Time-dependent climate impact and energy efficiency of combined heat and power production from short-rotation coppice willow using pyrolysis or direct combustion

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Abstract

A life cycle assessment of a Swedish short-rotation coppice willow bioenergy system generating electricity and heat was performed to investigate how the energy efficiency and time-dependent climate impact were affected when the feedstock was converted into bio-oil and char before generating electricity and heat, compared with being combusted directly. The study also investigated how the climate impact was affected when part of the char was applied to soil as biochar to act as a carbon sequestration agent and potential soil improver. The energy efficiencies were calculated separately for electricity and heat as the energy ratios between the amount of energy service delivered by the system compared to the amount of external energy inputs used in each scenario after having allocated the primary energy related to the inputs between the two energy services. The energy in the feedstock was not included in the external energy inputs. Direct combustion had the highest energy efficiency. It had energy ratios of 10 and 36 for electricity and heat, respectively. The least energy-efficient scenario was the pyrolysis scenario where biochar was applied to soils. It had energy ratios of 4 and 12 for electricity and heat, respectively. The results showed that pyrolysis with carbon sequestration might be an option to counteract the current trend in global warming. The pyrolysis system with soil application of the biochar removed the largest amount of CO$_2$ from the atmosphere. However, compared with the direct combustion scenario, the climate change mitigation potential depended on the energy system to which the bioenergy system delivered its energy services. A system expansion showed that direct combustion had the highest climate change mitigation potential when coal or natural gas were used as external energy sources to compensate for the lower energy efficiency of the pyrolysis scenario.

Keywords: biochar, climate impact metrics, land use change, LCA, pyrolysis, Salix, soil organic carbon, SRC, willow

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Introduction

Climate change is a natural phenomenon that can be observed in paleoclimate records stretching back millions of years in time (Hansen and Sato, 2012). However, the rate at which the temperature has changed since the mid-20th century is unprecedented in modern human history. The major part of this change can be attributed to increased concentrations of carbon dioxide (CO$_2$) and other greenhouse gases (GHG) in the atmosphere. The use of fossil resources has historically contributed approximately 75% of the anthropogenic emissions of CO$_2$, while land use change is responsible for the remainder (Denman et al., 2007). Reducing the use of fossil resources and reversing the trend of carbon (C) losses from soils are two important steps to prevent further temperature increase.

Biomass can be used to replace fossil fuels and is a major source of renewable energy in Sweden, corresponding to 23% of the total energy supplied to the Swedish energy system in 2013 (Swedish Energy Agency, 2015). It can be used as fuel in combined heat and power (CHP) plants for the simultaneous generation of electricity and heat. Cogeneration of electricity and heat is an energy-efficient use of the feedstock in the Nordic climate due to the relatively high heat demand.

Biomass can be pretreated in a decentralized way using pyrolysis to improve its storage and handling properties. Pyrolysis is a thermochemical process in which the biomass is converted into bio-oil, noncondensable gases and char at temperatures between 300 and 800 °C (Brown, 2011). All three product fractions can be used for energy service generation, both on site or at a centralized CHP. Char from pyrolysis has also received attention due to its agronomic properties (Sohi et al., 2010) and recalcitrance when applied to soils (Liang et al., 2008). In this context, it is commonly
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referred to as biochar. Biochar can be a potential soil improver and C sequestration agent. Application of biochar to arable soils has been suggested as a way to counteract the effects of GHG emissions (Gaunt and Lehmann, 2008). There is, however, a trade-off between the use of char for energy service generation and for C sequestration, as biochar (Pourhashem et al., 2013). Furthermore, the biomass can also be used as raw material for nonenergy products where it can replace fossil sources (Gallezot, 2012). This creates a situation with multiple trade-offs in which the function of the product cannot always be used to compare the climate impact of land use systems.

The advantages of pretreating biomass with pyrolysis could benefit short-rotation coppice (SRC) willow bioenergy systems, as the raw biomass is wet, bulky and biologically active (Noll and Jirjis, 2012). Willow is a fast-growing, high-yielding, lignocellulosic plant species that can be readily used for cofiring with other biomass in existing CHP plants. It has been established on more than 14,000 ha of land in Sweden since the 1980s. In Sweden, large agricultural areas are not being used for productive purposes (SJH, 2008). A large share of these are unused cropland and excess grassland. Using part of this land for energy crop production could offer both an extra source of income to farmers and increase the share of renewable electricity and heat in the Swedish energy system.

The environmental sustainability of bioenergy systems is often assessed using life cycle assessment (LCA) methodology (ISO 14040, 2006; ISO 14044, 2006). The climate impact is commonly characterized in LCA using the global warming potential (GWP) (IPCC, 1991). Common LCA practice is to multiply the net life cycle emission of different GHGs with their respective characterization factor (CF), after which they are summed to calculate the total climate impact of the system. To derive the CFs, it is necessary to choose a time horizon over which the impacts are being assessed. There are two issues related to time inherent in this way of determining the climate impact: (i) it disregards when the impact actually takes place, treating all emissions as if they were emitted at the beginning of the assessment period (Peters et al., 2011), and (ii) the choice of time horizon is inherently subjective and effects the relative weight between different GHGs (Fuglestvedt et al., 2010). As a direct consequence of the modelling choice, a CF derived this way cannot possibly capture any impact from time-variable GHG fluxes where the net emission is 0 (Cherubini et al., 2011). The timing of emission may affect the evaluation of bioenergy systems from a climate impact perspective (e.g. Kendall et al., 2009; O’Hare et al., 2009; Levasseur et al., 2010).

There are several approaches for including timing of emissions in bioenergy scenarios in LCAs (e.g. Zetterberg et al., 2004; Levasseur et al., 2010; Kendall, 2012; Porsø et al., 2016; Pourhashem et al., 2016). All approaches include a characterization model which converts the emissions to climate impacts. To be able to describe time-dependent impacts, it is necessary to record the timing of emissions in a time-distributed inventory. The impacts can then be described either by introducing a time-dependent weighting function in the elaboration of the CFs (e.g. Courchesne et al., 2010; Levasseur et al., 2010; Kendall, 2012) or through the use of a time-dependent indicator (e.g. Zetterberg et al., 2004; Peters et al., 2011; Pourhashem et al., 2016). The use of an absolute, instantaneous and time-dependent indicator can compliment the use of CFs in LCA as they contribute to information on both timing and rate of change, as well as provide a visual representation of how the climate impact evolves over time.

A common indicator to describe the time-dependent climate impact is the radiative forcing (RF), which describes a perturbation in the earth’s energy balance due to the emission or removal of a climate forcer (Fuglestvedt et al., 2003). The global mean surface temperature change (ΔTS) can also be used for this purpose. Peters et al. (2011) compared the use of RF to ΔTS as time-dependent indicators in an LCA of different transportation modes, showing differences in the timing and rate of change between the two impact indicators. These differences are due to the inertia of the climate system which delays the response in ΔTS from a perturbation of the radiative balance when heat is being exchanged between the atmosphere and terrestrial sinks, especially the deep oceans (Berntsen and Fuglestvedt, 2008).

