochar, carbon dioxide is removed from the atmosphere. If biochar is placed in soil, most of the carbon will remain there for a long time. The use of biochar technology has the potential to reduce waste, enhance soil quality, combat climate change, and even generate energy as a by-product. However, these effects depend upon the entire life cycle of biochar from production to deployment.

The purpose of this report is to provide insights into reducing the climate impacts of Swedish agriculture and food through biochar deployment. This is done through a life cycle assessment (LCA) where biochar is produced from straw and used in crop production. In addition, there is a discussion on the potential and sustainability of biochar in Swedish agriculture and food systems.

The reported work started as a collaboration between Mistra Food Futures and the Vinnova project Biochar - systems analysis for climate change 2016-03392, which ended in 2021 with the Ph.D. thesis of Elias Azzi at KTH as its main output (Azzi, 2021). Most of the work with the LCA was done by Louise Jungefeldt at KTH, and the LCA has been finalised by Elias Azzi and Shivesh Karan. Cecilia Sundberg led the planning and made the outline of the report. Azzi, Karan, and Sundberg wrote the discussion. All authors have made substantial contributions and are listed in alphabetical order.

1.1. Objectives

This report aims to investigate and provide insights into the potential of biochar for climate change mitigation in Swedish agriculture. This is done through two specific objectives:

(i) Assess the climate impact of implementing biochar production from wheat straw at the farm level through an LCA

(ii) Discuss aspects such as sustainability, effects of geographic distribution, potentials, challenges in implementation, and the prospects of biochar deployment.

1.2. Structure of the report

The LCA case study is described in the first part of the Methods, Results, and Discussion chapters. The other parts of the report, on biochar potential and sustainability, are described at the end of the Methods section and in the Discussion section.

2. Methods

2.1. Life cycle assessment

The overarching aim is to investigate the potential of biochar from wheat straw for climate change mitigation within the Swedish agriculture at the farm level. This is achieved through assessing the climate impact from cradle to gate of the production of dried wheat grain, with three scenarios for straw management: (a) biochar production from straw and incorporation in the field, (b) straw incorporation in the field, and (c) straw for heat production. Alternative scenarios (b) and (c) were selected based on the standard practices within the Swedish agricultural system (SCB, 2013). The life cycle assessment (LCA) calculated both a static climate change impact, for comparison with previous studies, and a time-dynamic climate change impact, to further investigate the effects of soil carbon dynamics on the climate. For this, conventionally grown wheat at a hypothetical farm in the Mälardalen area of Sweden was considered as the study area. A time-distributed life cycle inventory (LCI) was used to evaluate the changes in biochar decay and soil organic carbon (SOC).

2.1.1. Scope definition

The functional unit was set to 1 tonne (megagram, Mg) of dried grain wheat per year. The modelling was performed using one hectare (ha) of agricultural land, cultivated with winter wheat, annually, during a 20-year-long production cycle.

For the static assessment, the climate change impact was characterized using Global Warming Potentials with a 100-year time horizon (GWP_{100}). For the dynamic assessment, the time distributed LCI spanned over 100 years. The dynamic climate change impact was characterized using absolute global temperature change potential (AGTP) (Ericsson *et al.*, 2013), ΔT (temperature response), which was evaluated for a period of 150 years. The starting year of the assessment was 2019.

The LCA only considered greenhouse gas emissions and removals from CH_4, N_2O, fossil CO_2, and multi-annual biogenic CO_2 fluxes. Non-fossil CO_2 emissions that occurred in the same year as the uptake was considered to have a net-zero climate impact. The life cycle inventory database used was ecoinvent, version 3.6, cut-off (Wernet *et al.*, 2016).

2.1.2. Scenario description

Figure 1 shows the main material flows and processes involved in the production of 1 Mg of wheat with different straw management options. Wheat production included cultivation and harvesting along with drying of grains and was similar for all three scenarios. All material and energy inputs occurring annually were included, starting with soil preparation and ending with the final product of dried wheat grain at the mill. Soil N_2O emissions and carbon sequestration from biochar application and SOC processes were also included.

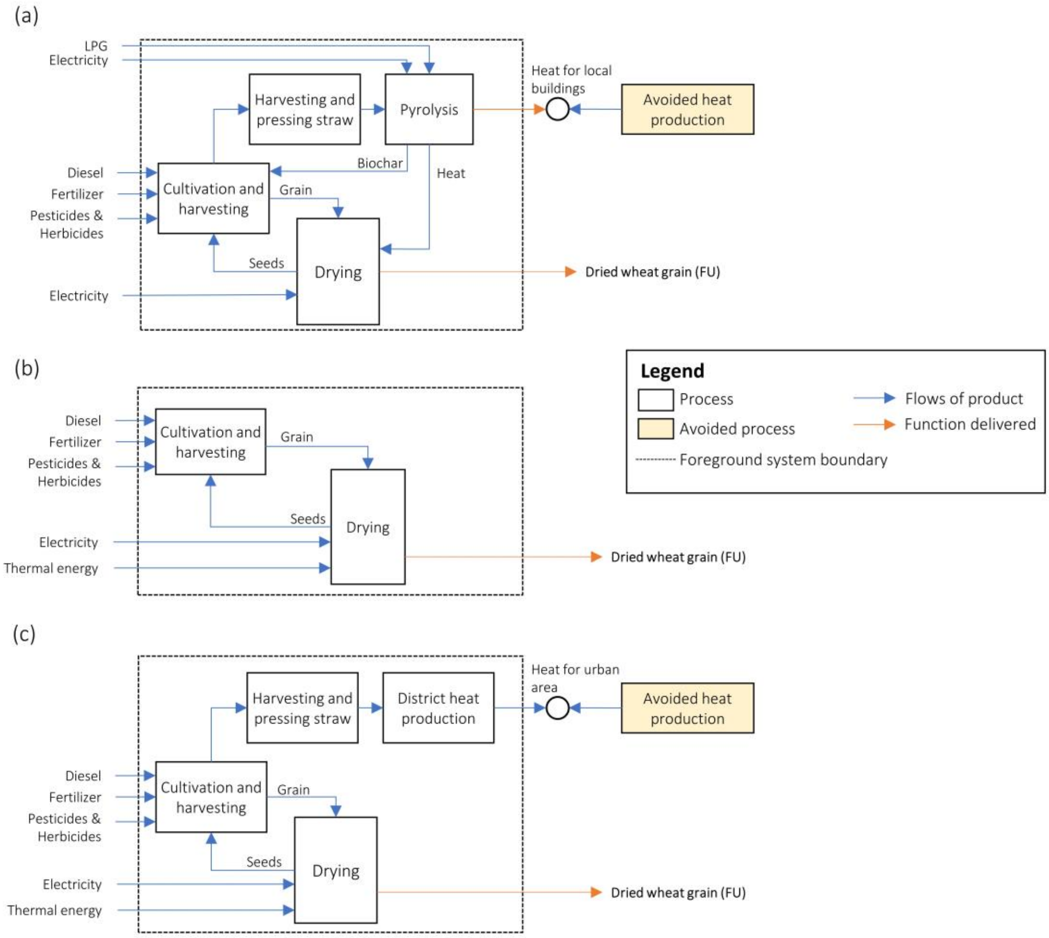

Figure 1: System description of material flows and processes for the production of 1 Mg of dried grain wheat (Functional Unit, FU) for three scenarios a) straw-to-biochar, b) straw-to-soil, c) straw-to- heat.

Straw-to-biochar scenario

In the straw-to-biochar scenario, the straw is baled and stored to be later chipped for pyrolysis at the farm. The heat generated from the pyrolysis process is used for drying grain and heating buildings at the farm (Figure 1a). All biochar produced from the pyrolysis is assumed to be applied as a soil amendment at the field where the straw was cultivated. No biochar effects on soil processes were included in the default case; however, biochar effect on crop yield was investigated in a sensitivity analysis. In this scenario, substitution was used to solve the multifunctionality issue arising from the heating of farm buildings. The avoided process was heat production from either wood pellet combustion (default case), or from natural gas combustion (sensitivity analysis).

Straw-to-soil scenario

In this scenario, straw is assumed to be incorporated back into the soil after being chopped. The modelling of straw incorporation and tillage included additional use of machinery in the field. In this scenario, external thermal energy is used for drying the wheat grain. The drying heat was assumed to come from the combustion of rapeseed methyl ester (RME), in the default case, or from natural gas combustion in the sensitivity analysis (Figure 1b).

Straw-to-heat scenario

In the straw-to-heat scenario, the straw is baled at the field and transported to a district heating plant, where it is incinerated with energy recovery (Figure 1c). Here as well, substitution was used to solve the multifunctionality issue arising from district heat production. The avoided process was heat production from either wood pellet combustion (default case), or from natural gas combustion (sensitivity analysis).

The modelling excluded construction, maintenance, and alterations of existing machinery and buildings. Storage of straw and wheat was assumed to have negligible impacts. No material losses were considered in the wheat and straw processing.

It is worth noting that large amounts of straw are used in animal husbandry, as animal bedding, after which most of the straw is returned to the soil with manure. Therefore, the scenario straw-to soil can serve as a relevant proxy for this fate, with the limitation that manure-straw-soil interactions have not been considered here.

2.1.3. Life cycle inventory modelling

Detailed data and equations behind the LCA model are available upon request of access to an online repository[1]. Below, important aspects of the inventory modelling are highlighted.

Cultivation and harvesting

The wheat yield for one hectare of managed soil in the Mälardalen area was assumed to be 6.0 Mg dried wheat grain (14 % water content). The cultivation and harvesting process included field operations, transportation on the farm and to and from the field, fertilizing, and treatment with pesticides. All three scenarios had nearly identical process inputs. The straw-to-soil and straw-to-biochar scenarios required harvesting with a straw cutter. Fertilization and use of herbicides, insecticides, and fungicides were based on the

[1] https://github.com/SLU-biochar/MFF_StrawBiochar
Request of access can be made to cecilia.sundberg@slu.se

recommendations from Flysjö, Cederberg and Strid, (2008); Glaser and Lehr, (2019); Swedish Board of Agriculture, (2020).

Straw management

In the straw-to-biochar and straw-to-heat scenarios, straw was assumed to be dried at the field to a level of 18 % water content. This was followed by pressing the straw into bales and transporting it to a non-heated storage unit at the farm. The amount of straw yield per ha corresponded to 2.7 Mg/ha.

Biochar production

In the straw-to-biochar scenario, straw is cut in a woodchipper and processed on farm in the Pyreg500 pyrolysis unit (Pyreg, 2021). Manufacturing data for the pyrolysis unit was obtained by scaling data from the manufacturing of furnace from Ecoinvent 3.6 (Wernet *et al.*, 2016) as specific data on material and energy inputs for manufacturing of the pyrolysis unit were unavailable. The percentage of total impacts from the Pyreg500 unit was calculated as 0.028 % per Mg of biochar, based on the assumed lifetime of the pyrolysis unit and annual biochar production capacity.

