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Research article

Assessing the diverse environmental effects of biochar systems: An evaluation framework

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ABSTRACT

Biochar has been recognised as a carbon dioxide removal (CDR) technology. Unlike other CDR technologies, biochar is expected to deliver various valuable effects in e.g. agriculture, animal husbandry, industrial processes, remediation activities and waste management. The diversity of biochar side effects to CDR makes the systematic environmental assessment of biochar projects challenging, and to date, there is no common framework for evaluating them. Our aim is to bridge the methodology gap for evaluating biochar systems from a life-cycle perspective. Using life cycle theory, actual biochar projects, and reviews of biochar research, we propose a general description of biochar systems, an overview of biochar effects, and an evaluation framework for biochar effects. The evaluation framework was applied to a case study, the Stockholm Biochar Project. In the framework, biochar effects are classified according to life cycle stage and life cycle effect type; and the biochar's end-of-life and the reference situations are made explicit. Three types of effects are easily included in life cycle theory: changes in biosphere exchanges, technosphere inputs, and technosphere outputs. For other effects, analysing the cause-effect chain may be helpful. Several biochar effects in agroecosystems can be modelled as future productivity increases against a reference situation. In practice, the complexity of agroecosystems can be bypassed by using empirical models. Existing biochar life cycle studies are often limited to carbon footprint calculations and quantify a limited amount of biochar effects, mainly carbon sequestration, energy displacements and fertiliser-related emissions. The methodological development in this study can be of benefit to the biochar and CDR research communities, as well as decision-makers in biochar practice and policy.

1. Introduction

Actions and declarations to mitigate greenhouse gas (GHG) emissions have never been as numerous as in recent years. Still, global GHG emissions are not decreasing, exceeding 50 Gt CO_2-eq year^{-1} in 2017.[1] At this rate, the carbon budget left to meet the 1.5 °C target will be exhausted in less than a decade (IPCC, 2018; Mercator Research Institute on Global Commons and Climate Change, 2020). While most efforts should be targeted at decreasing emissions (Fuss et al., 2014), the latest IPCC reports have concluded that it will be necessary to complement emission reduction efforts with carbon dioxide removal (CDR) technologies (Arneth et al., 2019; IPCC, 2018). The amount of CDR needed is not intrinsically set (Grubler et al., 2018; van Vuuren et al., 2018), but rather depends on the chosen development pathway.[2] CDR dependence is estimated to vary widely e.g. from 5 to 50 Gt CO_2-eq year^{-1} in 2100 (Huppmann et al., 2018; Tisserant and Cherubini, 2019). However, reaching even the lower range requires pilot projects to start today, and is likely to require unprecedented deployment rates of sound CDR in the next two decades (Nemet et al., 2018). Among the proposed CDR technologies, the conversion of biomass to biochar through pyrolysis is considered one of the most economic (Fuss et al., 2018), available at both small and large scale, across income-levels, and with

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[1] Absolute emission reductions have so far only been observed when exogenous disruptions of the economic system occurred (Haberl et al., 2019).

[2] As the IPCC puts it: "1.5 °C pathways that include low energy demand, low material consumption, and low GHG-intensive food consumption have the most pronounced synergies and the lowest number of trade-offs with respect to sustainable development and the SDGs *(high confidence)*. Such pathways would reduce dependence on CDR" (IPCC, 2018).

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both low- and high-tech solutions (Woolf et al., 2010). Biochar is often used as a soil amendment in agriculture (Smith, 2016; Woolf et al., 2010), but other industrial applications are being developed. The global CDR potential of biochar is estimated to vary between 0.65 and 35 Gt CO_2-eq year^{-1} (Tisserant and Cherubini, 2019), a wide range explained by different assumptions on the biomass resources available for biochar production.

All CDR technologies have positive and negative side effects, risks and potential unintended consequences (Fuss et al., 2018). A specific feature of biochar is that it has been promoted, within both the academic and public spheres, for its multiple positive side effects (Smith, 2016; Sykes et al., 2019). These positive side effects mean that biochar is not just a CDR technology, but also a valuable product, thereby reducing the cost of CDR and increasing its acceptance. In agriculture, frequently mentioned biochar effects are increased crop yields (Jeffery et al., 2017), reduced GHG emissions from soils (Borchard et al., 2019a; Cayuela et al., 2014; Jeffery et al., 2016), reduced environmental pollution (Fischer et al., 2018), and improved animal health (Man et al., 2020). In urban environments, biochar may improve tree health, reduce storm water contamination (Mohanty et al., 2018) or be used for remediation of contaminated soil (Beesley et al., 2011; Yuan et al., 2019). In industrial applications, carbon materials can replace other resource intensive materials (sand, aggregates) or even fossil coal. If produced from waste streams, biochar provides waste treatment services, and can be used to improve other treatment processes (Akdeniz, 2019; Sanchez-Monedero et al., 2018; Sun et al., 2020).

The diversity of effects provided makes the systematic environmental assessment of biochar projects challenging. Reviews on individual biochar effects have been published e.g. (Cayuela et al., 2014; Gao et al., 2019; Razzaghi et al., 2019), but there is no common evaluation framework for those effects. Side effects are also an important topic for biochar research and practice, because biochar is unlikely to be produced just by a few large industries (like afforestation, but unlike most other CDR technologies). Rather, biochar is already being produced and used by a diversity of actors, e.g. private individuals, smallholder and medium-scale farmers, municipal and private waste management companies, construction companies, and agricultural cooperatives. Choices are made by these actors based not only on the CDR aspect of biochar, but also on other expected positive side effects that are currently not always covered in evaluation tools such as life cycle assessment (LCA). Several biochar LCA studies have been performed (Matuštík et al., 2020; Tisserant and Cherubini, 2019) focusing mainly on climate change impacts and modelling a few side effects. LCA is an appropriate tool for evaluating biochar side effects as it is widely used for environmental support of decisions and helps understand inter-relations and trade-offs. However, better representation of biochar effects in LCA is necessary and may result in stronger policy support.

In this paper, our aim is to structure the discourse on the environmental effects of biochar, using a systematic approach based on life cycle thinking. The goals are to (i) categorise the variety of biochar effects reported in the literature, (ii) describe biochar effects in a systems perspective, and (iii) apply the findings to a case study, Stockholm's Biochar Project. An intended outcome is an evaluation framework that can provide initial guidance to decision-makers to evaluate their biochar projects in a life cycle perspective, with a focus on biochar effects beyond CDR.

2. Methods

2.1. Defining "side effect"

A side effect can be defined as a secondary effect to the intended primary effect. In this study, the primary effect of biochar was considered to be CDR, also referred to as biochar carbon sequestration, and the side effects were considered relative to CDR. In addition, the term side effect is neutral: it describes both positive and negative effects. The terminology "biochar effect" is used here for concision.

The definition of biochar effects is further specified with the following propositions.

