Prospective life cycle assessment of large-scale biochar production and use for negative emissions in Stockholm

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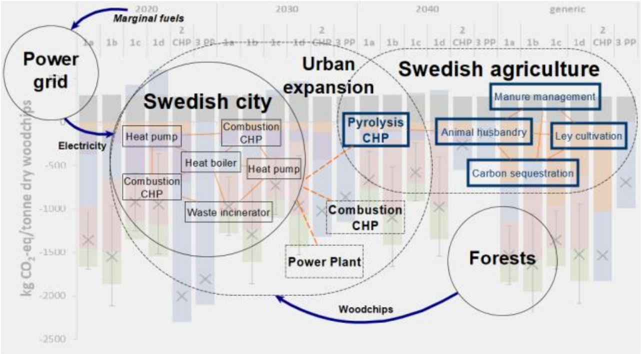
ABSTRACT – Several cities in Sweden are aiming for climate neutrality within a few decades and for negative emissions thereafter. Combined biochar, heat and power production is an option to achieve carbon sequestration for cities relying on biomass-fuelled district heating, while biochar use could mitigate environmental pollution and greenhouse gas emissions from the agricultural sector. Using prospective life cycle assessment, the climate impact of the pyrolysis of woodchips in Stockholm is compared with two reference scenarios based on woodchip combustion. The pyrolysis of woodchips produces heat and power for the city of Stockholm, and biochar whose potential use as a feed and manure additive on Swedish dairy farms is explored. The climate change mitigation trade-off between bioenergy production and biochar carbon sequestration in Stockholm's context is dominated by the fate of marginal power. If decarbonisation of power is achieved, building a new pyrolysis plant becomes a better climate option than conventional combustion. Effects of cascading biochar use in animal husbandry are uncertain, but could provide 10-20% more mitigation than direct biochar soil incorporation. These results help designing regional biochar systems that combine negative carbon dioxide emissions with increased methane and nitrous oxide mitigation efforts, and can also guide the development of minimum performance criteria for biochar products.

KEYWORDS – Biochar, life cycle assessment, climate impact, negative emission technology, energy system, district heating, agriculture, dairy farming.

ABSTRACT ART



Introduction

Meeting the climate targets set by the Paris Agreement requires deep, immediate cuts in greenhouse gas (GHG) emissions and changes in resource management. Pathways that could meet these targets consider varying types and degrees of technological development and consumption change[1,2]. Among the technology-based solutions, one set of scenarios considers the large-scale deployment of negative emissions technologies (NETs)[3,4]. The necessity, feasibility and share of NETs in the future technological mix are still being discussed, but recent reviews highlight a lack of bottom-up[5] and upscaling studies[6,7], which are needed for actual development of the sector.

Biochar systems have been presented as one of the most readily available NETs, bringing desirable co-benefits such as improved soil structure, nutrient management and water holding capacity, and reduced soil nitrous oxide emissions[8–12]. Some have also praised biochar systems for being overall more compatible with the planetary boundaries than other bio-based NETs[13]. However, several effects of biochar remain uncertain and practical ways of large-scale production and incorporation of biochar to soils have yet to be designed and assessed regionally.

In Sweden, woodchips are commonly used in combined heat and power (CHP) plants to produce district heating and power. In efforts to further reduce their carbon footprint and achieve negative emissions, cities and energy utilities are considering the pyrolysis of woodchips for biochar, heat and power production, instead of burning woodchips in conventional CHP plants, for their future installations. The biochar produced in the city could then be used, in cascades, in the agricultural sector as an animal feed additive, manure management additive and soil improver[14]. Biochar mixed with manure is also thought to be a more practical way to return carbon to soil than direct biochar application[14,15]. Thereby, biochar systems have the potential to reduce the GHG emissions from the agricultural sector, which are often considered partly inevitable due to the continuous need for human food[16].

A key feature of biochar systems is their lower level of energy production compared with conventional bioenergy systems[17]. To estimate the potential climate effects of biochar in relation to its production chain and in comparison with alternative technologies, life cycle assessment (LCA) is an appropriate tool. Previous LCA studies of biochar systems have found sequestration of carbon and fossil fuel substitution effects to be the main contributors to the climate mitigation potential[18–21]. Few studies were set in an energy context where heat is the main product, included the combustion of biomass as a reference[22] or investigated specific industrial applications[23]. However, to our knowledge, no previous study has dealt with the cascading effects of biochar in animal husbandry before land application with manure, or has analysed the effects of biochar production on a city's district heating network.

The aim of this study was thus to analyse the potential climate benefits of large-scale biochar production, connected to Stockholm's district heating system, and biochar use in dairy farming, an illustration of where biochar could serve as an animal feed additive, manure additive and soil improver. The objectives were (i) to identify the requirements for a new biochar system to outperform, from a climate perspective, alternative energy uses of biomass, and (ii) to explore the range of potential agricultural GHG effects when biochar is used in cascades in dairy farming.

Methods

Scope definition

Functional unit. An input-related functional unit[24] was defined as the use of 1 tonne (dry weight) of woodchips acquired on the global market. This choice is motivated by the multiplicity of outputs of biochar systems and enables comparison with previous studies[18–20,22]. This functional unit places the emphasis on using biomass resources efficiently from a climate change mitigation perspective.

Scenario description. The LCA was conducted at system level, which took into account the effects of biochar production on the city's energy system and of biochar use in the agricultural sector. The assessment was comparative and prospective[25]: four large-scale pyrolysis plant configurations (1a-d), producing different amounts of heat, power and biochar from woodchips, a technology under development, were compared with combustion of woodchips for heat and power production in Stockholm (2) or combustion of woodchips in a conventional power plant in Sweden (3) (Figure 1).