A 25 % biochar yield was assumed for wheat straw as feedstock, along with equal ratios, 37.5%, for syngas yield and bio-oil. Pyrolysis in the Pyreg500 results in biochar yields of about 20-30 % from dry biomass. Both syngas and bio-oil are fully combusted in the Pyreg500 unit, which operates between 500 – 750 ˚C. The pyrolysis temperature was set as 500 ˚C, as biochar yield decreases with increasing pyrolysis temperature (Wang *et al.*, 2020).

The excess heat was then divided into two parts assuming that heat was only used for one process at a time, either drying wheat or heating buildings. The part used for drying was included indirectly through the modelling of zero RME input and zero combustion emissions in the drying process. The part used for heating local buildings was then calculated as the excess produced from the pyrolysis of straw (from one ha) after the 6 Mg of wheat was dried. The 9149.6 MJ per ha (16530.5 MJ per Mg biochar) of excess thermal energy was then handled as avoided burdens by subtracting the corresponding amount of heat which the district heating system would have otherwise provided.

Wheat drying

For the straw-to-soil and straw-to-heat scenarios, drying of wheat relied on externally sourced energy, namely rapeseed methyl ester oil (in the default case). The grain was dried from 20% to 14%, requiring 108 kWh heat/Mg dried grain. Electricity was also consumed during drying, at a rate of 18.8 kWh/Mg dried grain (Edström *et al.*, 2005). Production and supply of rapeseed methyl ester oil were derived from the ecoinvent database.

For the straw-to-biochar scenario, drying of grain was achieved by using the heat generated during pyrolysis of a fraction of the straw available, within a month after harvest. Later in the year, excess straw is fed into the pyrolysis for heating of local buildings and hot water.

District heat production

An energy substitution was performed for the straw-to-heat and straw-to-biochar scenarios to solve the multifunctionality issue arising from the heat produced. The substituted heat was assumed to be derived from wood pellets produced from logging residues, with climate impact derived from Porsö et al., (2018).

Transportation

All transports on the farm and between the farm and field were included in the cultivation and harvesting process. Other transports outside of the farm were modelled using Ecoinvent 3.6 datasets for transportation with a lorry which includes the complete life cycle of machinery and takes into consideration the empty return. All lorries were set to have EURO6 classification and ranged between sizes 3-32 Mg. A general distance of 100 km was assumed for transporting grain from the farm to the mill and fertiliser and pesticides from the wholesaler. Distance for straw from the farm to the district heating plant was assumed to be 10 km.

SOC changes

The Introductory Carbon Balance Model regional (ICBMr) by Andrén, Kätterer and Karlsson, (2004) was used to calculate the change in SOC pool resulting from varying straw management.

The ICBMr was initialised with a 1000-year period to reach a steady state of the soil carbon balance and provide initial values for the SOC stocks. Carbon input during the initialisation period included roots, residues, and straw from wheat production. Every second year, straw was assumed to be removed from the field instead of being incorporated back into the soil. This reference land management corresponds to an average between the two straw management options considered in scenarios b and c. After the 20 years of grain production studied, straw management returned to this reference land management.

Straw-to-heat and Straw-to-biochar scenarios were modelled with 25% of the straw left at the field during the 20-year production period, based on the salvage coefficient for wheat straw. In straw-to-soil, 100% of the straw was assumed to be incorporated back into the soil. The rate of change for the total stock, ΔSOC, was then used to calculate the corresponding CO_2 emissions. As a simplification, SOC was assumed to be converted into only CO_2, meaning no CH_4 emissions were considered. After the production period, the total SOC stock returns to its steady state within a few years.

Biochar carbon sequestration and mineralisation

Once applied to soil, biochar was assumed to decay following a double-exponential decay model, without interaction with other soil organic pools and no priming effects. The decay model was parametrized using data compiled by Woolf *et al.*, (2021), for straw biochar produced at 500°C and incubated in laboratory conditions (Liu *et al.*, 2020). The 100-year permanence of the biochar carbon was approximately 73%.

N_2O emissions

Direct N_2O emissions were estimated using the model of Rochette *et al.*, (2018) and adjusted for Swedish conditions as in Henryson, Hansson and Sundberg, (2018). In brief, the model depends on applied N fertiliser, total precipitation, annual average air temperature, soil sand content, and soil pH. Weather and soil data were kept constant throughout the 20-year production period. Indirect N_2O emissions were estimated using the IPCC Tier 1 methodology (Hergoualc'h *et al.*, 2019), considering both N lost as NH_3 and NO_3^-.

2.1.4. Sensitivity analysis

Two sensitivity analyses were performed separately: i) energy context and ii) biochar effect on crop yield.

Energy context

In the default case, thermal energy used for grain drying or heating was derived from biomass combustion (rapeseed methyl ester and wood pellets, respectively). Here, a fossil-fuel context was represented by assuming that thermal energy would be provided by natural gas combustion.

Biochar effect on crop yield

In the default case, no crop yield effects were assumed. Here, the application of straw-derived biochar to the land where it was sourced (about 0.5 tonne ha^{-1} $year^{-1}$ for 20 years, cumulative application of 10 tonne ha^{-1}) was assumed to either increase crop yield by +15% or reduce it by -10%. The positive response (+15%) corresponds to the grand mean value presented in Ye *et al.*, (2020). The negative response (-10%) corresponds to a worst-case scenario. The yield effect was assumed to last only one year, although multi-year effects have been observed but not systematically (Haider *et al.*, 2017; Ye *et al.*, 2020). It is worth noting that the biochar application rate is smaller than commonly investigated in the literature (for pure biochar amendments) but is repeated annually for 20 years. This rate (0.5 tonne ha^{-1} $year^{-1}$) corresponds well to biochar co-application with fertilisers. Finally, differences in area of land use induced by crop yield differences were neglected, for simplicity. When biochar leads to a yield increase, some land is freed for other use, and vice versa.

2.2. Biochar potential and sustainability

Questions on other sustainability aspects, effects of localisation within Sweden, potential for implementation, factors affecting implementation, and timing of implementation were addressed qualitatively. Previous and ongoing work by the authors and their students were important sources, as well as published literature. The section on *Other sustainability aspects* was adapted directly from Azzi, Karltun and Sundberg (2021), and the section on geographic distribution within Sweden was adapted from Osslund, 2020 and Karan *et al.*, 2022.

3. Results

This section presents the main results of the LCA study presented in Section 2.1, for three straw management options.

3.1. Static climate change impact

The lowest climate impact, 235 kg CO_2-eq/Mg wheat, was observed for the straw-to-biochar scenario. When compared to straw-to-heat and straw-to-soil, this amounts to a 45% reduction in the climate impact of dried wheat grain production (Figure 2, Table 1). Straw-to-heat and straw-to-soil scenarios had similar GWP impacts of 425 and 429 kg CO_2-eq/Mg wheat. The better performance of the straw-to-biochar scenario is related to the large amount of carbon stored in the biochar over 100 years (201 kg CO_2-eq/Mg wheat). This carbon stock is more than ten times larger than the loss of SOC resulting from straw harvesting.

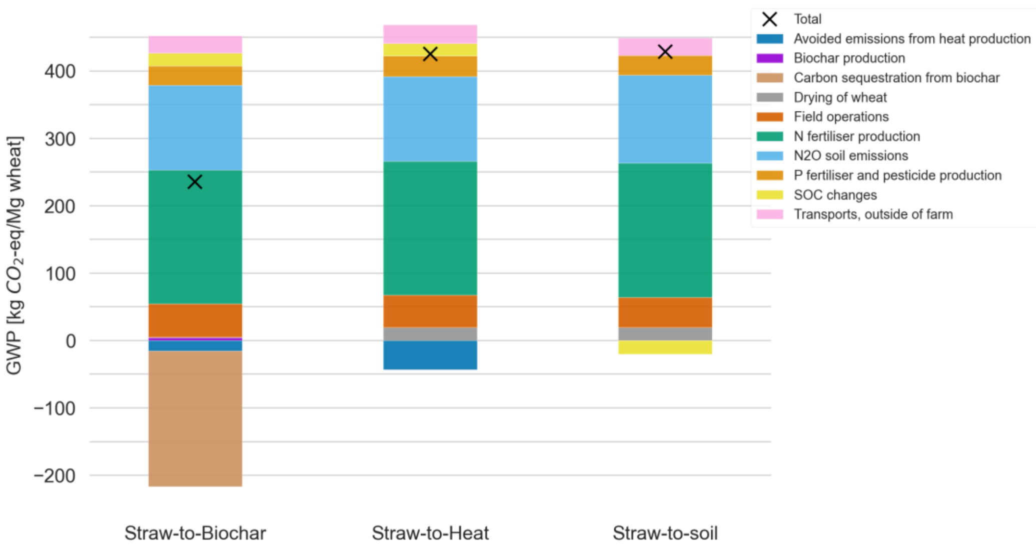

Figure 2: Static climate change impact of production 1 tonne of dried wheat grain, in kg CO_2-eq, in the three scenarios, with process contribution. The cross indicates the net -value. Corresponding data are shown in Table 1.

N fertiliser production was the main contributor to GHG emissions in all three scenarios. Direct and indirect N_2O emissions were the second largest contributing process resulting in almost a third of the total climate impact for straw-to-heat and straw-to-soil scenarios.

Soil processes of nitrification and denitrification mainly depend on the application rate of N mineral fertiliser and regional conditions; hence, impacts from these processes are similar in all three scenarios. Field operations, which also have a significant impact, mainly contribute by emissions from diesel production in the background system and diesel use in machinery.

Drying of wheat had a negligible contribution in the straw-to-biochar scenario because only some electricity is required, while the pyrolysis plant provides heat. This contrasts with the other scenarios where wheat drying represents about 4% of the net climate impact.

Table 1: Static climate change impact of production 1 tonne of dried wheat grain, in kg CO_2-eq/Mg wheat, in the three scenarios, by process contribution.

Process	Straw-to-biochar	Straw-to-heat	Straw-to-soil
Avoided emissions from heat production	-15.6	-43.3	0.0
Biochar production	3.86	0.0	0.0
Carbon sequestration from biochar	-201	0.0	0.0
Drying of wheat	0.964	18.8	18.8
Field operations	49.3	48.2	45.3
N fertiliser production	199	199	199
N2O soil emissions	126	126	131
P fertiliser and pesticide production	28.7	30.4	28.7
SOC changes	18.6	18.6	-20.4
Transports, outside of farm	26.4	27.7	26.4

3.2. Dynamic climate change impact

The time dynamic LCA with the instantaneous temperature response shows that straw-to-biochar had the lowest climate change impact during the 20-year period with wheat production and the period following the production (Figure 3). All scenarios had similar dynamics, with an increasing temperature response during the years of cultivation, a peak temperature a few years after the cultivation period, followed by a declining temperature effect thereafter. The reference scenarios straw-to-soil and straw-to-heat resulted in temperature responses of very similar magnitudes and time dynamics. In contrast, the straw-to-biochar scenario has ca. 50 % lower temperature response during the modelled period compared to the straw-to-soil and straw-to-heat scenarios.