Proposition 1. *A biochar effect always implies the existence of a reference situation to which the effect is compared (implicit or explicit). For instance, increased crop productivity implies a reference situation without biochar use, with a separately determined yield. The same system without biochar is often a relevant reference situation, but this is not the only possibility.*

Proposition 2. *A biochar effect always belongs to one or several domains, a matter of concern for the analyst. For instance, reduction in N_2O emissions from soil is an effect within the domain of climate change mitigation. Increased water infiltration in urban constructed soils is an effect where possible domains include flood management, storm water treatment, and urban tree irrigation. Effect domains can fall into environmental or socio-economic categories. In this paper, the focus was on environmental aspects, which dominate in the biochar literature.*

Moreover, it is worth bearing in mind that biochar effects are essentially complex and intertwined, and that multiple effects can often be identified along a single cause-effect chain. For instance, increased soil water retention and changes in soil biology functions are two intermediate effects that usually affect crop productivity, the final effect related to food provision and security, which is t matter of concern. Many biochar effects can be expressed in monetary terms (economic effects), but this was not the focus here.

2.2. Building the methodological framework

2.2.1. Biochar system boundaries

The assessment of a system usually starts by defining its boundaries. For biochar systems, general system boundaries were identified by analysing several actual biochar projects,[3] a selection of biochar LCA studies (Azzi et al., 2019; Dutta and Raghavan, 2014; Ericsson et al., 2017; Hamedani et al., 2019; Hammond et al., 2011; Homagain et al., 2015; Mohammadi et al., 2019; Peters et al., 2015; Roberts et al., 2010; Smebye et al., 2017; Sparrevik et al., 2013; Thers et al., 2019; Thompson et al., 2016) and general methodological reviews of bioenergy-biorefinery LCAs (Ahlgren et al., 2015; Cherubini and Strømman, 2011; De Luca et al., 2017; Finnveden et al., 2009; Keller et al., 2015). The analysis was performed with key concepts of industrial ecology in mind: processes, flows, stocks, product-systems and functions (Pauliuk et al, 2015, 2016). Material flow analysis (MFA) theory was used to provide a general model for accounting for flows and stocks of biochar carbon through the environment over its lifecycle. This model included four categories of biochar use (agriculture, forestry, urban, industrial) and possible cascading uses. The general description of biochar systems is presented in section 3.1.

2.2.2. Evaluation framework of biochar effects

The biochar effect evaluation framework was built iteratively. First, a long list of biochar effects was identified by reviewing a selection of biochar reviews with a general aim (Ding et al., 2017; Fuss et al., 2018; Hagemann et al., 2018; Ippolito et al., 2012; Kammann et al., 2017; Nair et al., 2017; Schmidt et al., 2019a; Smith, 2016; Smith et al., 2019; Sykes et al., 2019; Tisserant and Cherubini, 2019) (Table S1 in Supplementary Materials (SM)). Despite the review not being exhaustive, the biochar effects mentioned reoccurred, indicating that the major biochar effects had been identified. Second, the long list of biochar effects was analysed and classified by the three authors, first independently and then together until consensus was reached. As a result of this classification, a key topic to analyse in detail was selected, namely soil systems. Third, 45 biochar LCA studies were analysed in terms of which biochar effects were modelled. These studies were identified from recent reviews (Matuštík

[3] Stockholm Biochar Project, Lindeborgs Gård AB, Hjälmsäter Egendom, Skånefrö AB, Telge Nät AB, NSR AB.

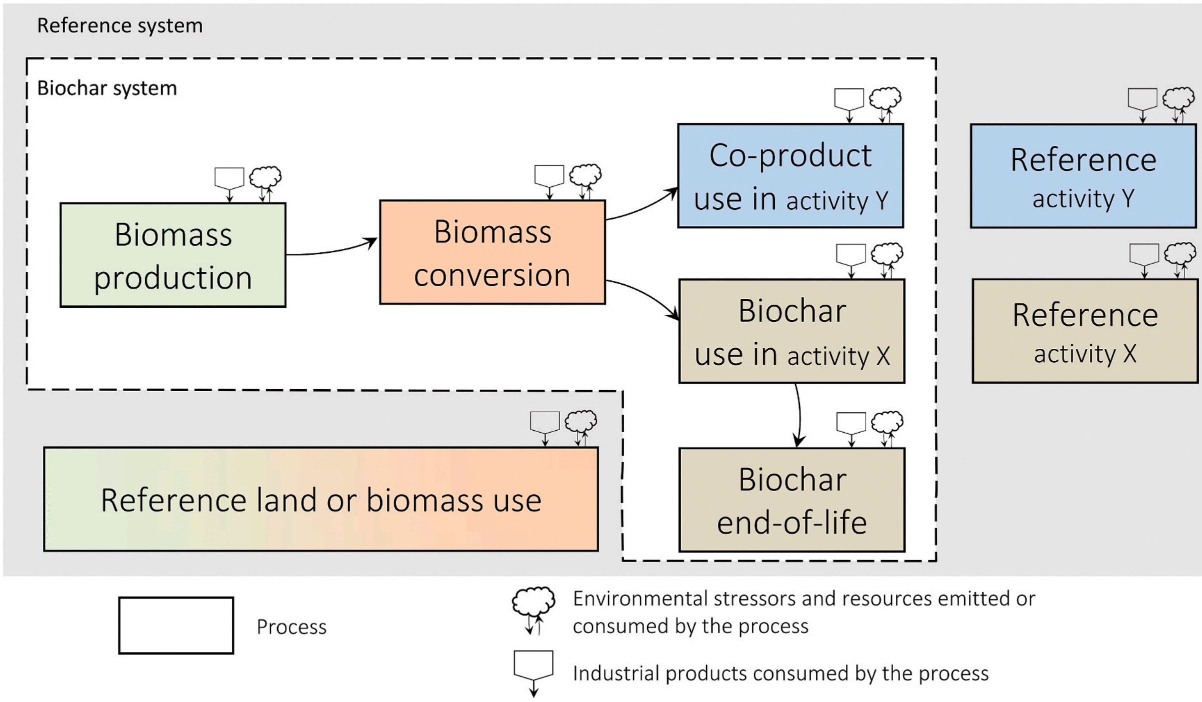

Fig. 1. General description of a biochar system, with its main processes and their explicit references. Each process may deliver one or several products valuable to society. A main process and its reference deliver, by definition, equivalent products.

et al., 2020; Tisserant and Cherubini, 2019) and forthcoming work (Table S2 in SM). Finally, the biochar effect analysis was combined with the general description of biochar systems to create an evaluation framework that can be used when assessing a biochar project, both retrospective and prospective. The results of this process are presented in section 3.2.

2.3. *Case study: the Stockholm Biochar Project*

The Stockholm Biochar Project (SBP) was selected to illustrate how the methodological framework can be used to evaluate biochar projects.

Project summary: Biochar use in Stockholm was initiated in 2013 by the city's tree officer to remediate tree growth problems in compacted urban soils and improve storm water management. For this purpose, trees had already started to be replanted in constructed soils, an arrangement of crushed rocks of various sizes filled with conventional peat-clay-sand soil. Biochar was introduced in the constructed soils to replace peat, and to further increase soil water retention and tree health. Biochar was initially imported from other European countries, mainly Germany. In 2014, the SBP led by an independent consultant received a grant from the Mayors' Challenge to buy and operate a pyrolysis unit (Mayors Challenge and Bloomberg Philanthropies, n.d.). The pyrolysis unit would convert the woody fraction of garden waste to biochar and district heat. Today, this project is being replicated in other cities across the world.