The production of heat, power and biochar was coupled to Stockholm's district heating network and the power grid. It included the supply of biomass, its conversion to biochar and use of the co-products for district heating and electricity generation. Pyrolysis oil was assumed to be directly combusted with the pyrolytic gases. The combustion scenarios (2) and (3) included the same supply chain of biomass and its use in modern plants. Apart from transport of bottom ash in these reference scenarios (2 and 3), the management of residues and capital equipment were excluded from the system boundary.

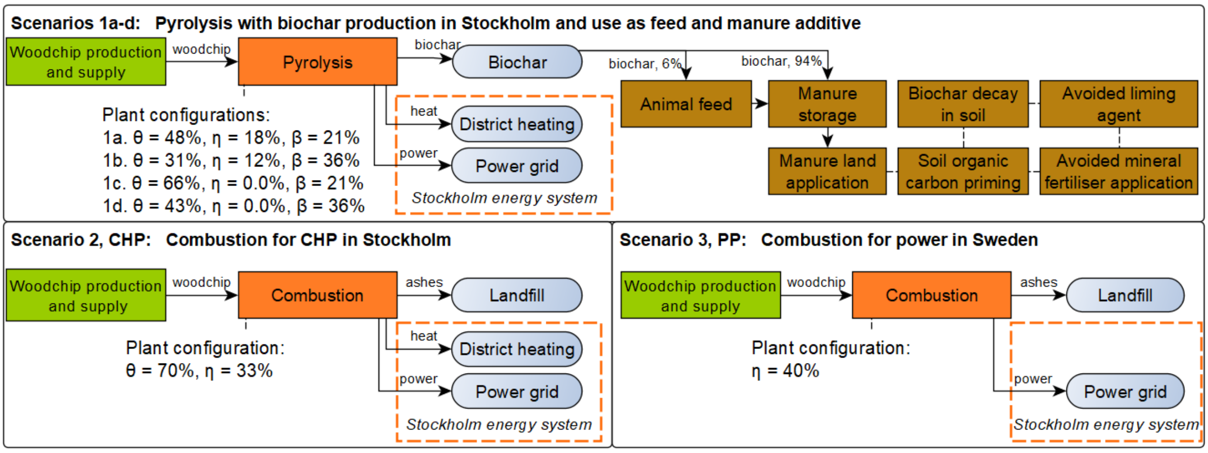


Figure 1: Flow chart showing the three scenarios analysed: (1) Pyrolysis for combined heat and power (CHP) and biochar in Stockholm. (2) Combustion for CHP in Stockholm (reference). (3) Combustion for power production in Sweden (reference). Transportation steps are not shown, but were included in the assessment. Biochar use ratios between feed and manure are given as percentage of dry mass. θ = thermal efficiency, η = power efficiency, and β = biochar yield (% total dry mass). Energy conversion efficiency are given with respect to the lower heating value (LHV) of the woodchips.

In scenarios 1a-d, biochar use included transport to an intensive dairy farm, handling on-site, agricultural benefits through biochar use as animal feed, mixing with manure and land application, avoided burdens in terms of mineral fertiliser and liming agent production, soil organic carbon (SOC) stock changes and biochar decay. No increase in crop yield was assumed, in accordance with Jeffery *et al.*[26]. Likewise, increase in animal productivity was disregarded as no data is yet available.

The foreground system included the biomass conversion step, energy generation and agricultural effects. The background system included production and supply of biomass and all transport steps. This distinction between background and foreground is particularly important in prospective LCA, because background technologies available in the future, when the technology under study will be deployed, are likely to differ from those available at present[25].

Geographical boundaries. The case is located in the region of Stockholm, Sweden. Production of biochar through slow pyrolysis was assumed to take place in Lövsta, Stockholm. This choice was motivated by availability of land for such a plant, feasibility of connection to district heating and expected growth in demand for heat in the area. The biochar was assumed to be used on dairy farms located within 300 km north, west and south of Stockholm. The supply of woodchips was based on the existing supply chains used by the main energy utilities and was assumed to comprise a mix of forest residues produced nationally and imported from the global market, mostly from the Baltic region.

Time boundaries. A large-scale pyrolysis facility operating for at least 25 years and then further retrofitted for continued operations was assumed. The time horizon selected for the impact assessment was 100 years.

Impact categories. The issue primarily assessed was climate change impact, which was evaluated using the static characterisation factor global warming potential with a time horizon of 100 years (GWP_{100}). The emissions modelled were of the three main GHGs relevant in energy and agriculture systems: carbon dioxide (CO_2), nitrous oxide (N_2O; $GWP_{100} = 265$) and methane (CH_4; $GWP_{100} = 30.5$)[27].

Uncertainty. In prospective LCA, uncertainties tend to be large[25] and difficult to estimate. Here, uncertainty regarding the large-scale pyrolysis plant was tackled with four configurations (1a-d) each modelling a different combination of power efficiency and biochar yield. For energy substitutions, two methods were compared. The uncertainty regarding the effects of biochar in the agricultural sector was investigated through three cases (worst, average and best cases) and via a Monte Carlo simulation. Moreover, some possible future developments of the background system were discussed qualitatively.

Intended audience. The intended audience includes researchers and stakeholders with an interest in future biochar production and use. The latter include Swedish municipalities, energy companies and farmer representatives.

Biomass production and supply

The woodchips were assumed to be produced from tops and branches harvested at final felling of conventional forestry activities in spruce and pine stands[28]. These forest residues are a by-product of the timber industry: if not harvested for energy purposes, the forest residues would be left to decompose in the forest and would contribute to forest carbon stocks.