The contribution to the temperature response for the three scenarios is shown in Figure 4. The lower climate change impact from the straw-to-biochar scenario results mainly from carbon sequestration by biochar and the utilization of excess thermal energy from pyrolysis for drying wheat grain and heating local buildings. For straw-to-soil, carbon sequestration instead occurs in the form of an increased SOC stock by straw incorporation. In the scenario, straw-to-heat, where straw is instead used as fuel in district heat production, the climate change mitigating effect results from avoided burdens of wood pellet production.

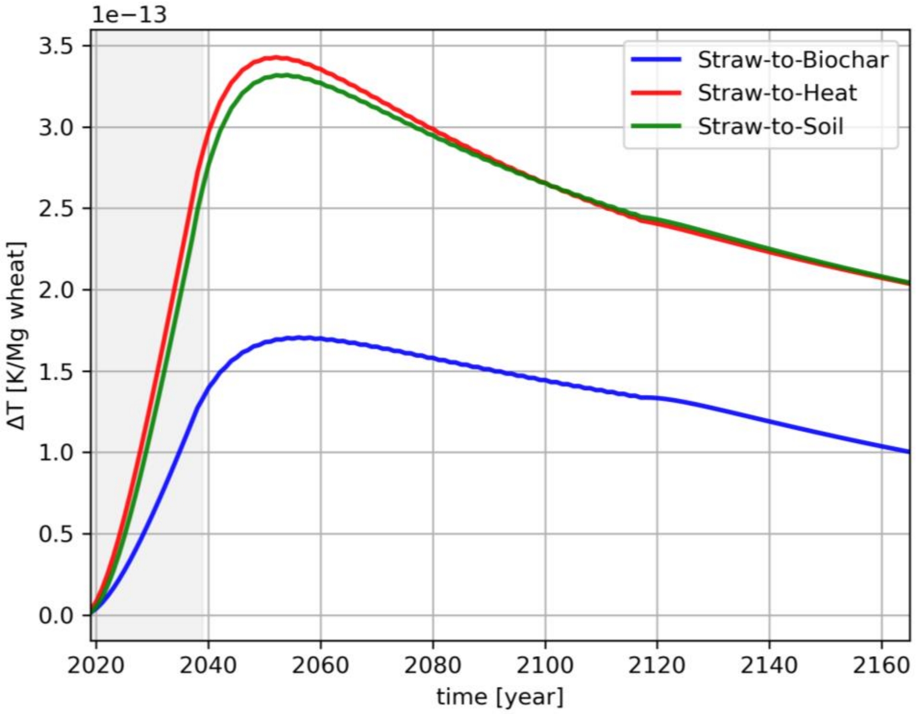

Figure 3: Instantaneous global average temperature response to 1 Mg dried wheat grain production, over a 20-year period (shaded area), for the three straw management scenarios.

The calculated SOC changes depend on the initial values obtained from the steady state reached after the 1000-year simulation. As the conditions for the steady state of the model are set to straw being returned to the soil every other year, the SOC stock increases when the straw is instead returned every year. Similarly, the SOC stock decreases when the straw is removed every year, as in the cases of straw-to-biochar and straw-to-heat, resulting in a contribution to the total climate impact. The opposite effect is seen during the years following the 20-year production period as the model again reaches a steady state where straw is returned every other year. These soil dynamics result in straw-to-heat having a lower temperature response than straw-to-soil in the year 2120 despite having a higher maximum temperature response in the year 2050 (Figure 3). As the decay rate for biochar is relatively low (73% remains after 100 years), there is no large contribution to the temperature response from CO_2 release by biochar decay (Figure 4).

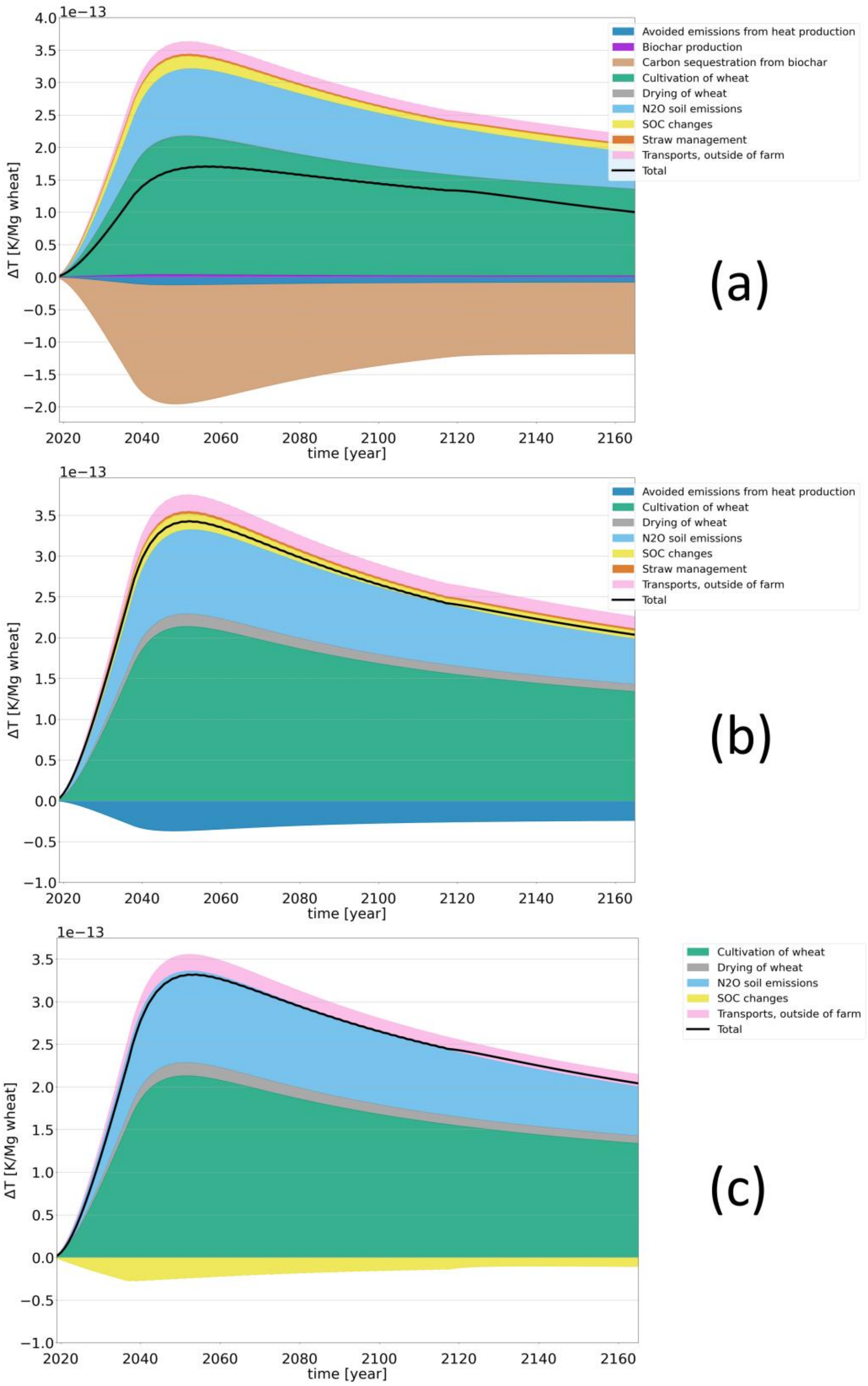

Figure 4: Global average temperature response to the production of 1 Mg dried wheat grain, over a 20-year period (shaded area), for the three straw management scenarios, with contribution analysis: a) straw-to-biochar, b) straw-to-incineration, c) straw-to-soil

3.3. Sensitivity analyses

Two sensitivity analyses were performed, and the results are presented below.

3.3.1. Energy context

In the first sensitivity analysis, the energy context was changed to a situation where natural gas is used both for drying of grain and for heating of buildings (Figure 5) instead of bioenergy. As a result, the scenario "straw-to-biochar" and "straw-to-heat" had a similar climate impact of 141 and 144 kg CO_2-eq/Mg wheat, respectively. This was 67% lower than the "straw-to-soil" scenario and was mainly due avoided emission from heat production and carbon sequestration from biochar (Figure 5a).

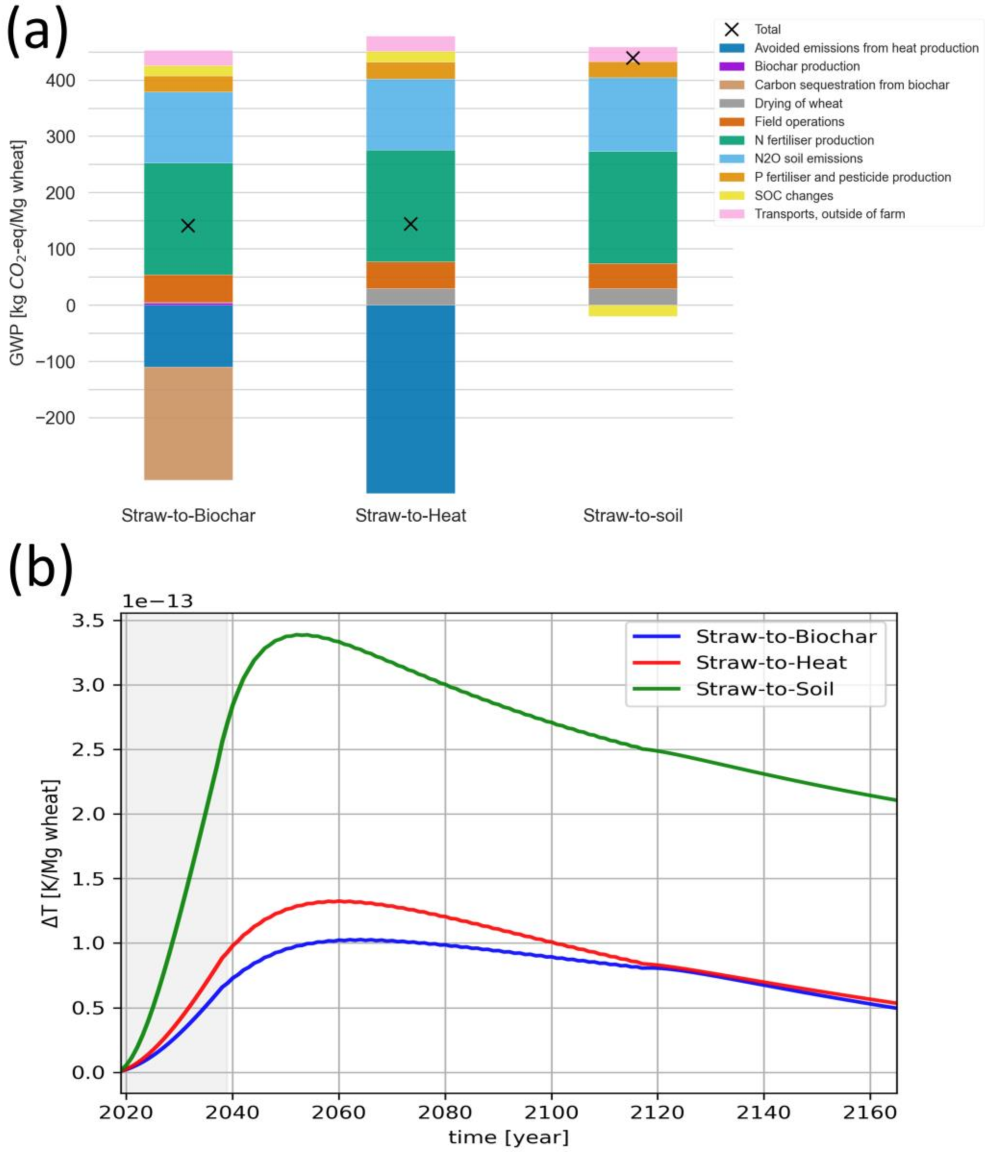

Figure 5: Static (a) and dynamic (b) climate change impact for the three scenarios, in an energy context where natural gas is used for heating buildings and drying grain.