A few studies have used ΔTS as an indicator for the time-dependent climate impacts of bioenergy systems (e.g. Cherubini et al., 2013; Ericsson et al., 2013, 2014; Hammar et al., 2014, 2015; Giuntoli et al., 2015; Ortiz et al., 2016; Porsø et al., 2016), but to our knowledge, no such study has been presented on pyrolysis-based bioenergy systems. However, several authors have investigated the climate impact and energy efficiency of pyrolysis-based bioenergy systems from a life cycle perspective based on GWP (Gaunt and Lehmann, 2008; Roberts et al., 2010; Hammond et al., 2011; Hanandeh, 2012; Ibarrola et al., 2012; Wang et al., 2013; Peters et al., 2015; Thornley et al., 2015). The biochar has been observed to have a large impact on the results in these studies.

Prior research (Ericsson et al., 2014) examined the time-dependent impacts from C returned to the field in an anaerobic digestion-based bioenergy system. They were observed to be large and act at a different
time scale than the impacts of other biogenic C stock changes and GHGs in the system. Similar effects can be expected in pyrolysis-based bioenergy systems where biochar is applied to soils. Furthermore, the biochar-energy trade-off can be expected to vary with time as the biochar will slowly decay once applied to soils.

The aim of this study was to improve the understanding of the time-dependent climate impact and its relation to the energy efficiency in willow-based bioenergy systems generating electricity and heat, with and without the production of biochar for C sequestration in soils. To achieve this, a case study focusing on a Swedish willow plantation used for electricity and heat generation was conducted and the time-dependent climate impact was determined using $\Delta T_5$ as an instantaneous and time-variable indicator. Both decentralized pretreatment with pyrolysis before energy service generation and direct combustion of the willow feedstock were considered. The char from the pyrolysis process was used either for energy service generation or as biochar through soil application. The multiple use of biomass in nonenergetic sectors was also considered by including two different functional units in the assessment: one output based that permits a fair assessment of energy systems and one input based that enables the comparison of systems having products that cannot be compared based on functional equivalence.

### Materials and methods

#### Scenarios and methodology

Life cycle assessment (ISO 14040, 2006; ISO 14044, 2006) was used to analyse the climate impact and energy efficiency of a bioenergy system generating electricity and heat from SRC willow feedstock. The electricity and heat were assumed to be fed into the electric grid and a local district heating (DH) system, respectively.

The impact on climate change was assessed with time-dependent climate impact methodology (Ericsson et al., 2013), using the contribution to $\Delta T_5(n)$ from each scenario as an indicator of the climate impact.

A 60 hectare (ha) SRC willow plantation was modelled to determine the annual net GHG emissions from the feedstock production system. All emissions related to the production of the biomass, feedstock conversion, transportation and final energy service generation were recorded in a time-distributed life cycle inventory. In this inventory, the net emissions of GHGs were recorded for each year of the study period. The change in atmospheric CO2 levels due to carbon stock changes in the live biomass, the SOC and the biochar pools was included in the assessment. Carbon taken up by growing biomass was recalculated to CO2 and recorded as negative emissions in the inventory.

Two feedstock conversion scenarios, pyrolysis and direct combustion, were compared with a reference scenario where natural gas was used in a large-scale CHP to generate the same amount of electricity and heat as in the most energy-efficient bioenergy scenario (Fig. 1). The pyrolysis scenario consisted of...
two cases, where alternative end use of the produced char was considered: using the char as biochar, i.e. applying it to the soil where it acted as a carbon sequestration agent, or using the char to generate energy services in a large-scale CHP.

- Scenario 1: The willow feedstock was pyrolyzed at the farm to generate bio-oil and char. The bio-oil fraction was then transported to a large-scale CHP, where it was co-combusted with heavy fuel oil to generate electricity and heat. The two end uses of the char were as follows:
  (a) Biochar-to-soil: The biochar was returned to the soil of the willow plantation to act as a carbon sequestration agent and potential soil improver.
  (b) Char-for-energy: The char was transported to a large-scale CHP plant where it was co-combusted with biomass in a biomass boiler to generate electricity and heat.
- Scenario 2: The willow feedstock was transported, without pretreatment to a large-scale CHP plant, where it was co-combusted with biomass of other origin to generate electricity and heat.
- Scenario 3: In the reference scenario, the same amount of electricity and heat as in the most energy-efficient scenario was generated in a combined cycle natural gas (NG)-fed CHP plant.

The CHP plants in scenario 1 and scenario 2 were assumed to use back-pressure steam turbines, having a power-to-heat ratio of 0.45, while the combined cycle CHP plant in scenario 3 was assumed to have a power-to-heat ratio of 0.95 (EU, 2012).

**Scope.** The assessment included the three major GHGs contributing to global warming: CO$_2$, nitrous oxide (N$_2$O) and methane (CH$_4$).

The primary energy use and emissions from all stages of production were included within the system boundaries. Production stages included were cultivation and harvesting of the willow feedstock, preprocessing and pyrolysis, transportation of the raw biomass and pyrolysis products as well as electricity and heat generation. The return transport of bottom ashes generated at the CHP plant as well as the biochar produced in the pyrolysis plant and their application to the soil were also included within the system boundaries. Handling of the fly ash was not included in the inventory as it cannot be used on productive land due to its possibly high heavy metal content. The handling and deposition of the relatively small amount of fly ash and flue gas cleaning residue generated were assumed not to contribute significantly to the climate impact and energy use in the studied scenarios.

Activities and losses associated with the distribution and use of the generated electricity and heat, after being fed into the electric grid and DH distribution system, were not included within the system boundaries.

The construction and decommissioning of the capital goods were not included in any of the scenarios as it has been shown in environmental product declarations (EPD) that infrastructure is responsible for <2% of the GHG emissions associated with the energy services generated in similar CHPs (EPD, 2013, 2015), without taking biogenic C stock changes into account. The authors are not aware of any EPDs on pyrolysis systems, but previous studies have shown that contribution from the biogenic C stock changes dominates the climate impact in similar SRC bioenergy systems (Ericsson et al., 2013, 2014). It was therefore assumed that the contribution from the capital goods in this case would not significantly change the relative outcome of the comparison between the scenarios.

Electricity used for preprocessing of the biomass and operation of the pyrolysis plant was assumed to be taken from the grid. Net energy delivered in scenario 1 was calculated by subtracting this amount of electricity, including distribution losses of an additional 7.5% for the used electricity (Gode et al., 2011), from the gross electricity delivered to the grid.

**Functional units.** The climate impact from different scenarios might depend on the function of the system and the consequential functional unit (FU) used. The goal of the LCA was twofold: on the one hand, it aims to guide decisions on the use of willow biomass in order to mitigate climate change, and on the other hand, it aims to provide information on climate impacts as a consequence of the use of land.

In this study, the SRC willow-based bioenergy system was considered to have two functions. Generation of electricity and heat was the main function of the system. It could also serve the important function of mitigating climate impact by representing an optional land management that may potentially act as a carbon sink, independent of its function as an energy system. This later function is rather related to the system using land, where energy generation is but one of many optional uses.