Extracting these forest residues, in Sweden, was recently estimated to have a climate impact of 48.6 kg carbon dioxide equivalents (CO_2-eq) per tonne of dry woodchips (harvesting, forwarding, and chipping) and to induce a loss in forest carbon of 89.1 kg CO_2-eq tonne^{-1} of woodchips in comparison with no harvesting in a long term perspective[28].

To model transport emissions, the mix of woodchips was assumed to comprise three fractions representative of the Stockholm's current consumption, where around 15% of the total is acquired in a radius of 100 km from Stockholm, 50% is transported from more distant Swedish forest by rail and the remaining 35% is transported from the Baltic states by ship[29].

Emissions data for transport processes were taken from the Ecoinvent database[30] and are presented in Supporting Information (SI). The Swedish emission data were extended to the fraction of imported biomass from the Baltic despite differences in climate, weather and management conditions. This was justified by the fact that Stockholm aims to use only Forest Stewardship Council (FSC)-certified woodchips[31] and that generic emission data available in the Ecoinvent database for woodchips were of the same order of magnitude.

Biomass conversion

Slow pyrolysis and combustion model. A mass and energy balance of the slow pyrolysis process was constructed. The main output of the model was an estimate of the amount of district heat that an optimised slow pyrolysis plant could generate in the context of Stockholm. The input data included a characterisation of the woodchips[29] and biochar properties meeting most criteria of the voluntary European Biochar Certificate (EBC)[32,33]. The pyrolysis temperature was set to 700°C, as currently used in a pilot plant operated in Stockholm, ensuring biochar stability[12,34,35] and agronomic properties. The yield of biochar was either 21% or 36%[36] (% total dry mass) and the power to heat ratio was either 0 (no power) or 0.37. The enthalpy of pyrolysis was assumed to be around 8% of the fuel's higher heating value, the mean value of the range reported in previous research[37]. The woodchips were assumed to have an initial moisture content of 50% and to be dried to 10% moisture content, using residual heat from the process, before entering the pyrolysis reactor.

For combustion of biomass, data were taken from the latest CHP plant built in Stockholm[29,38] and from the IEA[39]. The calculated and assumed efficiencies are compiled in SI.

Emissions from biomass oxidation. Pyrolysis and combustion of biomass are accompanied by emissions of air pollutants, some of which are climate forcers, resulting from incomplete combustion of the gases. Emissions of methane and nitrous oxide were assumed to be 0.011 and 0.006 g MJ^{-1} woodchips, respectively[40]. The same values were used for both pyrolysis and combustion, as nearly all the nitrogen contained in biomass is lost to the flue gas during pyrolysis and as both plants were assumed to be equipped with the same flue-gas cleaning technology.

Climate impact of energy substitution. One way of comparing scenarios with different outputs is the avoided burden approach or substitution approach[18–20,22,24]. Selecting the appropriate substituted product is a key part of LCA studies[41]. Here, EF values for different fuels were taken from Swedish-specific data[42,43], while fuel displacements were identified with two approaches, one generic and one Stockholm-specific.

In the generic approach, natural gas was selected for substitution, as it is a fossil fuel likely to remain in Europe's energy system for many years. It was assumed that heat and power from the evaluated systems substitute use of natural gas for heat (90% LHV efficiency) and power production (53% LHV efficiency), with EFs of 77.0 and 131 kg CO_2-eq GJ^{-1} respectively[42].

In the Stockholm-specific approach, fuel displacements were calculated using a model developed by Stockholm Exergi for long-term planning in the city's district heating network. As described in SI, the model calculates the change in consumption of a dozen fuels and net electricity production at city scale, following addition of a new plant in the system. For each scenario, the output of the model was used to calculate the climate impact of energy substitution. The EF for biomass fuel was set equal to that of the biomass used as functional unit, while for other fuels values were taken from[42]. The Stockholm-specific approach included three time horizons (2020, 2030 and 2040) with respective EFs of 1000, 550 and 200 g CO_2-eq kWh^{-1} of electricity[43]. These time horizons describes current projections for marginal electricity used in Sweden, with old coal plants to be phased out in the coming decade and replaced by efficient natural gas plants[43].

Biochar effects in dairy farms

The agricultural use of biochar was designed to be practical for farmers, to tackle various sources of methane and nitrous oxide emissions in the agricultural sector and to be implementable at large scale in Sweden. Practicality was ensured by integrating biochar use with the current management of manure. In particular, no extra field operations were then needed to apply the biochar to soils as biochar is mixed with manure. The emissions affected included enteric fermentation, manure management and soil emissions. Annually, the pyrolysis plant was assumed to produce 52 500 to 90 000 dry tonnes of biochar, for use in Stockholm and neighbouring regions. These regions have an available area of about 900 000 ha of agricultural land.

Reference farm. A dairy farm of 300 cows was modelled, based on characteristics of Swedish dairy herd structures obtained from the Swedish Farmer's Association (LRF)[44] and the national reporting to the UNFCCC[45]. The dominant manure management system in Sweden, storage of slurry under roof and annual application to soil[46,47], was modelled. Manure was assumed to be applied to land at a rate of 43 tonne ha^{-1} of slurry (i.e. 25 tonnes ha^{-1} of fresh manure), before cultivation of high-yielding grass ley requiring fertilisation. The fertiliser value of manure applied to land was calculated as in Hanserud *et al.*[48]. Additional mineral fertilisers were assumed to be ammonium nitrate, triple superphosphate and potassium chloride[49]. It was also assumed that the farm had access to enough land to accommodate the manure generated and that slurry application rates complied with any local restrictions on phosphorus addition.

The annual emissions of GHG taken into account for one cow, the management of its manure and inputs for growing grass on manure-fertilised land were calculated following the guidelines from IPCC[50] and were equal to 8.1 tonnes CO_2-eq per year, excluding SOC changes. This amount was potentially affected by biochar.