A similar result is obtained when looking at the dynamic climate impact assessment (Figure 5b). It is worth noting that the straw-to-biochar scenario seem to lead to less warming than straw-to-heat, in particular around the peak year, 2040-2060 (Figure 5b).

The findings from this sensitivity analysis confirm previously demonstrated results (Azzi, Karltun and Sundberg, 2019, 2022; Azzi, 2021) that natural gas is a balance point: whenever the energy system has a lower climate impact than energy from natural gas, biochar systems are likely to be preferable over bioenergy systems, and vice versa.

3.3.2. Biochar effect on crop yield

The second sensitivity analysis investigated the effect of crop yield increase (+15%) and decrease (-10%), in the straw-to-biochar scenario (Figure 6). A 15% wheat yield increase in the whole field would result in a 17% lower peak temperature response. With a wheat yield loss of 10%, straw-to-biochar still results in a considerably lower instantaneous temperature response as compared to the other two scenarios. Land use change effects were however not included in the simulation.

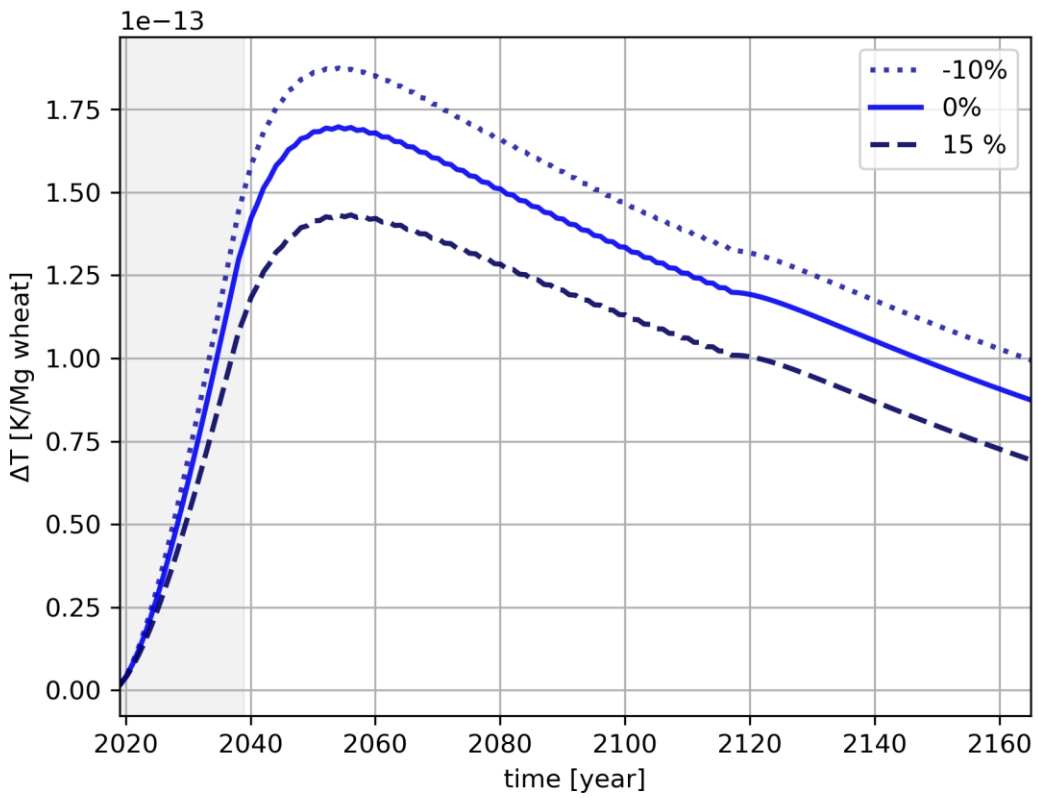

Figure 6: Sensitivity to the climate impact of straw-to-biochar, when including different crop yield responses (-10% crop yield, +15% crop yield).

4. Discussion

4.1. LCA case study

Biochar production was found to be a straw management practice with large potential for climate change mitigation. Around 50% of the total climate impact from wheat production could be reduced by implementing biochar production from straw, as compared to current practices of returning straw to the soil and energy recovery through district heat production. A net zero climate impact could however not be achieved with biochar production from only straw. The mitigating effect mainly results from carbon sequestration, though utilizing excess thermal energy for drying of wheat and heating local buildings further helps to reduce the total emissions. SOC changes when straw is removed, result in only a small increase in CO_2 emissions from organic carbon decomposition, which does not have a large impact on the overall result.

The total climate impact for wheat production, without straw management practices included, is at a reasonable level of about 429 kg CO_2-eq/Mg wheat. This compares well to previous LCA studies of wheat production which presented values of 381 kg CO_2-eq/Mg wheat and around 420 kg CO_2-eq/Mg wheat (Flysjö, Cederberg and Strid, 2008). The climate change mitigation impact also compares reasonably with similar previous studies of biochar production from herbaceous by-products by Uusitalo and Leino, (2019) and Thers *et al.*, (2019). The effect is smaller than the 73-83% emission reduction observed for oilseed rape by Thers *et al.*, (2019). However, the results differ from Uusitalo and Leino, (2019), which found that biochar production from side flows such as husk and small oats could mitigate 350 kg CO_2-eq/Mg oats which is considerably more than results from this study of 235 kg CO_2-eq/Mg wheat. This can be related to difference in biochar carbon content or permanence assumptions. In the same study, Uusitalo and Leino, (2019), found that there were small differences between the utilizing the side flows for energy production compared to biochar production. The differences in results among studies could depend on system boundaries, crop type, fertiliser use and soil emissions.

It is important to understand the impacts of the system boundaries, assumptions and system expansions when performing an LCA which includes by-products and side flows. The results will vary depending on type of energy source used in the system expansion;

renewable fuels, fossil fuels and waste as fuel will all have different outcomes for the impact of straw-to-heat and straw-to-biochar scenarios. In this study, biochar is viewed as having no added value other than carbon sequestration when applied to fields. However, as the market for biochar grows, other uses of biochar may result in climate change mitigation through avoided burdens (in addition to carbon sequestration), as it replaces other materials or has different uses during its lifespan. Developing a market for cascading material flows and increasing valorisation of biochar and agricultural by-products could therefore increase the climate change mitigation potential of biochar. For instance, pyrolyzing straw which has been used for animal bedding and producing biochar used for wastewater treatment before its use as soil amendment would probably result in further reduced emissions. As the effect of biochar on agricultural soils depends on climate conditions, soil properties, crop type and biochar properties, it also becomes important to consider under which conditions biochar application have the optimal effect.

In the sensitivity analyses, it was shown that having a low-carbon energy system is a requirement for biochar systems to outcompete bioenergy systems, from a climate perspective. Likewise, crop yield effects both positive or negative did not significantly affect the ranking of the scenarios.

Several other sensitivity analyses could have been performed. For instance, the effect of the biomass-to-biochar yield is interesting to investigate as it controls the trade-off between energy production and carbon sequestration in biochar systems. Other biochar effects in field and through cascading uses could also be modelled: in particular, reduction in N_2O emissions could be investigated as there is substantial evidence that biochar applied in combination with fertiliser can reduce N_2O emissions. A related effect which needs to be better document by farmers using biochar is whether the amounts of nitrogen fertiliser applied can be reduced when biochar is used. Finally, it can be worth considering if side flows of biomass (e.g. husk from grain processing, or wood from buffer areas) can be used to increase biochar production as suggested in Finland (Uusitalo and Leino, 2019).

Repeated straw removal over 20 years result in some SOC loss. Possible long-term effects on soil quality and crop yield from SOC losses are therefore necessary to consider. The soil amendment from biochar could possibly compensate for the SOC loss and provide improved soil properties. However, a continuous addition of carbon in the stable form of biochar could also have long-term impacts which are not yet thoroughly researched. Hence, both local conditions, such as soil health, and global impacts like climate change needs to be regarded to create a resilient environment for future food production. In addition, other LCA environmental indicators also needs to be analysed to include a holistic perspective, as this LCA only included climate change impacts.

4.1.1. LCAs of other ways of producing and using biochar in Swedish agriculture

The case study described here considered biochar production from straw and use of biochar in wheat production in Swedish agriculture. It fills a gap in the knowledge about biochar in Swedish agriculture. There is already knowledge from published research on biochar production and use in Sweden, in value chains that may be just as relevant as the straw case: biochar from willow (Ericsson *et al.*, 2014; Azzi, Karltun and Sundberg, 2022), biochar production adjusted to local energy needs on farm (Azzi, Karltun and Sundberg, 2021b), biochar production in large scale district heating and use in milk farms (Azzi, Karltun and Sundberg, 2019). Overall, these studies have shown that biochar systems provide larger climate change mitigation than conventional bioenergy systems, in Sweden's current energy context, with climate change mitigation potentials in the range of -0.5 to -1.5 tonne CO_2-eq per tonne biomass. Similar observations were made in a review of LCA studies (Tisserant and Cherubini, 2019) with a global scope.

A large share of the climate change mitigation potentials of biochar derives from carbon storage in biochar. However, when biochar is used efficiently, additional effects can contribute significantly to the climate benefits. On dairy farms, agricultural benefits of biochar can up to double the benefits from carbon storage, mainly through CH_4 and N_2O emission reductions, but also substitutions of fertiliser and limestone (Azzi, Karltun and Sundberg, 2019). Biochar derived from short rotation willow coppice had better climate performance than other biochar supply-chains because of the combination of increase in soil organic carbon during cultivation and carbon storage in biochar (Azzi, Karltun and Sundberg, 2022). Finally, although studied in an urban context, the replacement of peat by biochar in horticultural products and soils is also associated with large benefits when assuming that peatlands can be restored (Azzi, Karltun and Sundberg, 2022).

4.2. Effects on other sustainability aspects

Beside climate change mitigation, biochar production and use have effects on other sustainability aspects, both environmental and social. Here, environmental effects are discussed with a focus on agriculture. For other effects, including social effects, biochar is seen to have generally positive effects, and it is considered that possible risks of negative effects can be managed or mitigated (Nair *et al.*, 2017; Smith *et al.*, 2019).