Using an energy service as the FU describes the relative impact of the electricity or heat compared with that of other sources. It is a relevant FU when assessing the impacts caused by consumption of the delivered energy. The relative land use efficiency of the system can be described by relating the results to the area used to produce the willow feedstock for the electricity and heat generation. Such a FU may be better suited when land is a restricted resource, and the focus is to assess the climate and energy benefits from different types of land use.

When using an energy service as the FU, the amount of energy delivered from the system has to be equal in all scenarios. The energy delivered can be made equal in all scenarios using system expansion. System expansion is, however, not performed when land use is the FU, as the main function considered in this case is not that of generating energy, but the use of land. The amount of land used therefore has to be the same in all scenarios, while the amount of delivered energy might be different. This may lead to differences in the relative climate change mitigation potential between scenarios when different FUs are being used.

As neither of these two functions can be said to be more important a priori when assessing the climate impact and energy efficiency of a system, both the area and the energy services were used as FUs in this study. One hectare of willow cultivation was chosen to represent the area, while 1 kWh of electricity delivered to the grid and 1 MJ of heat delivered to...
the local district heating (DH) system were used to represent the energy services.

**External energy service generation.** Scenarios 1 and 2 were expected to deliver different amounts of electricity and heat from the same amount of feedstock due to the extra conversion step introduced in the pyrolysis process. The climate impact could therefore not be directly compared without taking the energy efficiency into account.

The reference flows were made equal in all scenarios using true system expansion when assessing the climate impact per kWh of electricity and per MJ of heat. The amounts of electricity and heat per ha of land were made equal in all scenarios by adding electricity and heat to the less energy-efficient scenarios. These scenarios were assigned emissions and primary energy use from external energy service generation, taking place outside the system (Fig. 2), hereafter referred to as external energy sources.

This method of system expansion differs from that recommended in the ISO standard (ISO 14044, 2006), which subtracts avoided emissions from the more energy-efficient system. The choice of method does not affect the relative comparison between different scenarios in a specific study. The only visible difference is that the absolute values appear smaller for all scenarios when the ISO method is used, as it credits the more energy-efficient system with avoided emissions rather than penalizing the less efficient system with indirect emissions.

The effect of the choice of energy sources on the climate impact and energy efficiency of the electricity and heat was investigated in scenario 1. The external energy sources compared were cogenerated electricity and heat from NG- and hard coal (HC)-fuelled CHP plants, electricity from wind power (WP) and heat from household waste (HHW).

All CHP plants were assumed to have a total energy efficiency of 90% (lower heating value, LHV). The NG plant was assumed to use the same technology as in scenario 3. The HC plant was assumed to use a back-pressure steam turbine with a power-to-heat ratio of 0.45 (EU, 2012). The HHW boiler was assumed to have a heat efficiency of 0.8. The primary energy factors, energy ratios and GWP$_{100}$ of the external energy sources can be found in the (Appendix S1: Table S1).

**Allocation between electricity and heat.** Electricity and heat represent two different types of energy services which can be generated independently of each other and fulfill different functions. In this study, the emissions and primary energy (PE) were therefore allocated between them to make the results comparable to other studies of electricity and/or heat generation.

The separate production reference method was used to perform the allocation (Beretta et al., 2012; Swedenergy, 2012) Eqn (1). According to this method, the allocation (a) between electricity and heat is different for different fuels (i). It is affected by the relative amount of electricity and heat generated at the CHP plant ($E_w$, $x$:electricity or heat), without including flue gas condensation or internal electricity demand. It is also affected by the efficiency by which electricity and heat can be generated separately, using the same fuel, at stand-alone power-only ($g_{el}$) and heat-only plants ($g_{heat}$), optimized to generate as much electricity and heat as possible, respectively.

Fig. 2 Energy service generation per ha was made equal in all scenarios using system expansion. Electricity and heat generated by external sources were added to scenario 1. It was assigned the primary energy and GHG emissions associated with this energy. Dashed dark boxes represent the external sources of electricity and heat.
Harmonized efficiency reference values \( \eta_{\text{ref}} \) for the separate production of electricity and heat from representative fuels were taken from EU (2011). Bio-oil and biochar are not present among the representative fuels. In this study, the harmonized efficiency reference value for wood fuels was used to represent the bio-oil, and the reference value for lignite was used to represent the biochar. In all cases, values for heat generation using steam/hot water were used. The harmonized efficiency reference values and allocation factors used in this study can be found in the (Appendix S2: Tables S2 and S3).

System description

Cultivation system. The SRC willow plantation was assumed to be established on set-aside agricultural land in central Sweden that had been under fallow for a period of 20 years. The rotation period of the willow plantation was 25 years, including eight subsequent 3-year coppicing cycles and 1 year of annual crops between each rotation to reduce pressure from perennial weeds. The activities associated with this year were not included in the bioenergy scenarios, as nonbioenergy goods were produced. One-third of the total area was established each year during the first 3 years, giving the total study period a length of 53 years. All coppicing cycles, except the first, were expected to yield 30 t dry matter (DM) per ha at harvest. This corresponds to an annual growth rate of 10 t of DM per ha. The yield of the first cutting cycle was reduced by one-third of full growth rate.

Two rotations were modelled, starting from ploughing of the soil to prepare for the willow in the year before planting the seedlings. Weed control was carried out prior to ploughing and several times during the establishment year, both mechanically and through the use of herbicides. Each rotation was terminated by applying herbicides to kill off remaining plants before cutting up the roots using a rotary cultivator. Shallow soil preparation was performed prior to the second rotation using a disc harrow. Seedling production and planting were also included in the cultivation activities.

The amount of nutrients supplied was identical in all three scenarios. Fertilizer was assumed to be applied to achieve recommended levels of nutrients (Aronsson and Rosenqvist, 2011). The amount of fertilizer was adjusted for the level of nutrients returned to the field with the biochar and ash in scenarios 1 and 2. The fertilizer levels, application method and amount of biochar and ash are found in the (Appendix S3).

Harvest and postharvest operations were included. In scenario 1a and 1b, the feedstock was pyrolyzed at the farm to generate bio-oil and char. The pyrolysis system and the mass and energy balance modelling are only briefly described here. A more detailed description is given in the (Appendices S4 and S5, Eqn (S1)).

Energy service generation. In all bioenergy scenarios, electricity and heat were generated in a central CHP plant located 30 km from the farm. All scenarios, including the reference case, had an overall conversion efficiency from fuel entering the CHP to electricity and heat of 90% (LHV).

As flue gases from biomass, bio-oil and biochar contain a considerable amount of steam, the CHPs in scenarios 1 and 2 were assumed to use flue gas condensation technology, recovering 90% of the potential heat in the flue gases. No flue gas condensation was assumed in the reference case as the excess air used in a NG combined cycle lowers the dew point of the exhaust gas to below the return temperature of the district heating network, making flue gas condensation for this purpose implausible.