Data collection on biochar effects: the former project manager and two city officers in charge of biochar tree planting were asked to list all effects of biochar in the specific case of Stockholm. Handbooks published by the municipality were also reviewed (Stockholm Stad, 2020).

Analysis and interpretation: The list of biochar effects compiled from the interview and other material was analysed and interpreted using the general description of biochar systems and the evaluation framework (section 3.3).

3. Results

3.1. *General description of biochar systems for environmental assessments*

Producing and using biochar is a human enterprise that converts material and energy for some social outcome. In other words, biochar systems can be described by sets of processes, functions provided, and reference situations (Fig. 1).

3.1.1. *Main processes*

For biochar systems, five main processes can be distinguished: biomass production, biomass conversion, use of co-products, use of biochar, and biochar end-of-life (Fig. 1). These processes consume other industrial products (hereafter called technosphere exchanges), and take up or emit environmental stressors and natural resources (biosphere exchanges).

Biomass production refers to the cultivation and harvest of biomass dedicated for pyrolysis, or to the collection of waste biomass not primarily produced for pyrolysis. Despite the divide between waste and non-waste biomass having unclear or changing boundaries, classifying biomass as waste is often used to justify that biomass allocation to biochar production does not compete with other important uses of land such as food provision. Still, sustainable biomass is a limited resource globally and its allocation for biochar raises the same land use concerns as for any other bioenergy system (European Commission, 2019; Prade et al., 2017). Suitable biomass types are wood-based, crop waste, other grasses, animal manures and biosolids (Ippolito et al., 2020). Assessing the impacts of biomass production (regardless of its final use) is in fact an entire field of LCA research that biochar research can build upon (Caffrey et al., 2013). A specific feature of biochar-biomass systems is the potential feedback loop that may be relevant in some cases, where biochar affects biomass productivity (Woolf et al., 2010).

Biomass conversion refers here to the use of a thermochemical process to produce biochar. Many reactor configurations exist at various scales and can produce pyrolysis products in different proportions and with different properties (Cornelissen et al., 2016; Meyer et al., 2011; Sørmo et al., 2020; Woolf et al., 2014). This includes possible pre- and

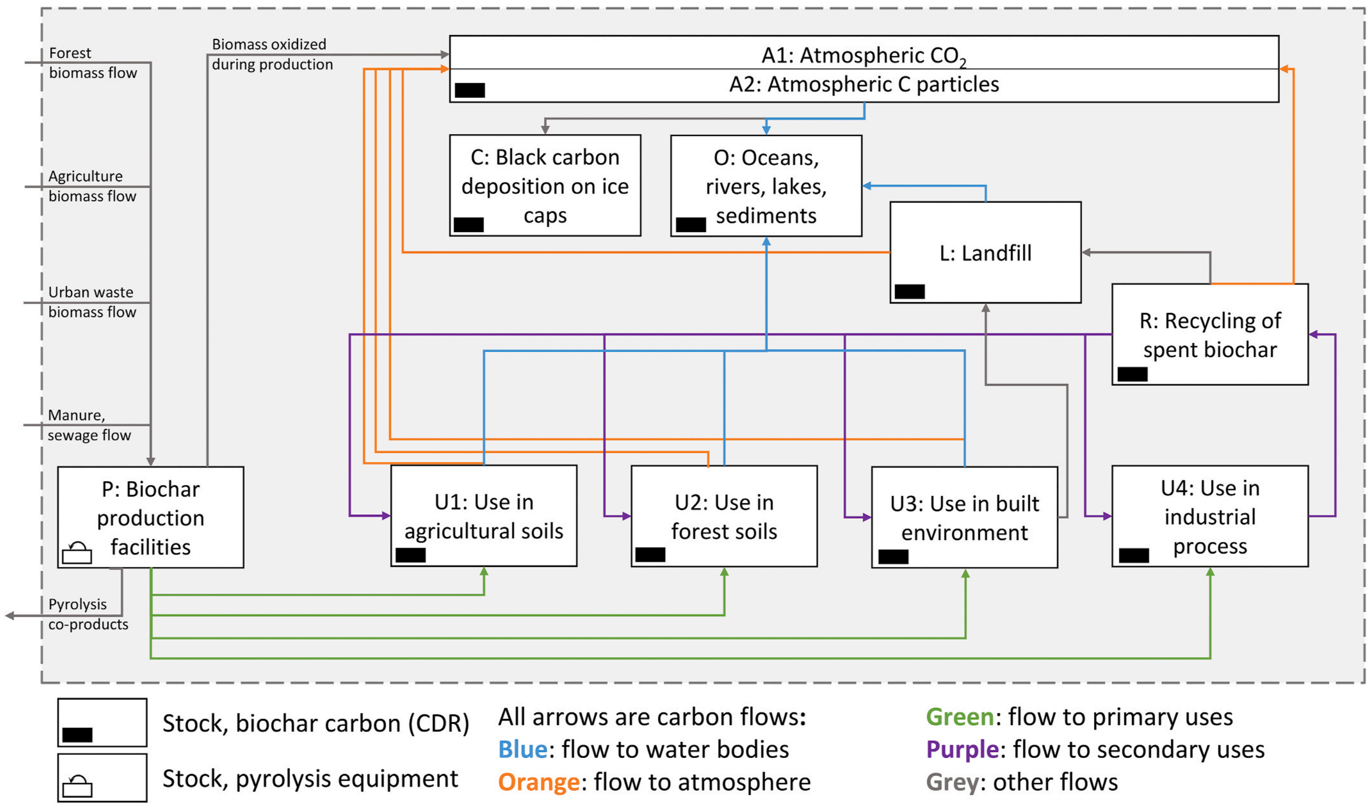

Fig. 2. Conceptual model for biochar carbon accounting during the use phase and end-of-life.

post-treatment of the biomass and the pyrolysis products (e.g. drying, steam activation, gas reforming). From a life cycle perspective, two additional properties differentiate reactors: the manufacturing and decommissioning requirements and the use phase emissions. These can vary substantially, e.g. between flame-curtain kilns (low capital requirement, high emissions) (Cornelissen et al., 2016), cooking stoves (medium capital requirement, medium emissions) (Gitau et al., 2019), pyrolysis plants with advanced combustion chamber (high capital requirement, low emissions) (Sørmo et al., 2020). However, data availability is still limited and no widely-available LCA database includes datasets for pyrolysis.

Co-product use refers to the fate of the pyrolysis gases and tars. They are often co-combusted on-site to provide energy services, including cooking, space heating, and biomass drying (Laird et al., 2009). Production of steam, electricity, and vehicle fuel occurs more seldom. However, materials can also be provided by the pyrolysis tars, especially in fast pyrolysis reactors. From a life cycle perspective, co-product use involves understanding substitution effects on energy systems and other supply chains.

Biochar literature and projects emphasize that biochar has several uses in agriculture (e.g. pure amendment, co-amendments), forestry (e. g. sapling growth substrate), landscaping (e.g. urban greening, remediation, construction materials) and industry (filters, bio-materials) (You et al., 2017), with even possibilities for cascading or sequential uses (Azzi et al., 2019; Wurzer et al., 2019). Biochar use usually extends over longer time scales than co-product uses, as it includes e.g. multi-annual crop effects or urban infrastructure that is likely to remain in place for decades. From a life cycle perspective, the biochar use phase is often included in the life cycle of an existing product or service.