Fundamentally, biochar effects arise from the changes in physical flows caused by the deployment of a biochar system, in comparison to a reference or historic situation. In that sense, biochar effects are always relative to a reference situation (Azzi, Karltun and Sundberg, 2021a). Biochar effects can arise at different stages of the biochar life cycle: many agricultural effects of biochar will arise from the use phase of biochar, but other effects on energy systems and the manufacturing industry will, for instance, arise from biochar production and investments in production capacity. Multiple effects can also be harnessed when biochar is used in cascade, for example biochar use in manure management before application to soil. Finally, biochar effects can relate to one or several domains of interests (e.g. reduction in N_2O emissions from soil is an effect within the domain of climate change mitigation, but is also related to nutrient use efficiency) (Table 2). A classification of biochar effects is presented in Table 2.

Table 2: Classification of biochar side effects to carbon dioxide removal, adapted from Azzi et al. (2021).

Domains of interest	**As a side effect to carbon dioxide removal, a "biochar system" affects**
	affects soil fluxes:
Climate	-soil GHG fluxes
Resource, Eutrophication	-soil nutrient fluxes and efficiencies
Water	-soil water fluxes and efficiencies
Climate, Air, Water, Health	-soil radiative (albedo, heat) and particle fluxes (erosion, runoff)
Soil status	affects soil status or quality or fertility -physical properties (e.g. density, porosity, structure) -chemical properties (e.g. pH, redox potential, ion exchange, metal availability) -biological properties (e.g. root growth, microbial diversity and functionality, symbiotic N_2 fixation rates)
NPP, Food security, Health	affects plant or crop productivity, quality and physiology
Animal, Food security	affects animal welfare and productivity
Soil status, Land use	provides soil contamination remediation
Land use, Climate	affects markets for biomass and land (e.g. increase biomass demand leading to land use changes and related impacts)
Industry	affects industrial inputs to agricultural sector (agrochemicals, water, machinery and material, seeds/saplings)
Industry	provides substitutes to of fossil-based products and other products by biochar (e.g. filter, sand, peat)
Energy, Industry	provides bioenergy and biochemical products from pyrolysis gases and tars (e.g. heat, power, vehicle fuel, lubricants)
Waste, Health, Climate, Industry	provides biomass waste treatment service (garden waste, agricultural residues) or enhances treatment processes (composting, anaerobic digestion)
Industry, Mining, Resource depletion	affects market for equipment manufacturing (e.g. pyrolysis)

Many of the effects listed in 2 relate to soils and agricultural productivity, because agriculture is the primary area of use for biochar. It is worth noting that biochar effects are not only about agricultural productivity, but also about other factors like soil status, plant quality and physiology during growth, animal health, or environmental quality (nutrient leaching, contaminant availability). These various agricultural effects have been investigated in numerous experimental studies across the world, from which many topic-specific reviews have been published[2]. For instance, biochar effects on water fluxes were reviewed by Fischer *et al.*, (2019) and Razzaghi, Obour and Arthur, (2020) effects on nitrogen fluxes were reviewed by Borchard *et al.*, (2019), and effects on roots were reviewed by Xiang *et al.*, (2017).

[2] The following Scopus request returned 747 review documents on 2020-12-14; it returned 1459 review documents on 2022-08-26: TITLE-ABS-KEY (biochar) AND (LIMIT-TO (DOCTYPE , "re"))

Recently, new attempts have been made to synthesise knowledge across the research areas. Joseph *et al.*, (2021) provides a review of mechanisms controlling soil and plant responses to biochar addition across the growth cycle, synthesizing 20 years of research to demonstrate that biochar, if used appropriately, can support climate change mitigation, food security, and nutrient circularity. Similarly, Schmidt *et al.*, (2021) published a review of 26 global meta-analyses, concluding overall positive effects of biochar for all studied parameters (e.g., effects on yield, root biomass, water use efficiency, microbial activity, soil organic carbon and greenhouse gas emission). This said, it is difficult to predict biochar effects in agriculture due to the diversity of biochars, the diversity of agroecosystems, and the inter-related dynamic nature of soil processes. This complexity is illustrated in Figure 7 by showing cause effect-chains starting with biochar addition, and resulting in final effects, through a network of soil processes.

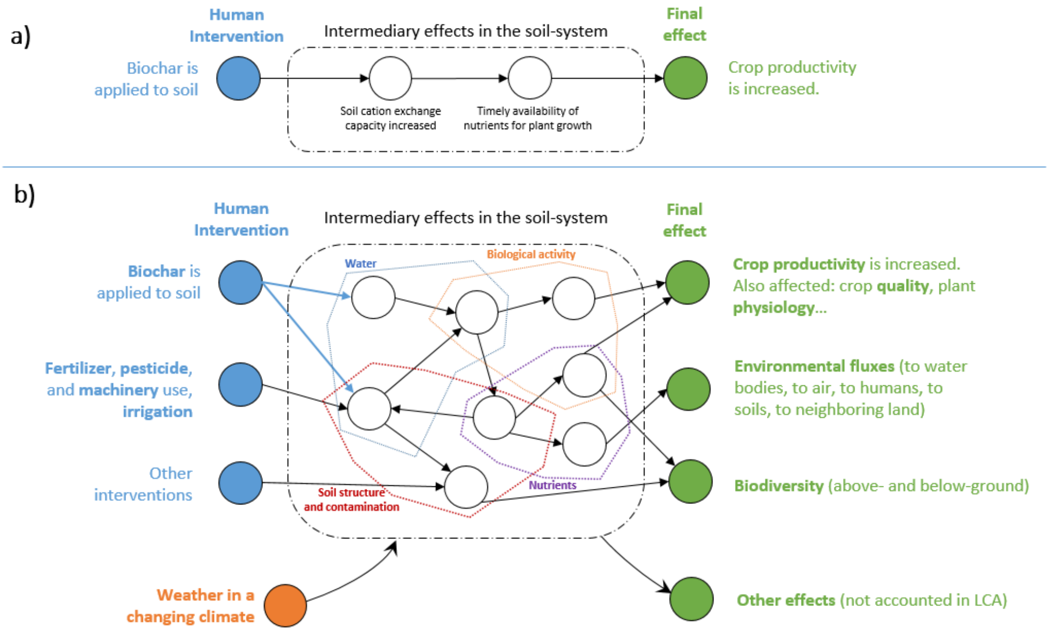

Figure 7: Conceptualising the complex cause-effect chains of human interventions on soil-systems, and their inclusion in LCA frameworks: a) a simplified single cause-effect chain, biochar application leading to crop productivity increase; b) more realistic multiple inter-related cause-effect chains, involving water, nutrient, soil structure and biological groups of processes, leading to various effects (productive, environmental-biodiversity, ecosystem services), and subject to exogenous weather events in a changing climate. From Azzi, Karltun and Sundberg (2021a).

For life cycle assessment (LCA), the distinction between final and intermediate effects is important. Indeed, LCA is primarily interested in an intervention's final effects, i.e. in terms of changes in inputs, outputs, and environmental emissions, because these are the changes that affect the life cycle inventory of the system. In a review of 45 biochar LCA studies (Azzi, Karltun and Sundberg, 2021a), the authors made an inventory of the biochar effects most commonly included in LCA modelling (Table 3).

Table 3: Biochar effects included in a set of 45 biochar LCA studies. Note: If a study modelled both N fertiliser reduction and P fertiliser reduction, the study is counted only once under "Agriculture: fertiliser use reduction". CDR: Carbon dioxide removal; NPP: Net primary productivity; SOC: Soil organic carbon; NA: Not applicable. Further details available in Azzi et al. (2021).

Effect description	No. studies
Effects included	
CDR: Biochar C sequestration	43
Co-products: avoided heat/power from other fuel	35
Agriculture: fertiliser use reduction	19
Agriculture: soil N_2O emission reduction	19
Pyrolysis: air emissions, relative to reference biomass/land use	12
Agriculture: crop harvest increase	10
Agriculture: biochar induced SOC change (priming, NPP increase)	7
Agriculture: soil CH_4 emission change	7
Agriculture: avoided nutrient leaching to water	5
Reference biomass/land: land use change emissions	5
Agriculture: avoided limestone production and use	3
Soil toxicity: reduced heavy metal mobility	2
Agriculture: avoided peat use	1
Agriculture: CH_4/N_2O/Nutrient flux change in animal husbandry	1
Agriculture: soil albedo changes	1
Other substitutions: clay/gravel/backfill material/landfill space	1
None[a]	1
Effect explicitly not included in the LCA[b]	
Agriculture: crop/NPP/SOC increase	8
Other substitutions: clay/gravel landfill cover substitution	1
Agriculture: soil N_2O emission reduction	1
Other	
Sensitivity on persistence of biochar effects over time	3

[a] This study exclusively modelled the material and energy inputs to run a pyrolysis plant.
[b] It is mentioned in the text that this effect exists, but is not included in the analysis

In agriculture, beside carbon storage in biochar, the most modelled effects were fertiliser use reductions, and changes in N_2O and CH_4 soil emissions. Nearly as many studies chose to include biomass productivity increases as to explicitly not include them. The persistence of biochar effects in agricultural soils over several years was often mentioned, but only three studies performed explicit sensitivity analysis on this parameter. Only one study included the effect of albedo change in its climate change impact assessment, and none of the studies analysed biochar effects on biodiversity.

Generally, modelling of agricultural effects of biochar in LCA often faces the same challenges as encountered in LCA of agricultural systems. A topic where efforts are needed is in adequately representing possible multi-annual effects of biochar, and the effects of repeated biochar use at small application rates (<1 tonne/ha).

4.3. Effects of geographic distribution within Sweden

Biochar, with its varied effects, can counter several challenges that are caused by, or observed in agriculture. These effects, however, differ spatially and are influenced by a number of variables, including the local climate, soil type, feedstock type and availability, and pyrolysis conditions (Joseph *et al.*, 2021). Additionally, LCA studies have demonstrated that the climate benefits of biochar systems are more significant under the following conditions:

1. Biochar is produced from biomass residues
2. When energy co-products are used
3. When biochar replaces products with high climate impacts
4. When biochar has additional advantages like increased yield, decreased nutrient leakage, or decreased soil nitrous oxide emissions.

Therefore, biochar deployment following the aforementioned requirements might aid in the solution of several challenges. In an ongoing work available as a pre-print manuscript (Karan *et al.*, 2022), the authors evaluate three narratives (*Improving soil quality, Improving crop resilience, and Reducing nitrogen leachin*g) for deploying biochar in the Swedish arable land. The findings show that significant proportions of the arable land in the study area[3] can potentially benefit from biochar application. For improving soil quality, improving crop resilience, and reducing nitrogen leaching, the arable land with higher priority ratings (ranging from 3 to 5) totals to 25% (0.6 Mha), 39% (0.9 Mha), and 7% (0.16 Mha) of the study area, respectively. However, as evident from Figure 8, which shows the spatial distribution of biochar application priorities to arable land, different narratives have different spatial indications of biochar prioritization. This implies that arable land with a high priority score for a given narrative does not necessarily score high for others, thus indicating that biochar application schemes can vary when adjusted to different objectives and local needs. For instance, the narrative *Improving crop resilience* aims to prioritize biochar in areas that might be more vulnerable to droughts in the future (2021 – 2050). This scenario considers low ground moisture (LGM) (SMHI, 2021) as a weighted criterion to derive the biochar prioritization map. The LGM criterion is derived by coupling the hydro-meteorological indices with climate models (SMHI, 2015). According to the LGM criterion, Sweden's South and South-West regions may have more dry days in the future compared to other regions (Appendix I, AF 1). This is reflected in the prioritization map shown in Figure 8 as well, where high priority is reflected in areas with higher values of LGM.