Data on primary energy use and emissions associated with the extraction, distribution and use of NG in the reference case were taken from Gode et al. (2011). Only the primary energy use and emissions related to the use of willow in co-combustion were included in the bioenergy scenarios as the aim of this study was to investigate the contribution to the climate impact from the willow biomass, not the co-combusted fuels, in the bioenergy system.
Energy efficiency

The external energy ratio (ER) (Murphy et al., 2011) was used to assess the energy efficiency in this study. To avoid confusion with the external energy sources used in the system expansion, the ER is simply referred to as the energy ratio for the remainder of this study. It was defined as the ratio between the energy delivered and all external energy inputs used to generate this energy Eqn (2). Note that the energy in the fuel is not considered in relation to the external energy inputs used in the production and delivery of the fuels to the CHP. It was calculated separately for electricity and heat after allocating the energy inputs for each scenario between the two energy services.

\[
ER = \frac{\text{Delivered energy}}{\text{Energy input}}
\] (2)

The ER indicates the amount of useful electricity and heat delivered in relation to the external energy inputs used in the production and delivery of the fuels to the CHP. It was calculated separately for electricity and heat after allocating the energy inputs for each scenario between the two energy services.

Greenhouse gas and carbon fluxes

Emissions from the technical system and non-C emissions. The GHG emissions from the technosphere were assigned to the year in which activities took place. Upstream emissions were assigned to the same year as the main activity.

Primary energy use and emissions from return transport and application of the bottom ash, as well as the handling of the biochar, were assigned to the year following harvest.

Direct and indirect N2O emissions were calculated using emission factors from the IPCC guidelines for national greenhouse gas inventories (IPCC, 2006). According to these, 1% of the N in the applied fertilizer and in the decomposing biomass was assumed to be converted to N2O. Indirect emissions were calculated assuming that 30% of the N fertilizer applied was leached and that 0.75% of this fraction was converted to N2O. Indirect N2O emissions were assigned to the year in which the fertilizer was applied and the biomass litter was generated.

Biogenic carbon fluxes. The C fluxes between the atmosphere and the biosphere were calculated for three different compartments: live biomass, SOC and biochar. The net annual flux for each year of the study period was based on the net annual C stock change and was calculated using different approaches for each compartment. Only C stock changes occurring during the study period were included in the assessment. This was carried out as these emissions depend on the decisions made by the farmer choosing to cultivate the willow. All emissions taking place prior to and after the end of the study period were consequently ascribed to the preceding and subsequent cultivation systems.

Live biomass. Net annual C stock change in the live biomass was calculated based on the expected yield, interannual growth rate and C allocation pattern of the willow (Rytter, 2001). The C stored in the stems was considered to be combusted within a short time frame and returned to the atmosphere in the year of harvest.

SOC. The annual SOC stock changes were modelled using the ICBM model (Andrén et al., 2004), adjusted for a SRC willow system (Ericsson et al., 2013; Fig. 3).

ICBM is conceptually divided into two pools, a young (Y) and an old (O) pool. Fresh input (i) enters a Y pool. A fraction of the young pool is broken down every year. Part of this fraction enters the O pool, and the rest is returned to the atmosphere as CO2. The humification factor (h) determines the fraction of the aboveground (subscript a) and belowground (subscript b) C leaving the Y pool every time step that will enter the O pool. The original ICBM model was modified to fit the willow system by keeping above- and belowground input in separate Y pools and multiplying the h values of the Yb pool by a factor of 2.3 (Kätterer et al., 2011). The equations and parameter values used in this study can be found in Eqsns (S2) and (S3), and Table (S9).

The initial SOC stock was calculated by performing a spin-up simulation of 1000 years using only annual crop input followed by 20 years of fallow input (Appendix S6: Table S10). Total initial SOC level was 85 t of C per ha.

Biochar. The biochar was assumed to be applied to the soil of the willow plantation, where it was subsequently mineralized and returned to the atmosphere through physical and biochemical processes. As SOC and biochar exhibit very different physical and biochemical properties, and the ICBM model

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Climate impact characterization

In this study, the contribution to the global mean surface temperature change as a function of time \( (\Delta T_S(n)) \) was used as an indicator for the time-dependent climate impact (Aamaas et al., 2013). The \( \Delta T_S(n) \) was chosen as an indicator for its ability to express the impact on the climate at varying points in time, thereby indicating both the timing and rate of change. Furthermore, the temperature might be easier to relate to as a metric than RF to many people. It also describes a physical response in the climate system which lays closer to impacts on ecosystems and human society than RF. These are ultimately what concerns human society and decision-makers.

When calculating the contribution to the global mean surface temperature change \( (\Delta T_S(n)) \), the individual temperature response \( (\Delta T_S(t)) \) from each annual \( (i) \) net GHG \( (x) \) emission was calculated and summed for every year of the study period \( (n) \) Eqn (3). The net annual emissions of every GHG therefore had to be specified in a time-distributed life cycle inventory. A detailed explanation of the methodology can be found in Ericsson et al. (2013).

\[
\Delta T_S(n) = \sum_{i=1}^{3} \sum_{t=1}^{n} \Delta T_S^x(t) \quad [K] \quad (3)
\]

The equations used to calculate \( \Delta T_S^x \) in this study can be found in Eqns (S5–S7).

The evaluation period of the time-dependent climate impact was set to 100 years, beginning in the first year of the study period. The difference between the evaluation period and the study period was that activities and carbon stock changes giving rise to GHG emissions only took place during the study period, while the effects of these emissions on the climate were evaluated up until the end of the evaluation period. This is important when using \( \Delta T_S(n) \) as an indicator together with time-dependent climate impact methodology as the major contributions from emissions occurring close to the end of the study period would otherwise not be recognized (Ericsson et al., 2014). The upper limit of the evaluation period was set to 100 years because a longer time frame increases the uncertainty and decreases the usefulness of the metric results. The later needs to be kept in mind when interpreting the results from response functions that reach far into the future. The IPCC decided not to include GWP values with a longer TH than 100 years in AR5 for this specific reason (Myhre et al., 2013).

Results

Energy efficiency

The amount of energy delivered in scenario 1a and 1b was considerably lower than in scenario 2, while the energy input was only marginally smaller (Table 1). The smaller energy input was mainly due to reduced transport requirement between the farm and the CHP. The conversion efficiency from feedstock energy (HHV) into electricity and heat at the CHP was 42% in scenario 1a and 67% in scenario 1b, compared with 88% in scenario 2.

Scenario 2 used its energy inputs (not including the feedstock energy) a little more efficiently than scenario 1b when producing electricity and heat while it was almost twice as efficient as scenario 1a and scenario 3 (Table 1). This was not entirely reflected in the ER of
the generated electricity and heat because of the difference in allocation of the energy inputs caused by the higher electricity-to-heat ratio in the combined cycle used in scenario 3, compared with that of the steam turbines used in the bioenergy scenarios. The heat delivered from the natural gas fed combined cycle CHP system in scenario 3 also had a lower ER than that of the willow scenarios due to the higher amount of energy input required to produce and transport the fuel and the use of flue gas condensation technology in the biomass CHPs.

When performing the system expansion in scenario 1a and 1b, the ER of the heat decreased in most cases. This was due to the relatively low ER of the external energy sources used compared to the ER of the heat in the unexpanded systems.