Explorative modelling of biochar effects. Biochar was assumed to be delivered to dairy farms for addition to feed[14,33,51], at an average rate of 0.12 kg dry biochar cow^{-1} day^{-1} (about 1% of daily feed intake), and for mixing with manure, at an average rate of 30 kg dry biochar tonne^{-1} of freshly excreted manure (3% mixing rate). Annual consumption of biochar for one cow and its manure was then 696 dry kg (6% as feed, 94% as manure additive), and for a 300-head farm it was 209 dry tonnes. The resulting application rate of biochar to land (0.80 tonne ha^{-1} year^{-1}), was significantly lower than in most former studies, but application was assumed to take place every year. With these biochar use rates, about 75 000 dairy cows (22% of all Swedish dairy cows) and 66 000 ha of land (7.3% of available agricultural land in the region) would be needed to consume an annual biochar production of 52 500 tonnes (at 21% biochar yield).

The effects of biochar were represented by 11 emissions reduction factors, for four compounds (methane, nitrous oxide, ammonia and nitrate) and six steps (enteric fermentation, slurry storage, slurry application, fertiliser application, lime application, and land methanotrophism). To explore the possible range of effects, the emission reduction factors were given three set of values: worst, average and best case (Table 1). The worst case modelled negative or null effects and a low biochar stability. The best case modelled optimised biochar effects and high stability. The emission reduction factors were selected based on meta-analyses when available, new experimental studies or expected effects otherwise. The agricultural effect of biochar was calculated by multiplying the emissions reduction factors to the emissions from the reference farm, and the total scaled by the biochar yield was taken as an avoided burden for the biochar scenarios (1a-d).

Table 1. Emission reduction factors (% of emission in reference farm, for each step and gas, available in SI) and parameters used to explore the potential biochar soil effects and biochar stability.

Step	**Gas**	Worst, **Average**, Best	**Source**
Enteric fermentation	CH_4	0%, **2.5%,** 5.0%	In-vitro experiments highlighted no increase in emissions, and probably a small decrease could be expected[52].
Indoor storage	CH_4-C	0%, **12.5%**, 25%	*Assumed effects on manure storage. No negative effects were reported in one experiment[53].*
	NH_3-N	0%, **12.5%**, 25%	
	d-N_2O-N	0%, **12.5%**, 25%	
Slurry application	NH_3-N	0%, **20%**, 40%	*Assumed reduced ammonia loss by biochar adsorption.*
	NO_3-N	5.7%, **26%**, 41%	Meta-analysis[54]. Value for longer studies, with widest 95% confidence interval.
	d-N_2O-N	-10%, **16%**, 42%	Meta-analysis[9]. Value for small application rates.
Mineral fertiliser application	NH_3-N	0%, **20%**, 40%	*Assumed reduced ammonia loss by biochar adsorption.*
	NO_3-N	5.7%, **26%**, 41%	Meta-analysis[54]. Value for longer studies, with widest 95% confidence interval.
	d-N_2O-N	-10%, **16%**, 42%	Meta-analysis[9]. Value for small application rates.

Soil methane sink	CH_4	0%, **-25%**, -50%	In upland soils, the strength of the methane sink may slightly be reduced[55–57]. Increased emissions.
Parameter	**Unit**	Worst, **Average**, Best	**Source**
Biochar liming effect	% $CaCO_3$	1.0%, **10%**, 20%	Assumed liming effect based on liming classes from[58].
SOC decay rate change	-	-0.80%, **3.8%**, 8.1%	Meta-analysis[12]. Grand mean and 95% confidence interval.
Biochar carbon recalcitrance	%C	70%, **80%**, 90%	Higher value supported by meta-analysis, for woody biomass[12]. Lower value suggested as in[14].

Agricultural effects of biochar not taken into account were: animal health improvement, entailing lower mortality and medical inputs; and increased biomass yields[59].