After the use phase, biochar has an end-of-life that differs from other products, for which common end-of-life processes are disposal in landfill, energy recovery or recycling. Biochar placed in a given environmental compartment, at a given time, is subject to chemical transformation like ageing and decomposition (Sorrenti et al., 2016) and transport to other environmental compartments through various processes. This biochar end-of-life, which characterises its CDR function, spans time scales (centuries) that are longer than the time frame of most biochar project and LCA studies. Understanding and mapping the flows and stocks of biochar carbon, across the entire life cycle is of particular importance in accounting of CDR and climate change mitigation measures. It is also important for the broader study of the pyrogenic carbon cycle described by Bird et al. (2015). Attention to date has focused on the recalcitrance of biochar carbon in soils (Leng et al., 2019; Wang et al., 2016), while processes such as erosion, bioturbation, and infiltration are mentioned but rarely studied (Haefele et al., 2011; Jaffe et al., 2013; Kätterer et al., 2019; Major et al., 2010; Schmidt et al., 2019a; Singh et al., 2015; Tisserant and Cherubini, 2019). Sequential or cascading uses of biochar also contribute to dispersion of biochar carbon in the environment. Fig. 2 presents a conceptual model for accounting for biochar carbon stocks and flows, between 4 categories of uses, including potential sequential uses, and making explicit the biochar end-of-life (mineralisation, movement to other pools, and landfill). Various stocks of biochar carbon were identified, which together, constitute the biochar CDR stock (Fig. 2, black boxes).

The main inflow to the CDR stock is production of biochar from various biomass streams. The outflows from the CDR stock are mainly decomposition in soils (agriculture, forest, urban) and partial (or full) oxidation during recycling of biochar from industrial applications. The pathways of biochar movement between pools are numerous: cascading uses, transport to landfills, losses to water bodies and air, and transport to deeper soil horizons. The conceptual model in Fig. 2 can be used quantitatively – for scenario making and environmental modelling, and qualitatively – for supporting analysis of specific biochar systems in terms of material cascade and end-of-life modelling.

3.1.2. *Multi-functionality*

Another characteristic of biochar systems is their multi-functionality, i.e. multiple products and services are delivered to society in the

Table 1
Four type of effects between a process and its reference, for inclusion in environmental life cycle assessment.

Type	Description	Example
I	Changed technosphere inputs	Biochar changes the inputs to an activity, e.g. reduced fertiliser use
II	Changed technosphere outputs	Biochar changes the outputs of an activity, e.g. increased crop harvest
III	Changed biosphere exchange	Biochar provides a change in environmental emissions, e.g. reduced nitrate emissions to surface water
IV	Other: new or altered function, itermediate effect	Biochar provides a new function, modifies the quality of an existing function (e.g. crop quality change), or provides an intermediate effect that leads to a type I-III effect (e.g. soil properties changed resulting in increased crop harvest).

different life cycle stages (Fig. 1). The main functions are: (i) waste treatment services, (ii) energy co-products, (iii) industrial chemical, filter, or construction products, and (iv) soil amendments. Due to their multi-functionality, biochar systems face the same LCA methodological challenges as biorefineries (Ahlgren et al., 2015).

In particular, the choice of functional unit (i.e. the measure of products and services that system must provide) is important for interpretation of the LCA results. The choice of functional unit must be in line with the goal of the study, and will affect how multi-functionality is addressed by focusing the attention on some of the products. The main categories of functional unit used in biorefinery studies are related to: (i) input of biomass, land or waste (e.g. 1 kg of garden waste treated), assessing the best use of that resource; (ii) a single product (e.g. 1 kg of wheat cultivated with biochar, or 1 tree planted with biochar), assessing the impacts related to that product; (iii) the function of a single product (e.g. 1 MJ of nutrition; or 1 square meter year of urban greening), assessing the same issue as in ii); (iv) several products (e.g. 1 MJ heat and 2 kg wheat) or time-based production (e.g. 1 year of operation), assessing the hotspots of the biorefinery or the benefits of process integration (Ahlgren et al., 2015).

3.1.3. References and type of effects

The discourse on biochar effects also involves the notion of a reference situation. It was argued in the definition of biochar effects (section 2.1) that a reference is always necessary. In bioenergy LCAs, for instance, choice of a reference land or biomass use is an important methodological decision (Agostini et al., 2020; Cherubini and Strømman, 2011; Koponen et al., 2018; Soimakallio et al., 2015). Biochar systems do not differ in that respect, and even require the definition of reference activities for the use of each pyrolysis products (Fig. 1). The reference is often implicit, and may mean “without biochar, and doing as usual” (status quo reference) but it can also mean “without biochar, but with an alternative product or process” (alternative reference). Besides, several references can be compared, and they can also vary in time.

Between a process and its reference, life cycle methodology can easily model three types of effects: type I, a difference in technosphere inputs; type II, a difference in technosphere outputs; type III, a difference in biosphere exchanges (Table 1). The terms technosphere and biosphere are employed in classical LCA methodology to mark the boundary between human processes and environmental processes (Weidema et al., 2018). Biochar systems are expected to affect both kind of processes, e.g. the use of biochar in soils modifies biological processes (biosphere) and may affect human management of soil and harvest productivity (technosphere). A fourth effect type (IV) is necessary to describe aspects that are either not captured by the functional unit of an LCA (e.g. new or altered function) or intermediate effects (Table 1). In practice, several effect types can occur simultaneously (see section 3.2.2).

Table 2
Main biochar effects themes identified in the selected literature (see Table S1 in SM). NPP: Net primary productivity.

	This “biochar system” provides carbon dioxide removal (CDR). A side effect is that the “biochar system” also: affects [something]/provides [a function] …	Domains of interest
1	affects soil fluxes	
1.1	- Soil GHG fluxes	Climate
1.2	-Soil nutrient fluxes and efficiencies	Resource, Eutrophication
1.3	- Soil water fluxes and efficiencies	Water
1.4	- Soil radiative (albedo, heat) and particle fluxes (erosion, runoff)	Climate, Air, Water, Health
2	affects soil status or quality or fertility	
2.1	- Physical properties (e.g. density, porosity, structure)	
2.2	- Chemical properties (e.g. pH, redox potential, ion exchange, metal availability)	Soil status
2.3	- Biological properties (e.g. root growth, microbial diversity and functionality, symbiotic N_2 fixation rates)	
3	affects plant or crop productivity, quality and physiology	NPP, Food security, Health
4	affects animal welfare and productivity	Animal, Food security
5	provides soil contamination remediation	Soil status, Land use
6	affects markets for biomass and land (e.g. increase biomass demand leading to land use changes and related impacts)	Land use, Climate
7	affects industrial inputs to agricultural sector (agrochemicals, water, machinery and material, seeds/saplings)	Industry
8	provides substitutes for fossil-based products and other products (e.g. filter, sand, peat)	Industry
9	provides bioenergy and biochemical products from pyrolysis gases and tars (e.g. heat, power, vehicle fuel, lubricants)	Energy, Industry
10	provides biomass waste treatment service (garden waste, agricultural residues) or enhances treatment processes (composting, anaerobic digestion)	Waste, Health, Climate, Industry
11	affects the market for equipment manufacturing (e.g. pyrolysis)	Industry, Mining, Resource depletion