Greenhouse gas and carbon fluxes

Emissions from technical system and non-C emissions. The GHG emissions from the production system, including induced N₂O emissions from decomposing biomass, were very similar in scenario 1a and 1b and scenario 2 (Fig. 5). The small difference in CO₂ and CH₄ emissions could be attributed to the difference in the amount of transport work required between the farm and the CHP.

Scenario 1a and 1b and scenario 2 emitted much less CH₄ than scenario 3. The high CH₄ emissions in scenario 3 originated from distribution losses and unburned gas when flaring. In total, 11 g CH₄/kg NG fuel was emitted (Gode et al., 2011).

Of the external energy sources, HC contributed much of the CO₂ and N₂O emissions in scenario 1a and 1b (Fig. 6). Natural gas contributed much more CH₄ than all the other sources due to the distribution losses and flaring emissions mentioned earlier.

Table 1  Electricity and heat delivered, total energy input and energy ratios (ER) of the electricity and heat in the scenarios studied. Scenario 1a and 1b is given both excluding (unexpanded) and including (NG,HC,WP+HHW) the external energy service generation of the expanded system

| Scenario          | Energy delivered | Energy input | ER el | ER heat |
|-------------------|------------------|--------------|-------|---------|
|                   | El GJ ha⁻¹ yr⁻¹ | Heat GJ ha⁻¹ yr⁻¹ | GJ ha⁻¹ yr⁻¹ |         |
| Scenario 1a (unexpanded) | 7               | 58            | 5.7   | 3       | 19      |
| Scenario 1b (unexpanded) | 18              | 86            | 5.8   | 7       | 28      |
| Scenario 2        | 34               | 102           | 6.1   | 10      | 36      |
| Scenario 3        | 34               | 102           | 12.0  | 8       | 13      |
| Scenario 1a NG*  |                  |               | 6     | 16      |
| Scenario 1a HC†   |                  |               | 4     | 12      |
| Scenario 1a WP+HHW‡ |                |               | 8     | 20      |
| Scenario 1b NG*   |                  |               | 7     | 24      |
| Scenario 1b HC†   |                  |               | 5     | 20      |
| Scenario 1b WP+HHW‡ |                |               | 10    | 27      |

*Natural gas electricity and heat. Data are based on the Rya combined cycle CHP (Gode et al., 2011).
†Hard coal electricity and heat. Data are based on five Danish hard coal powered CHPs (Gode et al., 2011).
‡Wind power and household waste heat. Data for wind power are based on the wind power production of Vattenfall, and the data for household waste heat are based on production, distribution and use of HHW with low organic content in a Swedish waste-fuelled CHP (Gode et al., 2011).
Biogenic carbon fluxes. The live biomass C pool increased temporarily due to changing the land use to willow. On average, 14 700 kg of C per ha was stored in the live biomass aboveground pool in the willow plantation. The carbon stock increased and decreased periodically with the 3-year coppicing cycle. At harvest, all the C stored in the biomass was either converted into fuel for electricity and heat generation and returned to the atmosphere as CO₂ or applied as biochar to the soil. Further, CO₂ was withdrawn from the atmosphere and stored temporarily as C in the coarse roots of the willow plants, holding on average 1400 kg of C per ha. The C of the coarse roots was removed mechanically and incorporated into the soil at the end of each rotation. The coarse roots were then treated as input to the SOC model. The net sequestration of biomass as well as coarse roots was zero over an entire rotation.

Annual carbon input from leaves and fine roots and occasional input from coarse roots at the end of each rotation contributed to the increase in SOC stocks. On average, 390 kg of C per (ha per yr) was accumulated in each of the scenarios due to SOC stock changes. The SOC growth rate decreased with time as the system approached a new state of SOC equilibrium. The rate of growth was 430 and 360 kg of C per (ha per yr) during the first and second rotation, respectively.

In scenario 1a, the biochar C pool in the soil increased at a rate of 1300 kg of C per (ha per yr). Due to the recalcitrance of biochar, the rate of growth did not vary by more than 2% between the first and second rotations. The amount of biochar C remaining in the soil at the end of the study period was calculated to be 94% of the biochar C applied over the course of the study period.

Climate impact

Per hectare of land (no system expansion). When assessing scenario 1a and 1b and scenario 2 based on their function of mitigating climate impacts by representing optional land use systems, scenario 1a contributed much more to a decrease in ΔT₅ than scenario 1b (Fig. 7) and scenario 2, whose effects on ΔT₅(n) resembled each other. This was explained almost entirely by the temperature response from the CO₂ removed by the growing willow and kept out of the atmosphere for a long time as a consequence of diverting and applying C to the soil in the form of relatively stable biochar (Fig. 8).

The contribution from the SOC to ΔT₅ was of a similar magnitude, but of opposite sign to the combined contribution from the production system and the N₂O emissions (Fig. 8). They cancelled each other out almost perfectly and were similar in scenario 1a and 1b and in scenario 2. The total temperature response in scenario 1b and in scenario 2 therefore resembled that caused by

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**Fig. 6** Part of the inventory results showing the contribution of CO₂ (a), N₂O (b) and CH₄ (c) from the external energy sources in scenario 1a (biochar-to-soil) and 1b (char-to-energy). External energy sources included were natural gas (NG), hard coal (HC), wind power (WP) and household waste (HHW).

**Fig. 7** Contribution to the global mean surface temperature change (ΔT₅) per hectare (ha) of willow plantation in scenario 1a and 1b and in scenario 2. Note: Indirect climate impacts due to different amounts of heat and power produced in the scenarios are not included.
the CO₂ fluxes in the live biomass, while it was dominated by the biochar in scenario 1a (Fig. 7).

**Per unit of energy service (with system expansion).** When assessing the climate impact of all scenarios based on their function of delivering energy services, the impact from the external energy sources was included in scenario 1a and 1b. The biomass-based scenarios (1a, 1b and 2) always performed better than the NG-based scenario (3) (Fig. 9a–d).

In this study, the direct combustion used in scenario 2 was always a more favourable option from a climate change mitigation perspective than the char-for-energy alternative in scenario 1b. In this case, the impact from the external electricity and heat required to compensate for the lower energy efficiency in scenario 1b was higher than the difference between the pyrolysis system (scenario 1b) and the direct combustion system (scenario 2). The contribution to ΔTₛ from scenario 1b was higher than that of scenario 1a for all external energy sources used in the system expansion, except for the heat produced using HC. With a less GHG-intensive external power source, such as WP or HHW, applying the biochar to the soil, as in scenario 1a, became a better option from a climate change mitigation perspective than the direct combustion of scenario 2 (Fig. 9a and c). The contribution to ΔTₛ in scenario 1a was much lower than in scenario 2 when WP was used due to the impact from the CO₂ kept out of the atmosphere when applying biochar to the soil (Fig. 9a). However, scenario 1a was very sensitive to the external energy sources used in the system expansion due to its low energy efficiency.