Biochar long-term soil effects

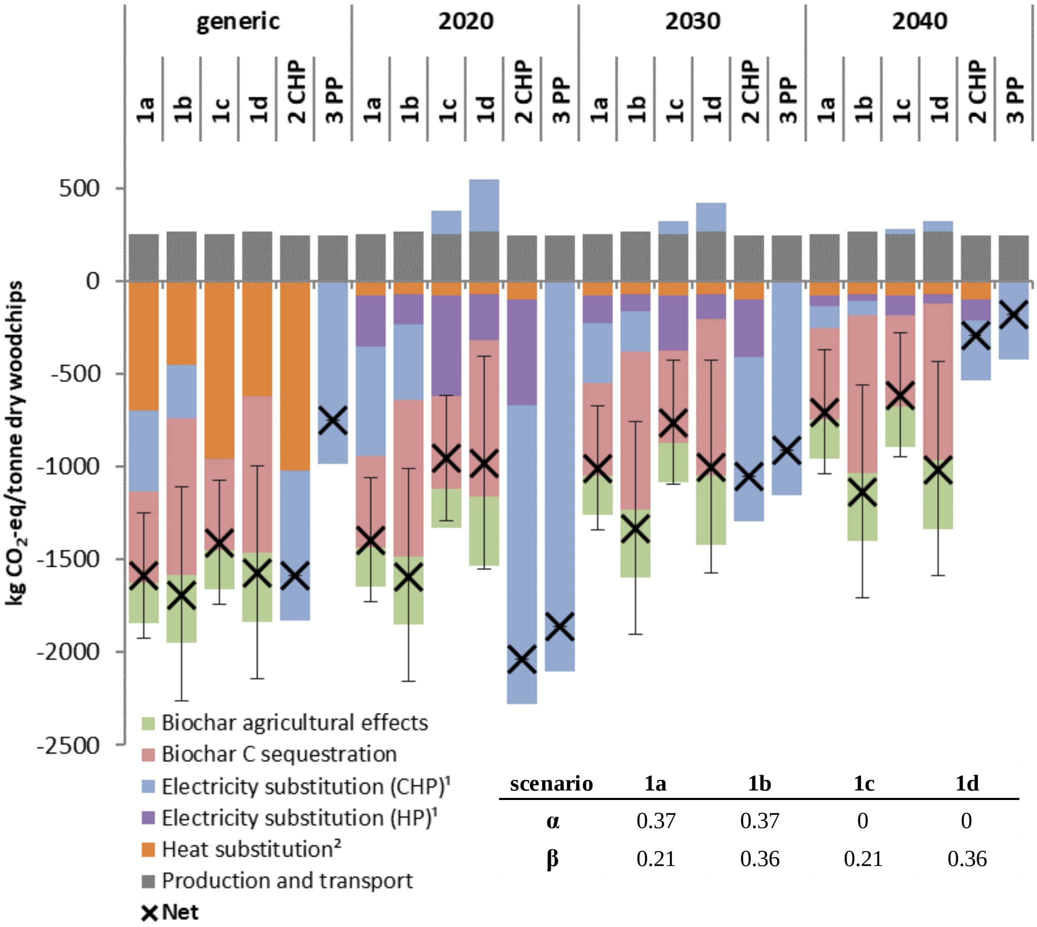
The carbon sequestration effect of biochar derives from its resistance to biological, chemical and physical degradation in soils. When using GWP_{100} as the climate metric, the figure usually reported is the amount of carbon remaining in the soil after 100 years. What happens after the first 100 years was not considered here. The carbon stability of biochar was set to 80% (± 10%), in accordance with a pyrolysis temperature above 500°C and a molar $H\!:C_{org}$ ratio below 0.40[12,14,35]. Assuming a biochar carbon content of 80%, the mean amount of carbon remaining 100 years after production was thus 64% of the dry amount of biochar initially applied to soil.

Application of biochar to soil is expected to affect SOC stocks. A decrease in the SOC decay rate was modelled as a consequence of annual applications of biochar. The initial SOC level was assumed to be 85 tonne ha^{-1} of land[22]. The new steady-state was assumed to be reached during the timeframe of the study. In the average case, the change of decay rate (3.8%, meta-analysis[12]) led to an increase in SOC levels, reaching 88.4 tonne ha^{-1}. This SOC change was scaled to the functional unit by dividing it by the total amount of biochar applied to the soil over the timeframe of the study (100 years) and multiplying by the biochar yield.

The liming effect of biochar was modelled using the classes defined in the IBI standard[58]. The EF for substitution of conventional liming agent was taken from Ecoinvent[30]. Biochar's liming effect was benchmarked against Swedish agricultural recommendations that vary for different soil types[60] and assumed a reference application of liming agent every 10 years.

Results and discussion

The study compared the life cycle climate impact of three biomass options for expanding Stockholm's energy system. The ranking of these options varied mainly with assumptions on the background energy system and the magnitude of agricultural effects (Figure 2).



scenario	1a	1b	1c	1d
α	0.37	0.37	0	0
β	0.21	0.36	0.21	0.36

Figure 2: Climate impact (kg CO_2-eq tonne^{-1} dry woodchips) for the six systems studied under different substitution methods (generic natural gas assumption and Stockholm-specific 2020, 2030 and 2040). The high and low bars indicate the possible variation in biochar agricultural effects and carbon sequestration (worst and best case). In the Stockholm-specific approach, the scenario 3 PP is modelled as exogenous, i.e. due to the size of the Nordic electricity market, we assumed that this new plant would not affect the district heating network.

α = power to heat ratio, β = biochar yield (% total dry mass).

[1] In the Stockholm-specific approach, electricity substitution is split between electricity used in heat pumps and net electricity produced in CHP.

[2] In the Stockholm-specific approach, heat substitution denotes the change in (non-electricity) fuel consumption for the CHP plants and the heat-only boilers.

Generic energy substitution

With the generic approach, where natural gas is the alternative fuel for both heat and power production, a CHP plant outperforms a power-only plant, as expected, as do all biochar scenarios (Figure 2). For the biochar scenarios, distinctions must be made between the levels of agricultural effects achieved. In the worst case, where only biochar C sequestration is achieved with negative agricultural effects, no pyrolysis scenario (1a-d) outperforms the CHP reference (2). With natural gas as the alternative fuel and biochar C sequestration only, the trade-off between bioenergy and biochar production is in favour for bioenergy: increasing the biochar yield (1a to 1b, 1c to 1d) reduces the climate performance (Figure 2, generic). It is only if the full range of agricultural effects is achieved that biochar scenarios can outperform the CHP reference and that the trade-off is in favour of biochar production (Figure 2, generic).

These generic considerations are relevant for understanding the trade-offs of biochar systems[17,61]. However, they do not reflect the current and future states of Stockholm's energy system where, for instance, heat production is mostly fossil-free, large heat pumps are in operation, and marginal power-consumption may still include some coal power plants.

Stockholm-specific substitution

In the long run (Figure 2, 2040), with a decarbonised marginal electricity (at 200 g CO_2-eq kWh^{-1} electricity), all biochar configurations except 1c outperformed the reference plants even with low biochar agricultural effects (worst case). In 2030 (at 550 g CO_2-eq kWh^{-1} electricity), only the plants with high electricity or biochar outputs (1a-b and 1d) ranked better than the references under the condition that the high biochar agricultural effects were achieved (Figure 2, 2030). In today's context, with marginal electricity at 1000 g CO_2-eq kWh^{-1} electricity, no biochar configuration could outperform the reference scenarios except in one case (1b), when high power and biochar yields with high agricultural effects are achieved (Figure 2, 2020).