3.2. Biochar effects: overview and evaluation framework

3.2.1. Overview of biochar effects in non-LCA literature

The inventory and classification of biochar effects mentioned in 11 biochar review articles resulted in 12 themes, including CDR (Table 2). Effects 1–5 were related to soils and agricultural productivity. The effects on soil systems were numerous and had to be organised. A distinction between soil fluxes and soil status was made. For soil fluxes, each sub-group related to key domains of interest, e.g. climate change mitigation, water, or nutrient. These are usually key concerns in agricultural LCA and, if quantified, many of these fluxes can be directly used in relevant environmental impact categories (type III effect in Table 1). For soil status, the sub-groups distinguished between the physical, chemical, and biological properties of soils. However, there is no established way of grouping all soil processes and properties (Kuzyakov and Zamanian, 2019) and they cannot be directly related to LCA effect types. Crop and animal productivity effects and land remediation effects are related to biomass production, an end-goal of agriculture. It is worth noting that for effects 3–5, it is not just productivity that matters, but also other factors like plant quality and physiology during growth. Effects 1–5 are inter-related, and further discussed in section 3.2.2. The other effects (6–11) were either related to non-agricultural uses of biochar, or to effects taking place elsewhere in the life cycle of biochar, including market-mediated effects like land use changes.

3.2.2. Biochar use in soil systems

The use of biochar in soils affects several inter-related, time-

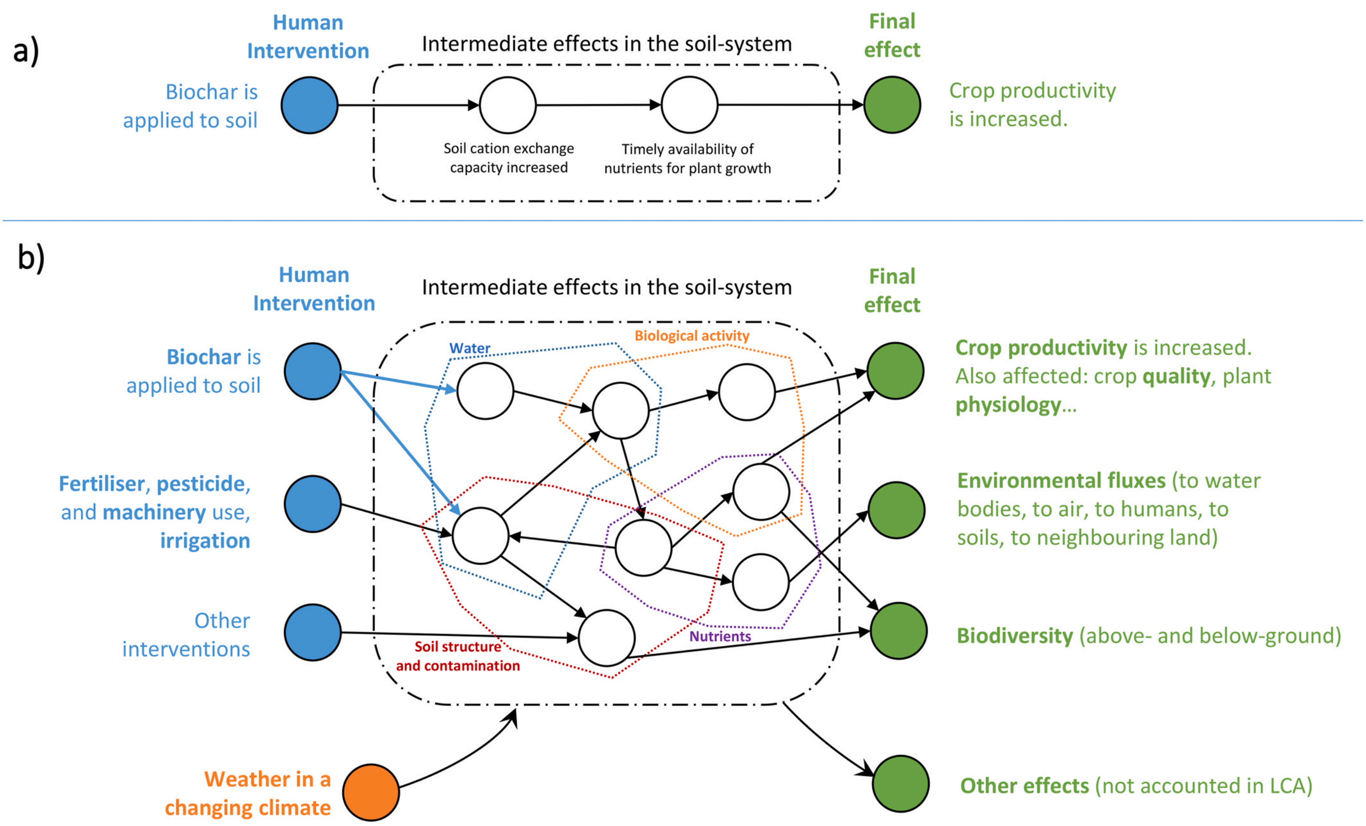

Fig. 3. Conceptualising the complex cause-effect chains of human interventions on soil-systems, and their inclusion in LCA frameworks: a) Simplified single cause-effect chain, with biochar application leading to crop productivity increase; b) More realistic multiple inter-related cause-effect chains, 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.

dependent, and complex processes. However, life cycle thinking is mainly interested in an intervention's final effects, e.g. in terms of productivity changes and environmental emissions (Weidema et al., 2018). Distinguishing between final and intermediate effects in a cause-effect chain is therefore key to categorising the diversity of biochar effects on soils discussed in the literature.

To illustrate, a linear cause-effect chain is presented in Fig. 3a: biochar is amended to a highly weathered soil (intervention), which increases nutrient retention (effect 1). This provides timely availability of nutrients for plant growth (effect 2), and ultimately leads to increased crop harvest (final effect). In soils, cause-effect chains are more complex and have ramifications: in the previous example, nutrient retention changes can also lead to a reduction in N_2O emissions from microbes (second final effect, as it affects GHG balance; not shown in Fig. 3a).

A generalised cause-effect chain is visualised in Fig. 3b: on the *left*, human interventions on soils are listed (e.g. biochar, fertiliser, pesticide, machinery, irrigation); in the *middle*, soil-plant processes are grouped by themes identified in Table 2 (e.g. soil structure, water, nutrient, biological activity; themes can overlap); on the *right*, possible final effects are listed according to types identified in Table 1; and finally *below*, the influence of weather in a changing climate is depicted. The cause-effect chain in Fig. 3b has to be interpreted as a complex system: all processes (circles) may vary in time, and the links between them (arrows) may generate feedback loops and non-linear behaviours (Sierra et al., 2018).

With Fig. 3b in mind, two remarks for the assessment of biochar effects on soil-systems in LCA are made: (i) complexity is in practice bypassed through the use of empirical models; and (ii) many biochar effects can be expressed in terms of the soil's future productivity in specific situations.