**Fig. 8** Contribution to the global mean surface temperature change (ΔTₛ) per hectare (ha) of willow plantation from each of the system components of the SRC willow bioenergy system in scenario 1a.

**Fig. 9** Temperature response per kWh electricity (a and b) and MJ of heat (c and d) for all scenarios, including external electricity and heat from hard coal (HC), natural gas (NG), wind power (WP) and household waste (HHW) in scenario 1a (a and c) and scenario 1b (b and d). The temperature response for scenarios 2 and 3 (reference) is the same in (a) and (b), as well as in (c) and (d), respectively.
When HC was used as the external energy source, the emissions allocated to the heat in scenario 1a contributed more to an increase in $\Delta T_S$ than in scenario 1b (Fig. 9c,d).

The amount of external electricity and heat relative to the amount of delivered electricity and heat also influenced the apparent timing of the temperature response in scenario 1a and 1b. When examining the HC and NG response curves of these two scenarios (Fig. 9a,c and b, d), the temperature response of the heat was slightly delayed compared to that of the electricity. This could be explained by the external heat making up a smaller share of the total amount of heat delivered compared to the external electricity share of the total electricity delivered. As a consequence, the HC and NG contributed less to the total temperature response of the heat than to that of the electricity system. As the contribution from the external energy sources to the increase in $\Delta T_S$ of the heat was less pronounced, the temperature increase in the response curve also appeared delayed when compared to the electricity.

**Sensitivity analysis**

The two assumptions with the largest effect on the results in scenario 1a were the yield level and the use of flue gas condensation in the biomass CHP. Both of these influenced the energy efficiency. Increased yield lowered the contribution to $\Delta T_S$ from both the electricity and the heat by decreasing the need for external energy and also increasing the amount of C in the biochar pool (Figs 10 and 11). By excluding the use of flue gas condensation, the need for external heat increased, and as a consequence, so did the contribution to $\Delta T_S$ from the heat (Fig. 11).

The contribution to $\Delta T_S$ from a reduction in N$_2$O emissions and stability of biochar was of almost equal magnitude, but of opposite sign, for both electricity and heat. Their contribution was significantly smaller than that of the assumed yield increase and exclusion of flue gas condensation.

However, if biogenic C stock changes had not been included in this study, the impact from reduced N$_2$O emissions would not have been insignificant. The changes contributed approximately 70% of the temperature response from the production system, which excludes the response from SOC, live biomass and biochar C stock changes.

Given the magnitude of the contribution from the biochar to the temperature response of the system, it was expected that the stability of the biochar would be an important parameter. However, in this scenario analysis, the degradation rate was increased by 2.6-fold without a large impact on the contribution to $\Delta T_S$ from the system. This indicates that biochar with much lower stability than that used in this study might still offer significant climate change mitigation benefits in pyrolysis systems with soil application of biochar.

**Discussion**

The results of the present study show that using land to grow SRC willow for bioenergy in central Sweden can have a cooling influence on the global mean surface temperature. The time-dependent model and climate impact indicator used in this study showed that this influence will prevail for at least 50 years after the end of the cultivation of the willow (Fig. 7). Converting the feedstock into bio-oil and char using pyrolysis before generating electricity and heat, as in scenario 1b, did not lead to a significant change in the contribution to $\Delta T_S$ from the bioenergy system compared with combusting the raw willow chips directly in a large-scale CHP, as in scenario 2. However, from a land use
perspective, the cooling effect can increase substantially if the char is applied to soil in the form of biochar, as in scenario 1a. This is due to the large C sink created by the biochar, which is very stable and keeps part of the C sequestered by the willow out of the atmosphere for a very long time. When the climate impact of bioenergy systems is compared, it is however advisable to include the indirect effects that different amounts of energy services deliver.

Converting the feedstock to bio-oil and char using pyrolysis inevitably reduces the energy efficiency of the system. When comparing the climate impact of the electricity and heat in scenario 1a and 1b to scenarios 2 and 3, the outcome was very dependent on the external electricity and heat sources considered in the system expansion. The system expansion performed to compensate for the lower energy efficiency of the pyrolysis system showed that the direct combustion system in scenario 2 contributed more to a decrease in $\Delta T_{5}$ than when pyrolysis was applied and all products were used for energy service generation (scenario 1b), regardless of the external energy source used to generate the electricity and heat in the expanded system. When using GHG-intensive sources (e.g., hard coal and natural gas), the expanded system even contributed to an increase in $\Delta T_{5}$, but in all cases, the pyrolysis bioenergy system in scenario 1a and 1b was a better option from a climate change mitigation perspective than using the electricity and heat produced in the natural gas-fuelled combined cycle CHP in scenario 3.

In a situation where a choice can be made between the use of a pyrolysis bioenergy system in which biochar is applied to soils, as in scenario 1a, or where the biomass is used for energy generation, as in scenarios 1b and 2, substantial climate change mitigation benefits can potentially be achieved using a biochar system if the external energy sources that are needed to compensate for the lower energy efficiency of the pyrolysis-biochar system, compared to direct combustion, have lower GHG intensities than fossil fuels. This is in accordance with the climate mitigation potential study of biochar systems globally by Woolf et al. (2010).

The sensitivity analysis in this study showed the importance of the biomass yield for the climate change mitigation potential of a SRC willow-based bioenergy system producing and applying biochar to soils. This emphasizes the importance of good management practices to achieve high yields for the climate impact of the system, and also the importance of choosing high-yielding clones when establishing a new willow plantation. The temperature response curve for an increased biomass yield also showed that this might be a good strategy when trying to achieve continuous long-term climate change mitigation from the generated electricity and heat (Figs 10 and 11). The climate change mitigation effort effectively gets a boost every time yield improvements are achieved due to its influence on both C stocks and energy efficiency of the system.

The use of flue gas condensation was also an important parameter for the climate impact of the heat delivered by the system as it increases the energy efficiency, potentially avoiding the use of fossil fuels. However, most Swedish CHP plants use flue gas condensation, as it is a profitable investment (Axby et al., 2000). The stability of the biochar had a remarkably low influence on the climate impact of the system in this study, given its share of the total contribution to $\Delta T_{5}$. This may be due to the short time period used in this study. Climate impacts from biochar act on much longer time scales than those from SOC and live biomass due to the high stability of the biochar. Biochar stability may still be important for the long-term climate impact, but this was not studied here.

Much more information can be conveyed by the graphical representation of the time-dependent climate impact used in this study than what can be achieved by the use of a simple index, such as the GWP. This is why a time-dependent impact assessment methodology may serve as a useful complement to traditional impact assessment methods in LCA. It is, however, a more time-consuming endeavour to set up the time-distributed inventory model and gather data with the necessary temporal resolution to assess the temporal dimension of impacts in an LCA.

Several authors have proposed ways of integrating temporal information in LCI databases (Collinge et al., 2013; Beloin-Saint-Pierre et al., 2014; Tiruta-Barna et al., 2016). These might be useful to add temporal information to the background system and make the use of time-dependent impact indicators easier and less resource-consuming. However, the LCA community and database developers need to agree on how to store temporal information in a database format without bloating the storage space, and still provide useful data. In the present study, a more pragmatic approach was used towards the emissions from the background system. These were simply assigned to the year in which the associated main event took place in the foreground system. There is still plenty of temporal information in the foreground system to motivate the use of a time-dependent LCA methodology in many systems that have life cycles that extend over many years, which is typically the case in short-rotation forestry.