[3] The study area covered about 93% of the total arable land in Sweden, or 2.31 million ha. The remaining area, the arable land in Norrbotten, Västerbotten, Jämtland, and Västernorrland, was not included due to lack of data.

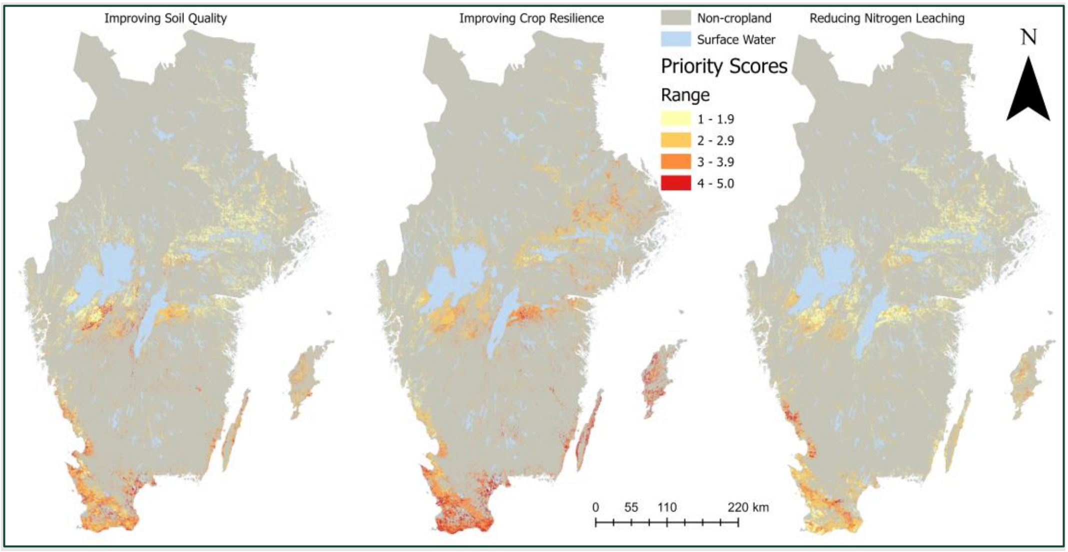

Figure 8: Biochar priority maps for improving soil quality, improving crop resilience, and reducing nitrogen leakage. A high score means a high priority from biochar application on arable land.

Although these possibilities seem appealing, a number of issues and bottlenecks need to be resolved before biochar can be produced and used on a large scale. Below we discuss some geographic factors that should be taken into consideration when planning deployment in agricultural land:

1. Soil properties
    a. pH: Biochar application to soil decreases soil acidity and has been shown to improve crop yield by improving soil fertility (Hailegnaw and Mercl, 2019; Shetty and Prakash, 2020). Studies have reported with high confidence that crop yield improvements from biochar application is best observed in acidic and pH-neutral soils (Jeffery *et al.*, 2011; Joseph *et al.*, 2021).
    b. Organic Matter (SOM): Organic matter facilitates adequate drainage and aeration while reducing erosion, which influences a number of soil properties, including the ability to retain water and nutrients (Oldfield, Bradford and Wood, 2019), thus supporting plant growth. Contrarily, biochar has several characteristics in common with soil organic matter, and its addition to SOM-depleted soils can increase SOM's quantity, thereby improving crop yield. The use of biochar can, however, also result in SOM mineralization, which may have an additional impact on nutrient leaching (University of Nebraska - Lincoln, 2015).
    c. Soil Texture: When applied to coarse-textured soils, biochar has more benefits for various agronomic properties than when applied to fine-textured soils (Jeffery *et al.*, 2011; Ajayi and Horn, 2017). It has also been suggested that adding biochar to sandy soils can increase SOM content and nutrient mineralization (Wang, Xiong and Kuzyakov, 2016). Sweden's most agriculturally intensive areas (South and South Centre) have higher sand

content, providing opportunities to facilitate biochar adoption in the cropping systems.

2. Climate properties

   Numerous studies have suggested that adding biochar to soils increases their ability to store water and protects them from moisture stress (Schmidt *et al.*, 2021), making crops more resilient to droughts. Some studies claim that adding biochar might also reduce rainfall runoff-induced soil loss (Khademalrasoul *et al.*, 2019).

3. Cropping systems

   Different crops respond differently to biochar fertilization, and there is strong evidence that crop yield improvements are evident in tropical locations. For temperate locations, however, there is limited literature on biochar's effects on crop productivity, and some studies report that biochar amendments to soil do not lead to any improvements in crop yield. Hence, more study is required on biochar effects on crop yields in Swedish agriculture, since crop yield improvements through biochar fertilization in temperate regions are difficult to predict.

4. Feedstock type and availability

   Biochar feedstock has a significant effect on biochar quality and therefore on different agronomic parameters. For instance, biochar made from lignin-poor materials like crop residues, straw, and manure has a more noticeable effect on crop yield (Dai *et al.*, 2020), whereas biochar produced from woody biomass can significantly reduce NO_3^- leaching (Borchard *et al.*, 2019).

Biochar’s effect on soil properties endure for a significant amount of time and differs spatially depending upon the soil type and the local climate, thus, planning for deployment should consider regional variabilities.

4.4. Potential, timing, and factors affecting implementation

4.4.1. Potential for biochar in the Swedish food system

Biochar potential is a concept that needs to be defined and this can be done in various ways. In this section, we first discuss biochar potential in terms of volumes for supply and demand for biochar, and in the later part, we focus on potentials from the horizon of effects of biochar application. For simplicity, we rephrase these two aspects in the following two questions:

1. How much biochar can be produced and then deployed?
2. How large is the impact of biochar deployment?

Biochar potentials from the perspective of supply and demand

Biomass resource assessment is the first step towards answering the question on how much biochar can be produced. The biomass resource assessments often employ a hierarchical structure for reporting biomass potentials at different levels. Using similar concepts, we build upon the framework that comes from biomass resource assessments (Vis and van den Berg, 2010) and adapt it for representing biochar potentials.

The graphic (figure 9) illustrates in a reverse hierarchy, different biochar potential levels and the factors that restrict them. These potentials are defined and discussed in the sections below.

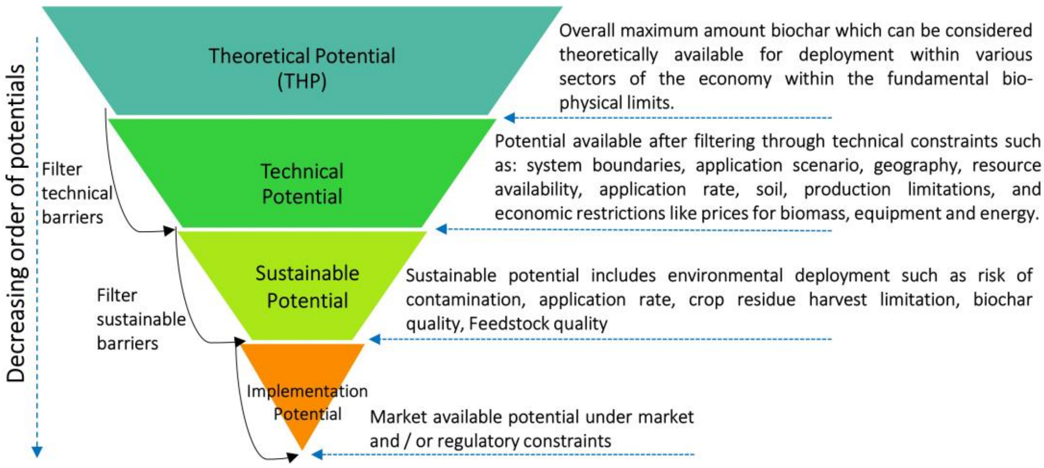

Figure 9: Biochar potentials with factors highlighting restrictions at different levels (Potentials not to scale)

Theoretical potential

The theoretical potential is defined as the maximum total quantity of biochar that, theoretically and within the bounds of basic bio-physical laws, is considered to be produced from the available resources and used within the different economic sectors without considering any limitation or adverse effect. These potentials are often determined through statistical or spatially explicit methods.

Theoretical potentials are rarely utilized to generate assumptions about reasonable expectations, both by definition and in practice. Realistic estimates are subject to a variety of context-specific constraints, which ultimately result in the quantity of market-accessible biomass being much smaller than the theoretically available biomass, as further detailed in Egnell & Börjesson (2012).

Technical Potential

The technical potential is a portion of the theoretical potential. On the supply side, the technical potential considers existing technological possibilities such as biomass harvesting techniques, biomass accessibility or biochar production techniques, and the considered techno-structural framework conditions, including system boundaries and the application context. On the demand side, the technical potential considers the restrictions brought on by biochar application conditions. For instance, the restrictions may relate to geographical factors such as the climate or soil of the region, ecological restrictions, and perhaps other non-technical limitations. It can also relate to the demand of the co-products of biochar production, in particular heat demand.

The technical potential can also include economic restrictions like high biomass prices or large transport distances: more distance to mobilize the resource directly translates to more money. Although some studies have considered economic restrictions as a potential in itself (Koornneef *et al.*, 2012).

The potential for biochar-based solutions may be acknowledged by policymakers tasked with achieving greenhouse gas emission objectives and addressing public concern about climate change that becomes more and more evident. The landowner or farmer is probably more likely to have a pragmatic or financial viewpoint. This constitutes the social aspect of the economic restriction.

Sustainable Potential

Attempts have been made earlier to define a sustainable-biochar concept (Woolf *et al.*, 2010). We build upon these existing efforts and define the sustainable potential of biochar as the potential derived from the technical potential after applying sustainability criteria. The sustainability criteria considers environmental restrictions that arise from risks such as bioaccumulation and leaching of heavy metals from uncertified biochar, the quality of biochar feedstock, high biochar application rates, or unrestricted withdrawal of residues which might deprive the soil of nutrients, and cause additional demand causing indirect emissions.

Implementation Potential

The implementation potential is a part of sustainable potential that includes these regulatory or market-based factors as restrictions.

Potentials catering to effects of biochar application

Impact of biochar deployment can be evaluated in terms of the function it is intended to deliver. However, biochar's effects are usually multifunctional and frequently extends beyond carbon storage. For instance, adding biochar to arable soil with the aim of increasing agricultural productivity may also provide other benefits like decrease in nutrient leaching, CDR, and reduced requirement of fertilizers. Therefore, representing the potentials with a single function does not capture every dimension of biochar's effects. Some units for biochar potentials are listed below as an example:

1. Yield improvement: kg-grain / unit of biochar applied
2. N_2O reduction: kg-N_2O removed / unit of biochar applied
3. CDR: kg-CO_2 removed / unit of biochar applied

In any case, the potential of biochar effects will depend on how it is defined, which should be clear.