Bypassing complexity through empirical models: One way to include a biochar effect while avoiding the complexity of soil science is to use controlled experiments, i.e. experiments where the intervention and several parameters are carefully measured. These empirical results can then be used in modelling of final effects, but are also useful for advancing understanding of the processes involved. Numerous empirical studies have been performed on biochar, as summarised in insightful meta-analyses and reviews.[4] These studies covered in particular soil-plant GHG, nutrient and water fluxes (e.g. Borchard et al., 2019b; Cayuela et al., 2015; 2014; Glaser and Lehr, 2019; Jeffery et al., 2016; Liu et al., 2016; Razzaghi et al., 2019; Song et al., 2016); and crop and animal productivity (e.g. Jeffery et al., 2016; 2011; Man et al., 2020; Schmidt et al., 2019b). However, for use in LCA, available empirical results are always limited in space and time, so results obtained in one region often have to be extrapolated to other regions. Likewise, effects measured over one or two harvests may be extrapolated to longer times, if effects are assumed to persist. Therefore, assumptions need to be made in LCA, and their validity and importance verified by sensitivity analysis.

Accounting for future soil productivity: many of the reported biochar effects on soil, such as adaptation to a changing climate, resilience to drought, or maintenance of soil fertility against some unspecified degradation mechanism (e.g. soil acidification), are related to future changes in soil productivity measured against a reference situation (Jeffery et al., 2017; Jin et al., 2019; Latawiec et al., 2019; Shin et al., 2019). Accounting for future soil productivity induced by biochar first requires an assumption on the duration of the effect. Effect duration can be shorter (e.g. liming), equal to (e.g. water holding capacity), or longer than (e.g. metal contamination) the duration of the biochar's presence in

[4] The following Scopus request returned 747 documents [2020-12-14]: TITLE-ABS-KEY (biochar) AND (LIMIT-TO (DOCTYPE, "re")).

the soil. Second, the reference situation has to be modelled explicitly over the duration of the effect: the reference can be static (i.e. equal to the initial situation for the duration of the effect) or dynamic (e.g. including effects of a changing climate, including agroecosystem degradation; calculation example in SM). In any case, the choice of reference has to be justified by supporting data or models.

3.2.3. Biochar effects modelled in LCA studies

An extensive list of 45 biochar LCA studies were analysed in order to identify the biochar effects most commonly included in LCA modelling (Table 3, Table S2 in SM).

Nearly all studies included biochar carbon sequestration. As highlighted by Tisserant and Cherubini (2019), biochar carbon sequestration often appears as a large contributor to the climate change score of biochar systems, unless special feedstocks or thermochemical processes are used (e.g. manure, sludge, hydrothermal carbonisation). Use of pyrolysis co-products was modelled most often as heat or power offsets, and more rarely as fuel or chemical substitution. Ten studies did not include energy offsets either because the functional unit was an energy unit (1 case), co-products were not recovered (2 cases), or co-product use was out-of-scope (7 cases). A quarter of the studies accounted for air emissions occurring during pyrolysis relative to a reference biomass fate. Land use changes (direct and indirect) were rarely included, often because the biomass was qualified as secondary or waste. Finally, climate change impact was the most commonly used impact category. Only a handful of studies included several environmental impact categories.

The nature of the effects modelled was, obviously, dependent on the systems studied and the choice of impact categories. Most studies had an agricultural use of biochar, while some also considered its use as a fuel in sub-scenarios, but only a few studies considered biochar use as a material outside of agriculture (e.g. urban uses). In agriculture, the most commonly modelled effects were fertiliser use reductions, and changes in N_2O and CH_4 soil emissions. Nearly as many studies decided 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 modelled biochar effects on biodiversity.

Further analysis of subsets of these LCAs is available in two reviews, focusing on more conventional LCA aspects (e.g. functional unit, system boundaries, reference system, feedstock type) (Matuštík et al., 2020; Tisserant and Cherubini, 2019).

Table 3
Biochar effects most commonly included in a set of 45 biochar LCA studies (see Table S2 in SM). 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.

Effect description	Count	Effect no. in Table 2
Effects included		
CDR: Biochar C sequestration	43	0
Co-products: avoided heat/power from other fuel	35	9
Agriculture: fertiliser use reduction	19	1.2; 7
Agriculture: soil N_2O emission reduction	19	1.1
Pyrolysis: air emissions, relative to reference biomass/ land use	12	6; 10
Agriculture: crop harvest increase	10	3
Agriculture: biochar induced SOC change (priming, NPP increase)	7	1.1; 3
Agriculture: soil CH_4 emissions change	7	1.1
Agriculture: avoided nutrient leaching to water	5	1.2; 3
Reference biomass/land: land use change emissions	5	6
Agriculture: avoided limestone production and use	3	1.1; 7
Soil toxicity: reduced heavy metal mobility	2	5
Agriculture: avoided peat use	1	8
Agriculture: CH_4/N_2O/Nutrient flux change in animal husbandry	1	4
Agriculture: soil albedo changes	1	1.4
Other substitutions: clay/gravel/backfill material/ landfill space	1	8
None[a]	1	NA
Effect explicitly not included in the LCA[b]		
Agriculture: crop/NPP/SOC increase	8	3
Other substitutions: clay/gravel landfill cover substitution	1	8
Agriculture: soil N_2O emission reduction	1	1.1
Other		
Sensitivity on persistence of biochar effects over time	3	NA

[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.

3.2.4. Evaluation framework

Based on the description of biochar systems and the review of biochar effects, an evaluation framework for biochar effects was developed (Fig. 4). The purpose is to provide guidance for systematic evaluation of biochar effects.

The first phase (system definition) is based on the general description of biochar systems provided in section 3 (Figs. 1 and 2). In the second phase (effect analysis), potential biochar effects are screened. Then, for each effect, a detailed analysis is made. This begins by identifying the relevant life cycle stage (LCS, using Fig. 1) and life cycle effect type (LCT, using Table 1). Depending on the LCT, the way of including the effect in LCA varies. If the LCT is unclear or relates to an unquantified change of function, it may be useful to analyse the cause-effect chain more carefully. This process can be iterative, in the sense that a potential effect may be split into several clearly defined final effects, while intermediate effects are left out. The analysis continues with the description of knowledge levels. Ideally, specific data and models are available. Otherwise, one can resort to empirical or explorative models and pick data from meta-analyses.

By the end of the analysis, each effect is categorised according to the life cycle stage, type of effect, relevant impact categories, and knowledge level. From there, the analyst can proceed with the environmental assessment of the biochar system.

3.3. Case study: Stockholm Biochar Project

The effect evaluation framework was applied to the Stockholm Biochar Project, with the goal of collecting Stockholm-specific data for LCA of the project encompassing several impact categories beside climate change.