Under all circumstances, SRC willow offers an opportunity for individual farmers to become part of the energy supply chain. The possibility of using the feedstock for either direct combustion or bio-oil and biochar production represents an opportunity which offers...
flexibility that could make the producers of the biomass less sensitive to fluctuations in market price. The commercial applications for bio-oil and biochar are currently limited, but substantial research has been carried out over the last 30 years, and the potential applications are numerous (Qian et al., 2015). Pyrolysis systems might not always be beneficial from an energy efficiency perspective, but other benefits such as improved handling, storage and fuel properties, as well as increased energy density and product flexibility, might be more important when choosing this energy conversion technology. In all cases, the SRC willow-based bioenergy systems included in this study offer a way of generating electricity and heat while at the same time contributing to a decrease in the global mean surface temperature change. This study was, however, limited to the energy efficiency and climate impact of willow-based pyrolysis bioenergy systems. These systems will also have other types of environmental impacts which should be scrutinized using a full life cycle approach before passing verdict on their environmental sustainability.

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References
Aamaas B, Peters GP, Foglstvedt JS (2013) Simple emission metrics for climate impacts. Earth System Dynamics, 4, 145–170.
Andrén O, Kätterer T, Karlsson T (2004) ICBM regional model for estimations of dynamics of agricultural soil carbon pools. Nutrient Cycling in Agroecosystems, 70, 231–239.
Aronsson P, Rosenqvist H (2011) Garmeforsk, Stockholm.
Beloïn-Saint-Pierre D, Heijungs R, Blanc I (2014) The ESPA (Enhanced Structural Path Analysis) method: a solution to an implementation challenge for dynamic life cycle assessment studies. The International Journal of Life Cycle Assessment, 19, 861–871.
Beretta GP, Iora P, Ghoniem AF (2012) Novel approach for fair allocation of primary energy consumption among cogenerated energy-intensive products based on the actual local area production scenario. Energy, 44, 1107–1120.
Berntsen T, Foglstvedt J (2008) Global temperature responses to current emissions from the transport sectors. Proceedings of the National Academy of Sciences of the United States of America, 105, 19154–19159.
Brown RC (eds.) (2011) Thermochroming Processing of Biomass. Conversion into Fuels, Chemicals and Power. Wiley Series in Renewable Resources, John Wiley & Sons, Ltd, Chichepenham, UK.
Cayuela M, van Zwietsien L, Singh B, Jaffrey S, Roig A, Sánchez-Monedero M (2014) Biochar’s role in mitigating soil nitrous oxide emissions: a review and meta-analysis. Agriculture, Ecosystems & Environment, 191, 5–16.
Cherubini F, Peters GP, Berntsen T, Stromman AH, Hertwich E (2011) CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. GCB Bioenergy, 3, 413–426.
Cherubini F, Bright RM, Stromman AH (2013) Global climate impacts of forest bioenergy: what, when and how to measure? Environmental Research Letters, 8, 014049.
Collinge WO, Landis AE, Jones AK, Schaefer LA, Bilec MM (2013) Dynamic life cycle assessment: framework and application to an institutional building. The International Journal of Life Cycle Assessment, 18, 538–552.
Courchesne A, Bécourt V, Rosenbaum R, Doschères L, Samson R (2010) Using the lasso accounting methodology to assess carbon mitigation projects with life cycle assessment. Journal of Industrial Ecology, 14, 309–321.
Denman K, Bursan G, Chidthaisong A et al. (2007) Couplings between changes in the climate system and biogeochemistry. In: Climate Change 2007: The Physical Science Basis (eds Solomon S, Qin D, Manning M et al.), chapter 7, pp. 499–588. Cambridge University Press, Cambridge, UK.
Environmental Product Declaration (EPD) (2013) Environmental Product Declaration of Rizziconi combined-cycle gas turbine plant, Italy.
Environmental Product Declaration (EPD) (2015) Environmental Product Declaration of Domat/Ems wood-fired power plant.
Ericsson N, Porsio C, Ahlgren S, Nordberg Å, Sundberg C and Hansson PA (2013) Time dependent climate impact of a bioenergy system - methodology development and application to Swedish conditions. GCB Bioenergy, 5, 580–590.
Ericsson N, Nordberg Å, Sundberg C, Ahlgren S and Hansson PA (2014) Climate impact and energy efficiency from electricity generation through anaerobic digestion or direct combustion of short rotation coppice willow. Applied Energy, 132, 86–98.
EU (2011) Commission implementing decision of 19 December 2011 establishing harmonised efficiency reference values for separate production of electricity and heat in application of directive 2004/8/Ec of the European parliament and of the council and repealing commission decision 2007/74/ec. commission implementing decision L343/91, European commission.
EU (2012) Directive 2012/27/EU of the European parliament and of the council of 25 October 2012 on energy efficiency, amending directives 2009/125/EC and 2010/30/EU and repealing directives 2004/81/EC and 2006/32/EC. Directive L351/1, European commission.
Fuglstvedt J, Berntsen T, Gødal O, Sausen R, Shine K and Skodvin T (2003) Metrics of climate change: assessing radiative forcing and emission indices. Climatic Change, 58, 267–231.
Fuglstvedt J, Shine K, Berntsen T et al. (2010) Transport impacts on atmosphere and climate: metrics. Atmospheric Environment, 44, 4648-4677.
Gillierot P (2012) Conversion of biomass to selected chemical products. Chemical Society Reviews, 41, 1538–1558.
Gaut J, Lehmann J (2008) Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. Environmental Science & Technology, 42, 4152–4158.
Guentoli J, Caserini S, Marelli L, Baxter D, Agostini A (2015) Domestic heating from forest logging residues: environmental risks and benefits. Journal of Cleaner Production, 99, 206–216.
Gode J, Martinsson F, Hågberg L, Oman A, Höglund J and Palm D (2011) Miljöfacktaboken 2011. Estimated emission factors for fuels, electricity, heat and transport in Sweden. Technical Report 1183, Värme forsk, Stockholm.
Hammar T, Ericsson N, Sundberg C, Hansson PA (2014) Climate impact of willow grown for bioenergy in Sweden. BioEnergy Research, 7, 1529–1540.
Hammar T, Ortiz C, Stendahl J, Ahlgren S, Hansson PA (2013) Time dynamic effects on the carbon balance when harvesting logging residues for bioenergy. Bioenergy Research, 6, 1912–1924.
Hammond J, Shackley S, Sohi S, Brownspot P (2011) Prospective life cycle carbon abatement for pyrolysis biochar systems in the UK. Energy Policy, 39, 2646–2655.
Hanadeh AE (2012) Carbon abatement via treating the solid waste from the Australian olive industry in mobile pyrolysis units: LCA with uncertainty analysis. Waste Management & Research, 31, 341–352.
Hansen J, Sato M (2012) Paleoecological implications for human-made climate change. In: Climate change (eds Berger A, Mesinger F, Sijacki D), pp. 21–47. Springer, Vienna, Austria.
Barrera R, Shackley S, Hammond J (2012) Pyrolysis biochar systems for recovering biodegradable materials: a life cycle carbon assessment. Waste Management, 32, 859–868.
IPCC (1991) Climate Change - The IPCC Scientific Assessment. Cambridge University Press, Cambridge, Great Britain, New York, NY, USA and Melbourne, Australia, reprinted edition.
IPCC (2006) 2006 IPCC guidelines for national greenhouse gas inventories, prepared by the national greenhouse gas inventories programme.
ISO 14040 (2006) Environmental management - life cycle assessment - principles and framework (ISO 14040:2006). ISO standard EN ISO 14040:2006:ISO/TC 207, CMC, European Committee for Standardization, Brussels.
ISO 14044 (2006) Environmental management - life cycle assessment - requirements and guidelines (ISO 14044:2006). ISO standard EN ISO 14044:2006:ISO/TC 207, CMC, European Committee for Standardization, Brussels.
Kätterer T, Bolinder MA, Andrén O, Kirchmann H, Menichetti L (2011) Roots contribute more to refractory soil organic matter than above-ground crop residues, as revealed by a long-term field experiment. Agriculture, Ecosystems and Environment, 141, 184–192.