System boundary aspects of biochar potentials

When quantifying biochar potential in agriculture of food systems, the system boundary of the system is of importance. Biochar can be produced from agricultural residues, or from dedicated crops. It may also be produced from wastes in food industry, or food waste. Potential biomass may come from marine sources, forestry operations or urban green waste. The biochar potential will vary depending on which of these biomass sources are accepted, which will depend on how system boundaries are set. In a similar way, system boundary aspects related to biochar use, and heat use. Biochar use is not only possible in cropland, but in any soil or plant bed, whether it is for food production or not. And while there is heat demand in food and agriculture, there is also large heat demand in other sectors. Consequently, a multitude of system boundaries are possible (see Table 4).

Table 4: Factors affecting different level of biochar potential from the supply and demand sides

Type	Supply	Demand
Theoretical Potential (The system boundary determines which of them are included.)	No limitation condition adhering to maximum withdrawal within the fundamental biophysical limits. 1. Agricultural residues 2. Forestry residues 3. Sewage sludge 4. Marine biomass 5. Food waste 6. Urban green waste 7. Dedicated energy crops	No limitation condition adhering to maximum supply to different systems. Land-based systems 1. Agricultural Land 2. Forest land 3. Contaminated Land Other systems 1. Waste-water treatment 2. Animal feed 3. Material for composite manufacturing 4. Urban applications 5. Energy 6. CDR
Technical Potential	Technical limitations arising from feedstock availability and geography: 1. Feedstock harvest limitation based on available machinery 2. Competition of feedstock with other uses 3. Biochar production limitation (Biomass suitability and biochar yields) Economic restrictions 4. Transport distance 5. Motivation for mobilizing residual resources. 6. Pyrolysis reactor cost 7. Feedstock price	Technical limitations arising in the deployment of biochar: 1. System boundary definition 2. Biochar dosing (Application rates for specific contexts) 3. Demand for heat / other co-products from pyrolysis Economic restriction 4. Biochar price
Sustainable Potential	Environmental restrictions 1. Crop residue harvest limitation 2. Feedstock quality 3. Biochar quality	Environmental restrictions 1. Biochar application rate 2. Soil conditions 3. Local climate / future climate

Implementation Potential	Implementation potential combines both supply and demand potentials and is restrictions can arise from: 1. Policy (or lack thereof) 2. Certification 3. Market for biochar products

Swedish examples of potentials

As highlighted before, there is little to no scientific evidence that biochar application improves crop yields in Sweden. Therefore, biochar use in Swedish agriculture should be coupled with scenarios where it provides additional benefits. Such benefits can relate to reducing the climate impacts (See section 3), or other sustainability aspects (see Section 4.2). In section 4.3, we observe that in the case of improving crop resilience, 39% of the studied arable land in Sweden could potentially benefit from biochar application. Furthermore, applying biochar at a rate of 0.5 t ha^{-1} yr^{-1} to these areas may theoretically remove 1 Mt CO_2 from the atmosphere[4] per year. Such application rate can be maintained for at least 10 to 20 years, leading to cumulative biochar application of 5 to 10 t per ha, and 10 to 20 Mt CO_2 stored. Deriving the priority areas for biochar application for the narrative of improving crop resilience considered restrictions based on soil properties (texture, organic matter and pH), and low ground moisture days (Karan *et al.*, 2022). This exemplifies a case of technical potential in terms of demand for biochar for a particular function.

Using recent Swedish crop production data, we observe that, around 54% of crop residues containing around 1.3 M tonnes of Carbon is ploughed back to the soil each year (see Appendix 1, AT 3, AF 2). In terms of energy, this fraction represents around 30% (14 Twh, See Appendix 1, AT 1) of the total Swedish heat consumption in 2020 (SCB, 2022). Mobilizing just 10% of the residues that are ploughed back to the soil for pyrolysis (assuming 25% biochar yield in a pyrolysis unit) could produce around 60 – 65 thousand tonnes of biochar annually, which is far higher than the current production in Sweden (See section 4.4.3). The above case exemplifies theoretical potential based on biomass supply.

An example of theoretical potential is also presented in SOU, (2020), where it is reported that producing 0.5 M tonnes of biochar (for use as soil amendment) in pyrolysis units with contemporary energy extraction can increase the carbon sink potential by 1 million tonnes of CO_2 per year. About 5.4 TWh of biomass, primarily from branches and tops as well as park and garden waste, would be needed to produce this much biochar. In addition, energy, primarily in the form of heat, could also be captured during the synthesis of biochar. As per their rough assessment, 2 – 4 TWh of heat can be produced with the simultaneous

[4] Applying on average 0.5 tonne biochar with a carbon content of 80% with 80% 100-year permanence to about 900,000 ha of arable land found suitable for biochar application (Karan *et al.*, 2022), converted to CO_2 using a conversion factor of 3.67.

production of around 0.5 M tonnes of biochar. This heat production decreases the demand for further biofuels in the district heating system.

Potential deployment of biochar in the forest sector is a major uncertain factor. There is research showing good potential for biochar to improve the growth of young trees in northern Sweden (Grau-Andrés *et al.*, 2021). Considering the large areas of forests in Sweden, biochar use in forestry could have significant effect on the total potential.

4.4.2. Factors affecting implementation

The barriers and drivers of biochar implementation in Sweden until 2045 was analysed by Simon Martelius in his MSc thesis (2022). The analysis was based on a literature review and stakeholder interviews. This chapter is largely based on Martelius' findings. Six factors of importance for biochar implementation were identified: financial viability, regulations, biomass availability, technical maturity, total deployment potential, and public and stakeholder opinion. Of these, biomass availability and total deployment potential have been discussed in the chapter on potential above, in chapter 4.4.1. Total deployment potential refers to the theoretical potential from a demand perspective.

Financial viability is crucial for the development of the biochar market. Because of the early stages of development of the biochar industry, the costs of biochar production is highly volatile and uncertain. Income in a biochar system can come from the sale of the biochar as a product, but also from heat or other energy products, and the value of biochar as a carbon removal product. The income of a biochar system will consequently depend on the prices of energy, carbon dioxide removal and other climate impacts, as well as the value of the benefits of the biochar product (Woolf, Lehmann and Lee, 2016). Climate funding may come either from government climate policy, or through the voluntary carbon market. There is currently a hype in the biochar prices in the voluntary market with biochar being sold at €150 to €535 per ton of CO_2 (carbon removal credits at https://puro.earth in August 2022), but the long-term price is highly uncertain. There is currently a market for biochar products for urban applications in Sweden, but very limited use in agriculture.

Regulations can support, or slow down or even stop the implementation of biochar in agriculture. There is very little regulation and policy in place regarding biochar in Sweden and the EU. Biochar has been listed as an approved soil amendment in organic agriculture in the EU. It has been included in the new EU fertiliser regulations (The European Parliament and the Council of the European Union, 2019). Biochar is included in the ongoing legislative processes of including carbon dioxide removal in the EU climate mitigation legislation (Erbach and Andreo Victoria, 2021) and in the Carbon Farming initiative. In Sweden, biochar was identified as an interesting negative emission technology in the government inquiry (SOU, 2020), but no specific policy has been implemented. Biochar was explicitly excluded from the planned policy to support bioenergy with carbon capture (BECCS). Investments in biochar production is eligible for government support from “Klimatklivet”, an investment aid scheme for green transition technologies (Naturvårdsverket, 2022).

As for technical maturity, there are a number of biochar production units available in the market, and some of them are well established for uninterrupted production (EBI report). There are about 100 production units in Europe and the industry projected a growth of 40 plants in 2022 (EBI, 2022). Maturity of biochar use is low in Swedish agriculture, but higher in urban applications, where there are handbooks and established practices (https://biokol.org). The ways in which biochar interacts with soil, and how this interaction varies depending on the characteristics of the biochar and the soil type, is still partly uncertain, and will remain so due to the variable nature of a large number of biochar and soil quality parameters (see more in section 4.2). This uncertainty in biochar-soil interaction can therefore also be considered a barrier to large scale deployment.

The public opinion on biochar, and on negative emission technologies in general, has the potential to be a large driver or barrier to implementation. In general, there seems to be a positive attitude to biochar among the public and stakeholders in Sweden, and there is no strong articulated opposition to biochar. However, there has been limited public attention to biochar. Instead, there has been much more attention on BECCS than on biochar in policy development as well as the public debate about carbon dioxide removal in Sweden. It has been argued from energy stakeholders that biochar is less energy efficient than using biomass for bioenergy, reflecting a way of thinking that does not consider the benefits of biochar as a material (Energimyndigheten, 2021). If biochar gets a larger role in Swedish climate policy, it is likely to be more questioned and debated. Some issues that can be expected to arise in such a debate are biomass availability and competition, emissions from pyrolysis, content of toxic substances in biochar and long-term fate and effects of biochar.

4.4.3. Timing

It is interesting to know not only the potential, but also the timing of the potential between the present and 2045. Considering that current volumes of biochar use in Sweden are small (estimated at less than 1000 t/yr used in agriculture, in the range of 10 000 t/yr in total in Sweden, no official figures available) and current growth rates (in %) are large for the biochar sector in Europe (50-85% per year, EBI, 2022) as a whole but unknown for Swedish agriculture, it is not possible to predict future growth with any certainty whatsoever. This said, national production of biochar does not seem to meet the current demand (mainly in urban areas) as illustrated by biochar imports from other European countries. Development of biochar in Swedish agriculture can be anything between zero and reaching the maximum potential (which is not uniquely defined, as discussed in 4.4.1 above) well before 2045. It is therefore of larger interest to discuss what factors limit the growth in the short term (until 2025), medium term (2025-2030) and long (2030-2045) term.

Currently two major limiting factors for biochar use in Swedish agriculture are its high price and lack of established knowledge on how biochar can contribute to increased productivity in agriculture or better environmental performance in agriculture. It is thus not economically interesting for farmers to use biochar, in particular pure biochar. Major factors that could change this in the short term are:

- Breakthroughs for productivity in some agricultural crop or animal husbandry that become a driver for implementation. This could for example be specific crops such as strawberries or feed additives for some animals such as piglets.
- Breakthroughs in the development of biochar-fertiliser products can become a major driver for implementation.
- Climate funding in the voluntary market. The emerging market for carbon dioxide removal credits is providing new financing opportunities (carbonfuture.earth, 2022; Puro.earth, 2022). Branding of food products as net-zero or "climate positive" may provide an avenue to direct funding of biochar use in agriculture.

In the medium term, research and innovation projects to answer the question of how biochar can provide increased agricultural productivity and thus make biochar profitable in agriculture could be important for accelerating implementation. New policy initiatives at the Swedish or European level are also possible in the medium term, which could lead to increased profitability and, thus faster implementation. In that respect, the EU Carbon farming and carbon removal policies are of relevance[5]. On-going work led by the EU commission is expected to provide a policy framework in the medium-term.