The main processes, the reference processes, and the functions delivered were specified (Fig. 5). The functions delivered were: (i) treatment of garden waste; (ii) district heating production; (iii) trees planted in constructed soil; and (iv) stormwater treated in constructed soil. Several observations can already be made at this stage. First, several options are possible for the reference tree planting process: planting a tree in a conventional way (without structural soil, thus not solving compaction problems), or planting a tree in a structured soil but with conventional soil substrates (peat instead of biochar). The latter was chosen, to separate biochar effects from structural soil effects. Second, the reference fate of biomass (combustion in an incinerator, co-producing heat and power) and the reference heat production activity (woodchip combustion in combined heat and power plant) are linked in this case since they provide the same product (heat in Stockholm). Third, it appears that these two reference processes are also multi-functional (power and heat co-generation) and that solving this multi-functionality would be necessary in a complete assessment (depending on the choice of functional unit). Finally, the biochar's end-of-life is uncertain. Across the lifetime of urban tree planting, i.e. several decades,

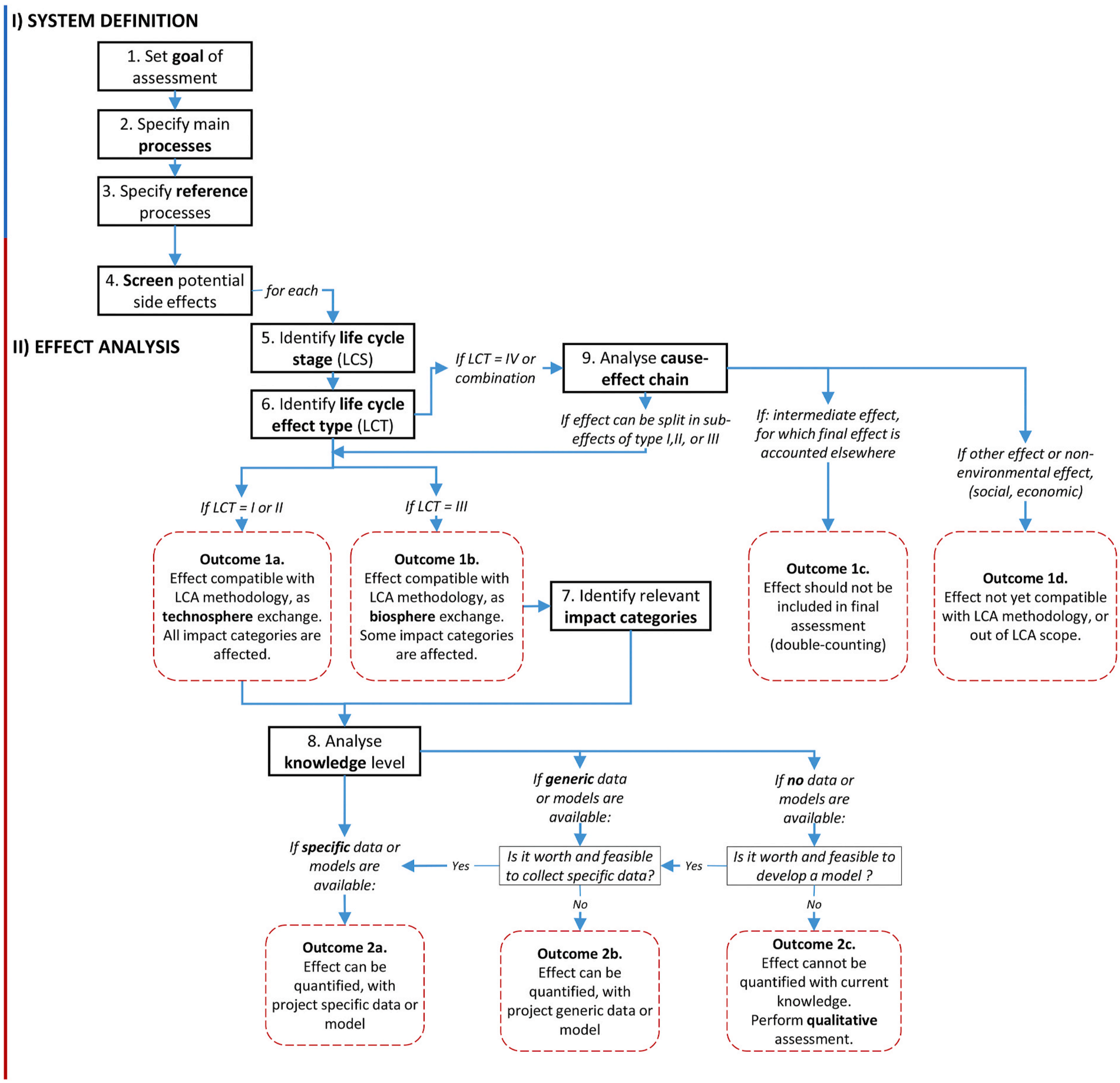

Fig. 4. Evaluation framework for biochar system effects.

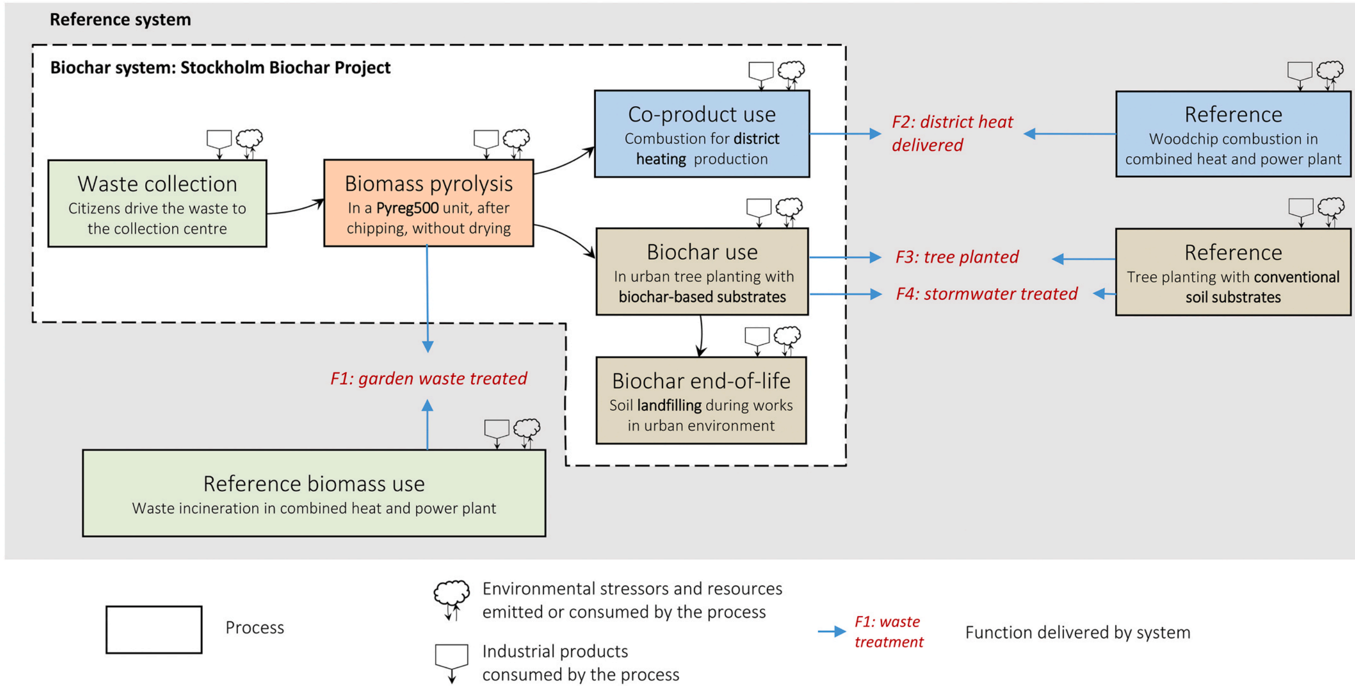

Fig. 5. System boundaries and reference system for the Stockholm Biochar Project.

biochar losses to water bodies may occur (especially via the stormwater management system) and disturbances may occur during construction and maintenance works, eventually leading to landfill of soil masses amended with biochar or their re-use on other sites.