© 2017 The Authors. Global Change Biology Published by John Wiley & Sons Ltd, 9, 876–890
Kendall A (2012) Time-adjusted global warming potentials for LCA and carbon footprint. *The International Journal of Life Cycle Assessment, 17*, 1042–1049.

Kendall A, Chang B, Sharpe B (2009) Accounting for time-dependent effects in biofuel life cycle greenhouse gas emissions calculations. *Environmental Science & Technology, 43*, 7142–7147.

Levasseur A, Lesage P, Margni M, Deschênes L, Samson R (2010) Considering time in LCA: dynamic LCA and its application to global warming impact assessments. *Environmental Science and Technology, 44*, 3169–3174.

Liang B, Lehmann J, Solomon D et al. (2008) Stability of biomass-derived black carbon in soils. *Geochimica et Cosmochimica Acta, 72*, 6609–6678.

Murphy DJ, Hall CAS, Dale M, Cleveland C (2011) Order from chaos: a preliminary protocol for determining the eori of fuels. *Sustainability, 3*, 1988–1907.

Myhre G, Shindell D, Breon FM et al. (2013) Anthropogenic and Natural Radiative Forcing, book section 8. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659–740.

Neves D, Thunman H, Matos A, Tarelho L, Gómez-Barea A (2011) Characterization and prediction of biomass pyrolysis products. *Progress in Energy and Combustion Science, 37*, 611–630.

Noll M, Jerje R (2012) Microbial communities in large-scale wood piles and their effects on wood quality and the environment. *Applied Microbiology and Biotechnology, 95*, 551–563.

O’Hare M, Plevin RJ, Martin JD, Jones AD, Kendall A, Hopson E (2009) Proper accounting for time increases crop-based biofuels’ greenhouse gas deficit versus petroleum. *Environmental Research Letters, 4*, 024001.

Ortiz CA, Hammar T, Ahlgren S, Hansson PA, Stendahl J (2016) Time-dependent global warming impact of tree stump bioenergy in Sweden. *Forest Ecology and Management, 371*, 5–14.

Peters GP, Aamaas B, T Lund M, Solli C, Fuglestvedt JS (2011) Bilansmyndigheten’s alternative “global warming” function in life cycle impact assessment. A case study with existing transportation data. *Environmental Science & Technology, 45*, 8633–8641.

Peters JP, Iribarren D, Dulour J (2015) Biomass pyrolysis for biochar or energy applications? A life cycle assessment. *Environmental Science & Technology, 49*, 5195–5202.

Pors O, Mate R, Vinterhäll J, Hansson PA (2016) Time-dependent climate effects of eucalyptus pellets produced in Mozambique used locally or for export. *BioEnergy Research, 9*, 942–954.

Pourhashem G, Spataris S, Beuteng AA, McAloon AJ, Mullen CA (2013) Life cycle environmental and economic tradeoffs of using fast pyrolysis products for power generation. *Energy & Fuels, 27*, 2578–2587.

Pourhashem G, Adler PK, Spataris S (2016) Time effects of climate change mitigation strategies for second generation biofuels and co-products with temporary carbon storage. *Journal of Cleaner Production, 112*, 2642–2653.

Qian K, Kumar A, Zhang H, Bellmer D, Huhneke R (2015) Recent advances in utilization of biochar. *Renewable and Sustainable Energy Reviews, 42*, 1055–1064.

Roberts KG, Clay BA, Joseph S, Scott NR, Lehmann J (2010) Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environmental Science & Technology, 44*, 827–833.

Ryter RM (2001) Biomass production and allocation, including fine-root turnover, and annual N uptake in lysimeter-grown basket willows. *Forest Ecology and Management, 140*, 177–192.

SJV (2008) Kartläggnings av mark som tagits ur produktion. Report 08:7, Swedish Board of Agriculture.

Sohi SP, Krull E, Lopez-Capel E, Bol R (2010) A review of biochar and its use and function in soil. *Advances in Agronomy, 105*, 47–82.

Swedish Energy (2012) Miljövärdering 2012. Guide for allokering i kraftvärmeverk och fjärrvärmens elanvändning.

Swedish Energy Agency (2015) Energy in Sweden 2015. Report ET015:19, Swedish Energy Agency.

Thorley P, Gilbert P, Shackley S, Hammond J (2015) Maximizing the greenhouse gas reductions from biomass: the role of life cycle assessment. *Bioenergy, 81*, 35–43.

Tiruta-Barna L, Pigáé Y, Gutiérrez TN, Benetto E (2016) Framework and computational tool for the consideration of time dependency in life cycle inventory: proof of concept. *Journal of Cleaner Production, 116*, 198–206.

Wang Z, Dunn JB, Han J, Wang MQ (2013) Effects of co-produced biochar on life cycle greenhouse gas emissions of pyrolysis-derived renewable fuels. *Biofuels, Bioproducts and Biorefining, 8*, 189–204.

Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S (2010) Sustainable biochar to mitigate global climate change. *Nature Communications, 1*, 56.

Zetterberg L, Uppenberg S, Åhman M (2004) Climate impact from peat utilisation in Sweden. *Mitigation and Adaptation Strategies for Global Change, 9*, 37–76.

Zimmerman AR (2010) Abiotic and microbial oxidation of laboratory-produced black carbon (biochar). *Environmental Science and Technology, 44*, 1295–1301.

Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

**Appendix S1** Energy data and emissions from external energy sources.

**Appendix S2** Harmonised efficiency reference values and allocation factors.

**Appendix S3** System description.

**Appendix S4** Pyrolysis step.

**Appendix S5** Pyrolysis mass and energy balance modelling.

**Appendix S6** Biogenic carbon modelling.

**Appendix S7** Climate impact characterisation.