The direction of the bioenergy-biochar trade-off changed with the time horizon and the magnitude of agricultural effects (Figure 2). The new base-load heat production capacity provided by all scenarios did not contribute to any further substitution of fossil fuel for heat production. Therefore, the performance of biochar systems in Stockholm is bound to the fate of marginal power consumption, which is largely dependent on imports from the Nordic and European Union grids. In the short term, pyrolysis plants with power production (1a, 1b) performed better than without (1c, 1d) (Figure 2, 2020). However, this will no longer be the case if low-carbon electricity production is achieved by other means in the future (Figure 2, 2040). Alternatively, biochar-based solutions would benefit from future scenarios where the energy and electricity demands decrease. Indeed, low energy consumption reduces the pressure on biomass resources[1] and thus enables its use for other high-exergy applications, such as biochar production.

In the next sections, we shed light on specific parts of the life cycle: production and transport, system effects at the city level, and biochar use phase.

Production and transport

At present times, forest and plant technical operations, transportation steps and forest carbon losses accounted for 242 kg CO_2-eq tonne^{-1} in the combustion scenarios and 253-262 kg CO_2-eq tonne^{-1} in the pyrolysis scenarios (Figure 2). A third of these emissions derived from losses in forest carbon stocks. The additional transport and handling of biochar only added 12-20 kg CO_2-eq tonne^{-1} woodchips. From a climate perspective, the production burden of the pyrolysis and combustion scenarios was rather similar.

In an optimistic prospective scenario, where efforts are made in all sectors of society to reach climate targets, the production burden would decrease. Other sources of woody biomass, such as willow grown on agricultural land, could even lead to increase in SOC stocks[22]. Besides, in the average and best cases, SOC increases following biochar application compensated for about 36% to 139% of the forest carbon loss arising from residue harvesting. The consequences of transferring carbon from forest to field for the long-term productivity of each land use were not assessed, but it is believed that higher SOC levels are an indicator of soil fertility with complex feedback mechanisms[62].

Fuel consumption changes at the city level

In terms of operation of Stockholm's district heating network, the addition of a new biomass-fuelled plant led mainly to lower consumption of biomass in older boilers and to lower consumption of electricity for running heat pumps (HPs) (Table 2). An increase in electricity production from CHP turbines was observed in scenarios 1a-b. To a lower extent, other fuels (multi fatty acids, EO5 oil, biodiesel and tall oil) were also displaced but with a negligible effect on the climate score of the different scenarios. Scenario 1b, due to its high power and biochar production, had a higher merit order than one facility using imported municipal solid waste (Table 2). This singularity did not affect significantly the climate score, and we therefore did not model indirect effects related to alternative waste management abroad. Further analysis of these city-level changes is provided in SI.

Table 2: Changes in fuel inputs and product outputs at the city level when introducing a new plant in the district heating network. CHP = combined heat and power; HP = heat pumps.

Scenarios	**1a**	**1b**	**1c**	**1d**	**2 CHP**
Output change	*tonne^{-1} dry woodchips*[a]				
Net electricity produced in CHPs (MWh)	0.59	0.40	-0.12	-0.29	1.6
Biochar output from pyrolysis unit (kg)	210	360	210	360	0
Input change	*tonne^{-1} dry woodchips*[a]				
Woodchip-like biomass (MWh)	-1.7	-0.96	-1.6	-1.5	-2.0
Net electricity consumed in HPs (MWh)	-0.27	-0.16	-0.55	-0.25	-0.57
Imported municipal solid waste (MWh)	0	-0.21	0	0	0
Other fuels[b] (MWh)	-0.17	-0.09	-0.22	-0.14	-0.37

[a] LHV of woodchips is 18.9 GJ tonne^{-1} or 5.26 MWh tonne^{-1}.
[b] Minor fuel changes for multi fatty acids, EO5 oil, biodiesel and tall oil.

The net biomass consumption change was +0.62 tonne per tonne of woodchips used in the new CHP plant (2), while it varied between +0.68 and +0.82 tonne per tonne of woodchips used in the pyrolysis plants (1a-d). A net change lower than 1 indicates that biomass use in newer, more efficient plants replaces biomass use in older plants. The fact that all values are strictly positive is linked to larger electricity or biochar outputs of the scenarios. At the city scale, building a large-scale pyrolysis plant (250 000 dry tonnes of woodchips per year) instead of a conventional CHP plant represented a net increase of 17 to 50 thousand tonnes of woodchips per year, while delivering the same heating service but different amounts of electricity and biochar. Apart from the direct climate impact, the consequences of this additional demand for biomass in Stockholm were not assessed here[63–65].

Biochar effects and variability

The average biochar use phase, including transport to and on the farm, yielded a climate impact of -3315 kg CO_2-eq tonne^{-1} of biochar (i.e. -696 and -1193 kg CO_2-eq tonne^{-1} of woodchips at biochar yields of 21% (1a, 1c) and 36% (1b, 1d) respectively) (Figure 3a). More than two thirds derived from sequestration of carbon in the biochar, while the remaining third derived from agricultural emissions reductions and field SOC increase. The average agricultural effect represented on average a 7.9% reduction in emissions from the dairy farm considered and was evenly distributed between methane (11%) and nitrous oxide (11% direct, 2.9% indirect) emissions reductions (Figure 3b). These non-CO_2 gases accounted for a non-negligible 25% of the total biochar effect (Figure 3b).