When it comes to the biochar effects, 18 items were identified thanks to the knowledge of three stakeholders, and then analysed through the evaluation framework (Fig. 4, Table S3 in SM).

All LCSs were represented by at least one biochar effect. However, most effects occurred during the biochar use phase and were related to tree and soil health. One feedback loop was mentioned: biochar improving tree growth potentially led to higher amounts of garden waste to be treated, but the effect remained unquantified. One social effect, awareness rising among citizens about biochar and CDR technologies, was disregarded, but can play a role in acceptance of CDR (Nemet et al., 2018).

All LCTs were represented. The iterative process and the cause-effect chain analysis allowed subdivision of some type IV effects into several individual effects of type I, II or III. Remaining type IV effects were biodiversity changes (which could also be considered type III, but are not yet mainstream in LCA), some intermediate soil processes related to plant water stress (linked to plant growth), an insurance product (avoided flood damage), and a local climate effect (reduced urban heat-island).

Impact categories: all environmental impact categories were affected due to the presence of type I and II effects. Impact categories of particular interest through type III effects were: eutrophication, air pollution, and climate change.

Knowledge levels: overall, it is unlikely that generic data can be found in the literature to model the specific biochar effects of SBP. Some information may be found in the statistics and inventories of the city department in charge of urban greening, e.g. for soil substrate consumption. For soil-related effects, there is a need for documented controlled experiments on different tree planting techniques. Future effects such as avoided damage from flood events remain explorative.

4. Discussion

4.1. Life cycle thinking relevant beyond LCA

This work was focused on LCA and the biochar effects were studied from an environmental-physical perspective. LCA is a widely accepted and recognised tool to provide understanding of environmental impacts, hotspots, and burden shifts (Finnveden et al., 2009). Understanding the physical flows that characterise biochar effects is also the first step for their quantitative assessment in LCA. Life cycle thinking is also relevant for decision-makers in general, as having a physical-environmental understanding of the biochar system, over its entire life cycle, is a sound basis for other types of analysis and assessment, including translation of biochar effects into monetary terms (Whitman et al., 2010). Understanding biochar carbon flows in the environment after application to soil is needed when designing monitoring, reporting, and verification schemes for biochar carbon credits or similar incentives (Whitman et al., 2010). Likewise, in the Stockholm Biochar Project, tree health effects may be valued in cost-benefit analysis.

4.2. Biochar effects in soil systems

The challenge when including biochar effects on soils in LCA is to identify and quantify relevant changes in technosphere or biosphere exchanges. This is difficult to do *a priori*, and differs with the type of soil system analysed. Indeed, biochar can be used in different soil systems with their own specificities and constraints, e.g.- arable land, forest soil (Mohammadi et al., 2019), soil substrate in nurseries (e.g. pine tree sapling production, plant production) (Nair et al., 2017), soil substrate in greenhouses (Fryda et al., 2019), and contaminated soil (Fellet et al., 2011). The challenge may be addressed by identifying the limiting factors of productivity in a given soil-system and then considering biochar effects which may be useful in overcoming these limiting factors (problem-solving approach). Tisserant and Cherubini (2019) provide a helpful list of factors explaining various biochar soil effects.

4.3. Biochar's end-of-life

While biochar carbon mineralisation in soil has been studied rather extensively and included in all biochar LCAs (Table 3), the movement of biochar between environmental compartments is less understood, not modelled in LCA, and rarely discussed in policy (Bird et al., 2015). Fig. 2 presented a generic representation of these carbon flows to encourage discussion and modelling. This is important for several reasons: (i) in terms of CDR, biochar mineralisation rates may not be the same in all environmental compartments; (ii) in terms of monitoring, reporting and verification of biochar carbon credits, movement of biochar to deeper soil horizons, other soils and water bodies may need to be accounted for and has been shown to be significant in some cases (Haefele et al., 2011; Kätterer et al., 2019; Major et al., 2010; Singh et al., 2015); and (iii) in terms of biochar effects in soils, the duration of most effects is limited by biochar presence in the soil. Biochar movement between environmental compartments can be expected to be highly site- and time-dependent, and the dominant mechanisms to model may depend on the time-scale analysed. Modelling does not need to start from scratch, however, as knowledge from soil organic carbon and pyrogenic carbon transport can be a starting point (Abiven and Santín, 2019; Güereña et al., 2015; Jones et al., 2019). Regionalised and time-dependent LCA may be relevant for inclusion of such modelling results (Mutel et al., 2012; Verones et al., 2020).

4.4. Inclusion of biochar effects in LCA

As mentioned in section 3.2.3, many biochar LCA studies were limited to climate change impacts. Some biochar effects in agriculture were modelled for their role in climate change mitigation (Table 3) but are also relevant for other environmental impact categories, e.g. eutrophication (Shin et al., 2019). Selecting several impact categories beyond climate change is therefore a first simple measure to better represent biochar effects in LCA. In addition, some biochar effects persist over time. More explicit assumptions and sensitivity analysis could be made on the duration of biochar effects. This was not commonly performed in the reviewed studies (Table 3), which differs for instance from common practice in cost-benefit and economic analyses were future benefits are accounted for (although discounted) (Dickinson et al., 2015). Finally, other biochar-induced changes in soil status (Table 2) are rather difficult to include in LCA without extensive modelling, as they need to be converted into some final effect, e.g. biosphere exchange or future productivity change.

5. Conclusion

An analysis of biochar systems was performed to clarify the discourse on biochar side effects to CDR. An evaluation framework grounded in LCA theory was developed and applied to the Stockholm Biochar Project. The framework's main focus was on qualitatively classifying biochar effects according to life cycle stage and life cycle effect type, and on making the biochar end-of-life and the reference situation explicit. Three types of effects were easily included in the LCA framework: changes in biosphere exchanges, technosphere inputs, and technosphere outputs. For effects that are difficult to classify, analysing the cause-effect chain may be helpful. Several biochar effects in soils can be modelled as future productivity increases against a static or dynamic reference. Biochar life cycle studies have often been limited to carbon footprint calculations and a limited number of biochar effects, mainly carbon sequestration, energy displacements and fertiliser-related emissions. Life cycle thinking is a relevant approach for systematic evaluation of biochar projects. The comprehensive but qualitative framework developed here provides preliminary guidance for decision-makers. Future developments of the framework could e.g. have a quantitative assessment of biochar-soil interactions and their effects.

CRediT roles

Elias S. Azzi: Conceptualization, Investigation, Methodology, Writing - original draft, Writing - review & editing, Erik Karltun: Investigation, Supervision, Writing - review & editing, Cecilia Sundberg: Conceptualization, Investigation, Supervision, Writing - review & editing, Funding acquisition.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.112154.

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