The longer term is more difficult to analyse and all we can say at this moment is that for large scale implementation to happen, all the factors important for implementation must be favourable; finances, policy, technical maturity in biochar production and use, biomass availability and public and stakeholder opinion (section 4.4.2).

[5] https://ec.europa.eu/clima/eu-action/forests-and-agriculture/sustainable-carbon-cycles/carbon-farming_en

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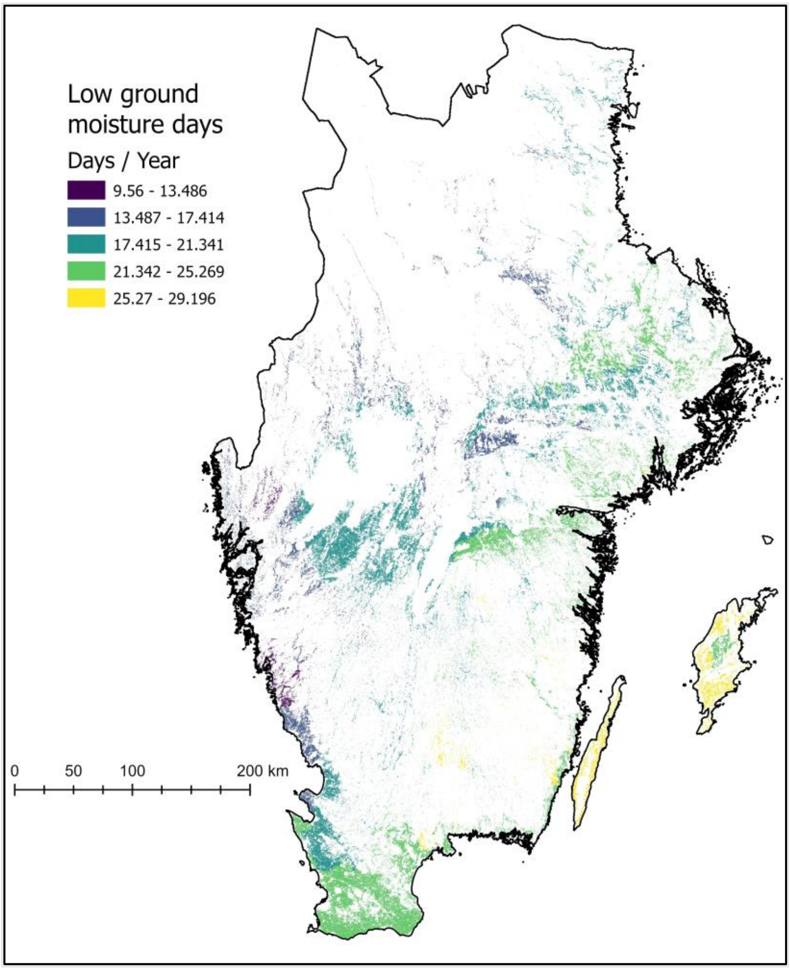
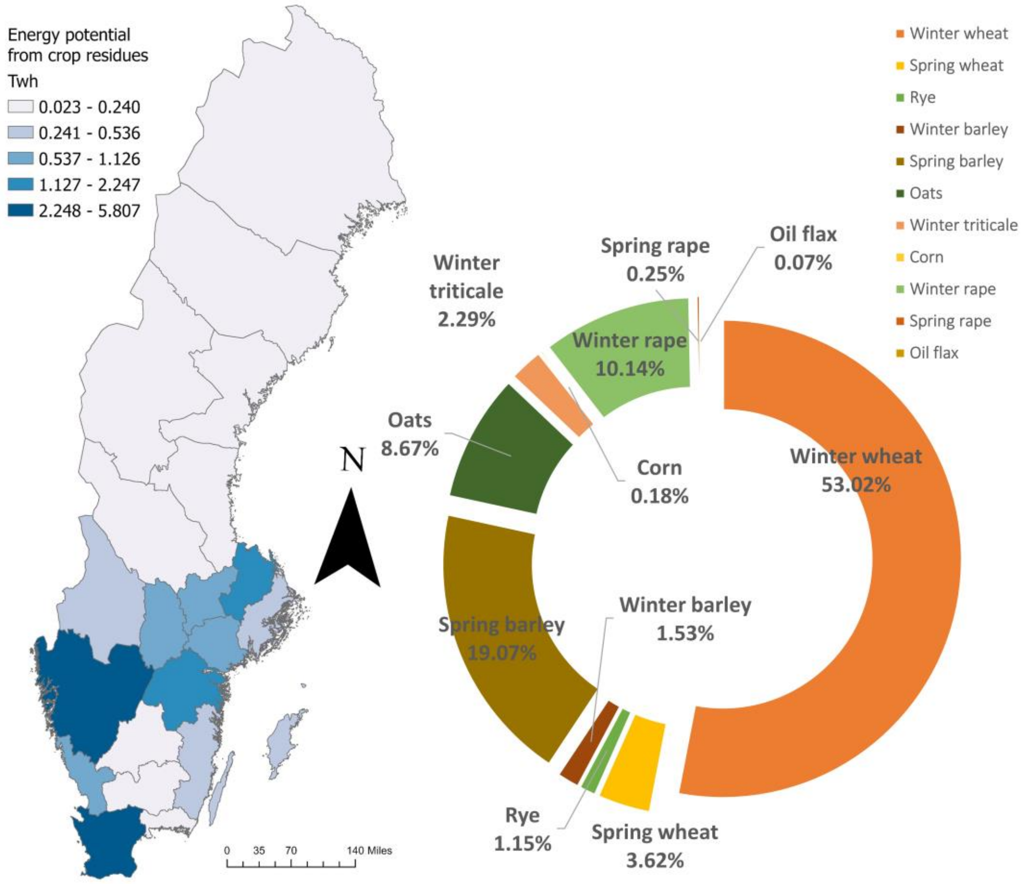
Appendix 1



AF 1: Annual low ground moisture days predicted by the Swedish Meteorological and Hydrological institute based on the RCP 4.5 scenario.

Crop residues /Straw: Although the use of straw for energy in Sweden is still very limited, it is becoming more valuable now than it was in 1997 (Adolfsson, 2005). As per estimates, around 54% of the straw is returned to the soil directly and about 40% is used for purposes such as direct feed, heat, animal bedding, and biogas, among other things (Rangel, 2012). In terms of energy, this translates to around 9.3 Twh. Table AT.1 shows the theoretical potential of crop residues from cereals and oil crops in Sweden.



AF 2: Spatial distribution of energy potentials from crop residues generated in Sweden (Availability will vary based on usage, See Table AT 1)

AT 1: Amount of crop residues produced and used in Sweden in the year 2021[6]

	Total Production in 2021 (1000 tonnes, wet)	Residue to product ratio (RPR)	Reference to RPR	DM Content (Adolfsson, 2005)	Total Residue production (1000 tonnes, DM)	Fraction used (%) Rangel, 2012)	Fraction ploughed (%) (Rangel, 2012)[a]	Energy content of fraction ploughed (Twh)[7]
Cereals								
Winter wheat	2866.8	1.02	(Bentsen, Felby and Thorsen, 2014)	0.85	2491.9	44%	53%	6.83
Spring wheat	144.5	1.39	(Bentsen, Felby and Thorsen, 2014)	0.85	170.3	37%	59%	0.51
Rye	129	0.49	(Ronzon and Piotrowski, 2017)	0.85	54.1	53%	41%	0.10
Winter barley	105.7	0.80	(Bentsen, Felby and Thorsen, 2014)	0.85	72.1	73%	26%	0.10
Spring barley	935.6	1.13	(Bentsen, Felby and Thorsen, 2014)	0.85	896.2	40%	53%	2.45
Oats	548.4	0.87	(Ronzon and Piotrowski, 2017)	0.85	407.5	32%	62%	1.31

[6] Data for 2021 collected from the Swedish Board of Agriculture

[7] See Table AT.2

Winter triticale	132.6	1.02	(Ronzon and Piotrowski, 2017)	0.8	107.8	34%	24%	0.13
Corn	9.8	1.10	(Bentsen, Felby and Thorsen, 2014)	0.8	8.6	6%	27%	0.01
Oil plants								
Winter Rape	326.9	1.60	(Ronzon and Piotrowski, 2017)	0.91	476.5	7%	7 ± 2	2.56
Spring Rape	6.2	2.06	(Ronzon and Piotrowski, 2017)	0.91	11.6	7%	7 ± 2	0.06
Oil flax	2.4	1.57	(Ronzon and Piotrowski, 2017)	0.91	3.4	56%	56 ± 12	0.01
							Total	14.07

[a] The sum of fraction used and fraction ploughed down does not equal 100% as some portion is used as green fodder

AT 2: Energy, Carbon, and Nitrogen content of selected crop residues

		Energy content ($MJkg^{-1}$)	Carbon content wt(%) daf	Nitrogen Content wt(%) daf	Comment (Source, in cases not mentioned is Phyllis database (Phyllis2, 2020)
Sl. No.	**Cereals**				
1	Winter wheat	18.62	48.16	0.80	Average of 13 records
2	Spring wheat	18.31	48.16	0.73	Average of 93 records
3	Rye	16.45	49.25	0.43	Average of 12 records
4	Winter barley	18.54	47.46	0.75	Average of 17 records
5	Spring barley	18.54	47.46	0.75	Average of 16 records
6	Oats	18.62	50.42	0.66	Average of 4 records
7	Winter triticale	18.70 (Ates *et al.*, 2017)	48.6	0.69	Average of cereals listed from 1 - 6
8	Corn	18.00	48.82	0.54	Average of 6 records
	Oil Crops				
9	Winter rape	20.81	50.09	1.96	Average of 17 records
10	Spring rape	Considered to be same as above			
11	Oil flax	43.10	43.10	0.66	Values taken from Naik *et al.*, (2010)

AT 3: Carbon and Nitrogen content in crop residues added back to the soil upon ploughing

	Total Residue production (1000 tonnes, DM)	Fraction ploughed (%) (Rangel, 2012)	Carbon added back to the soil from ploughing of crop residues (Considering no losses), C-tonnes	Nitrogen added back to the soil from ploughing of crop residues (Considering no losses), N-tonnes	Energy content of fraction ploughed (Twh)
Cereals					
Winter wheat	2491.9	53%	636048.7	10565.6	6.83
Spring wheat	170.3	59%	49085.7	733.5	0.51
Rye	54.1	41%	10928.2	95.4	0.10
Winter barley	72.1	26%	8899.1	140.6	0.10
Spring barley	896.2	53%	225417.3	3562.2	2.45
Oats	407.5	62%	127373.6	1667.3	1.31
Winter triticale	107.8	24%	12570.3	177.6	0.13
Corn	8.6	27%	1137.7	12.6	0.01
Oil plants					
Winter Rape	476.5	7 ± 2	221985.5	8686.2	2.56
Spring Rape	11.6	7 ± 2	5417.1	212.0	0.06
Oil flax	3.4	56 ± 12	621.6	9.5	0.01

MISTRA
FOOD FUTURES