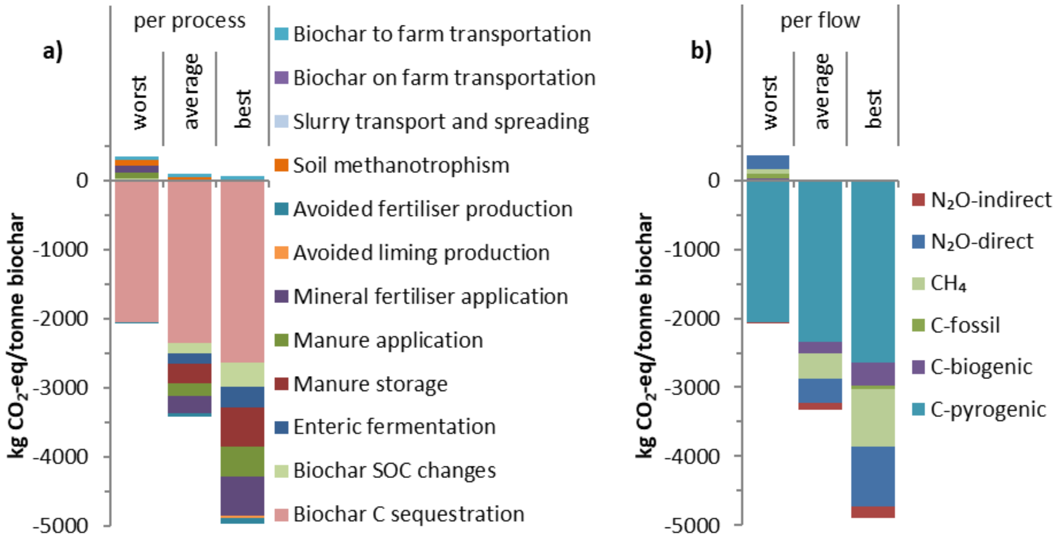


Figure 3: Per process (a) and per elementary flow (b) contribution to the climate impact of biochar agricultural effects and carbon sequestration (kg CO_2-eq tonne^{-1} dry biochar) for the three cases modelled (worst, average, best).

In the worst case modelled, the biochar effects were 48.4% lower than in the average case and were dominated by biochar carbon sequestration and some increased emissions (loss of SOC and increase in nitrous oxide emissions). In the best case modelled, the biochar effects were 47.7% higher than average and biochar carbon sequestration contributed to only 54% of the total effect. This modelling shows the importance of studying cascading biochar effects as they could, if identified and optimised, double the benefits provided by biochar, thereby mitigating up to 17% amount of non-CO_2 emissions from dairy systems; but also, if not optimised, lead to an estimated increase of emissions of 2.2%.

To compare these results with previous biochar LCAs, one can express the ratio between other mitigation effects and carbon sequestration. For the effects studied here (Figure 3), the ratios were -0.14, 0.44 and 0.88 (worst, average and best cases). Hammond et al.[18] had ratios of about 0.45, which was mostly due to assumed SOC increase. Other studies had ratios ranging from 0.071[19,23] to 0.17[19] depending on feedstock and effects modelled.

Energy system

Substitution approaches. In LCA, substitutions are a source of variability between studies because of choices made by modellers[41,48,66]. Here, the Stockholm-specific approach showed how energy system modelling could help identify fuel displacements that are more representative of the actual changes in operation of the energy system than a generic approach. This model however introduces more parameter uncertainty that was not evaluated here.

With the generic approach, the energy substitution impact is simply a function of the energy efficiencies and the EF of the selected supply chain for the energy product considered. For the Stockholm-specific approach, the energy substitution is a function of the change in energy supply to the entire city and the EF for each energy source. This means that the Stockholm-specific approach does not only assess the climate impact of a biochar plant but the contribution of this new plant to the existing energy system.

Besides, the different time-horizons selected for marginal power consumption in Sweden showed how the climate impact of different scenarios could vary significantly with changes in assumptions regarding the background system[67].

System boundaries. Using different reference scenarios, substitutions methods and timeframes also provides additional information for stakeholders. With the narrowest boundaries, only the performance of the plant can be assessed, which is probably of interest to plant operators for optimisation models or accounting (Figure 2, without energy substitution). At the city scale, more information on fuel markets is obtained, which is of interest for anticipating demand changes and securing supply (Figure 2, with specific energy substitution and Table 2). These demand changes are also associated with indirect effects on land use, whose impacts are difficult to assess and which should be avoided[63,65,68].

With wider boundaries, more alternative uses of biomass could have been considered. The woodchips used in Stockholm are potentially available on the global market. Therefore, the expansion of Stockholm's district heating network is in competition with other energy systems that could theoretically acquire the same biomass for production of transportation fuel or to replace coal-fuelled plants. In this second case, the additional benefits of a new biomass-fuelled plant in Sweden, regardless of combustion or pyrolysis, would be lower than the displacement of the most carbon-intensive energy sources. This suggests that the climate benefits provided by biochar systems in Sweden are relevant globally only if the material, social and financial means to phase out carbon-intensive energy sources are available to all countries. However, the reality of today's biomass[69] and carbon[70] markets may not incentivise such theoretical biomass transfers. Besides, the introduction of new biochar technologies remains relevant for continued improvements and competitiveness in Sweden, but also for the development of NETs, which is of international relevance in the longer term[4,7].

Biochar energy penalty. Compared with biomass combustion, biochar systems produce less heat and power because part of the energy in biomass remains in biochar[17]. The biochar energy penalty, defined as the difference in energy substitution between a biochar scenario (1a-d) and a reference scenario (2, 3), was dominated by the fate of power production.

The size of the biochar energy penalty is a critical indicator, as it sets a baseline for the performance of biochar during the use phase. It allows one of the key trade-offs between bioenergy and carbon sequestration[61] to be quantified: unless the use phase effects are greater than the energy penalty, biochar solutions cannot outperform the established technologies from a climate perspective.

Agricultural system

Knowledge gap in biochar effects. While using biochar for feed and manure management is a convenient way of returning carbon to soil[14], there is a knowledge gap regarding the effect of biochar use in dairy farming systems[71]. The modelling of the agricultural effects of biochar performed in this study was exploratory rather than predictive, as most values produced are very uncertain and not backed up by local field observations or detailed mechanistic understanding. Among the 11 reduction factors used in the model, 5 were documented with meta-analyses[9,12,57,72]. The other parameters were selected based on new experimental results[52] or expectations for engineered biochar[73,74] regarding leaching and volatilisation of nutrients and effects on storage of manure[53,75]. Likewise, the effects on manure management[53,75], but also composting[76] and anaerobic digestion[77], are still not sufficiently well understood to be used for anything other than prospective LCA studies. As commercialisation of biochar products for feed and manure management has already started in Europe[78], the need for rigorous academic documentation of these effects is needed, including potential animal health and productivity effects.

Nevertheless, the insights gained through prospective modelling are valuable for developers of biochar products[73,74], as it allows assessment of the relative sizes of expected effects. The potentially substantial reduction in agricultural emissions (10% of dairy farm emissions) is to be sought and optimised for different uses and environments. Here, only cascading use of biochar in animal husbandry was considered, but other uses in agriculture, construction or landscaping are possible[79].

Soil pH restrictions. The contribution of avoided production of liming agent to the climate impact was small, regardless of the biochar's liming class (Figure 3). However, the repeated application of biochar may lead to long-term changes in soil pH. Based on the Swedish liming recommendations for different soil types[60], restrictions on biochar application rates may be needed on soils that usually require little liming. That is the case of sandy and low-SOC soils[60] (SI). Restrictions on biochar application rates, whether for alkalinity or other factors, must be considered in future policy support and recommendations to farmers.

Policy support for environmental effects. Earlier research recommended to not establish biochar solutions in regions where energy production is carbon intensive and where agricultural yields are already high[80]. However, it was shown here that increase in agricultural yield is not a requirement for climate-efficient biochar systems, if other emissions are reduced. Nevertheless, agricultural yield increases are one of the main factors in acceptance of a new practice by farmers, as it contributes directly to better economic performance[81,82]. Therefore, if environmental benefits are obtained without agricultural productivity increase, policy measures providing payment for climate mitigation are needed to promote implementation.

Environmental assessment

Non-assessed climate factors. The present assessment was limited to the three main GHGs. Effects of biochar application on albedo and heat flux were not included, as such an assessment would require more site-specific data and as the effects would vary with soil management practices. Anyhow, biochar on the soil surface has a warming effect, due to its dark colour. Meyer and colleagues[83] estimated that the albedo contribution could reduce the mitigation potential by up to 15%. Albedo changes can be reduced by permanent soil cover, which is common on dairy farms due to grass cultivation, and incorporation of biochar into the soil. However, soil disturbance may have other consequences for SOC levels. Thus, the albedo penalty reinforces the need for biochar systems to perform significantly better than current technologies.

Under the assumptions made on biochar stability in this study, about 123 kg CO_2 tonne^{-1} of woodchips would be released from biochar decomposition during the first 100 years. The climate metric GWP_{100} does not take into account the effects on climate of progressively releasing the carbon dioxide contained in the biochar. Instead, what is implicitly assumed with this metric is that the progressively decayed carbon over 100 years is released at the production time. Time-dependent metrics[84] could account for the consequences of slowly released carbon.

Other environmental impacts. Particle, dust and soot emissions due to biochar mishandling contribute to reducing the climate benefits of biochar-based systems[85]. Their contribution to the climate impact of this study may be marginal when clean production principles are applied, but particles also have serious effects in other environmental impact categories[86] (air pollution, human health, biodiversity) that were not assessed here. Likewise, some co-benefits of biochar were not quantified. For example, the reductions in ammonia and nitrate losses were modelled because they lead to avoided indirect nitrous oxide emissions (Figure 3b)[50], but they also mitigate water-related impacts such as eutrophication[72,87].

Final recommendation. At the large-scale envisioned in this study, where woodchips are sourced on the global market, the suitability of biochar systems in Stockholm is subject to the decarbonisation of the electricity market and other carbon-intensive sectors. If this decarbonisation is achieved by 2040, biochar solutions would represent a suitable expansion for the district heating network, thereby providing a sound option for carbon dioxide removal. If agricultural effects of biochar are optimised, through cascading use in animal husbandry, manure management and fertiliser management, the climate benefits of biochar could at best be doubled. Such a prospective development requires research efforts, in both upscaling of pyrolysis technologies and mechanistic understanding of biochar agricultural effects. When developing new biochar products, the life cycle perspective is useful to assess trade-offs and the relative importance of various potential effects.

ASSOCIATED CONTENT

Supporting Information. The Supporting Information (SI) is available free of charge on the ACS Publications website at http://pubs.acs.org. It includes: activity and emissions data for biomass production and supply; slow-pyrolysis model key parameters; description of energy products in Stockholm's district heating network; description of city-scale district heating network model; list of fuel emission factors; description of reference dairy farm model; activity and emissions data for the reference dairy farm; description and diagram of biochar effect modelling; table of emissions reduction factors, application rates and soil effects; description of long-term effects of biochar on soil; detailed results on fuel displacement at city level; table of results; histogram of biochar use phase effects; compiled list of parameters; references.

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Author Contributions

Elias S. Azzi defined the scope of the study, performed the modelling and wrote the manuscript. Erik Karltun contributed to defining the scope of the study, model development and manuscript revision. Cecilia Sundberg initiated the project, contributed to defining the scope of the study, revised the model and revised and edited the manuscript.

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