This pre-print manuscript *Climate impact and energy efficiency from electricity generation through anaerobic digestion or direct combustion of short rotation coppice willow* was subsequently accepted by *Applied Energy*.

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Climate impact and energy efficiency from electricity generation through anaerobic digestion or direct combustion of short rotation coppice willow

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Abstract

Short rotation coppice willow is an energy crop used in Sweden to produce electricity and heat in combined heat and power plants. Recent laboratory-scale experiments have shown that SRC willow can also be used for biogas production in anaerobic digestion processes.

Here, life cycle assessment is used to compare the climate impact and energy efficiency of electricity and heat generated by these measures. All energy inputs and greenhouse gas emissions, including soil organic carbon fluxes were included in the life cycle assessment. The climate impact was determined using time-dependent life cycle assessment methodology.

Both systems showed a positive net energy balance, but the direct combustion system delivered nine-fold more energy than the biogas system. Both systems had a cooling effect on the global mean surface temperature change. The cooling

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Preprint submitted to Applied Energy *June 12, 2014*

impact per hectare from the biogas system was nine-fold higher due to the carbon returned to soil with the digestate.

Compensating the lower energy production of the biogas system with external energy sources had a large impact on the result, effectively determining whether the biogas scenario had a net warming or cooling contribution to the global mean temperature change per kWh of electricity. In all cases, the contribution to global warming was lowered by the inclusion of willow in the energy system. The use of time-dependent climate impact methodology shows that extended use of short rotation coppice willow can contribute to counteract global warming.

Keywords:
Land use change, Soil carbon, Life cycle assessment, Time-dependent climate impact, Biogas, Combined heat and power

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Glossary

ΔT_S	Global mean temperature change
C	Carbon
CH_4	Methane
CHP	Combined Heat and Power
CO_2	Carbon dioxide
DM	Dry Matter
ER	Energy Ratio
GHG	Greenhouse gas
GWP	Global Warming Potential
HHV	Higher Heating Value
HRT	Hydraulic Retention Time
ICBM	Introductory Carbon Balance Model
iLUC	indirect Land Use Change

LHV	Lower Heating Value
LCA	Life Cycle Assessment
MC	Moisture Content
N_2O	Nitrous Oxide
OLR	Organic Loading Rate
SOC	Soil Organic Carbon
SRC	Short rotation coppice
VS	Volatile Solids

1. Introduction

In order to decrease the climate impact from the European power sector, it is important to increase the share of renewable sources in the European power supply. Bioenergy is an important resource in the Swedish energy system making up 40 % of the energy input in 2011 [1]. Bioenergy is frequently used in combined heat and power (CHP) applications, for which the Swedish forest industry is the largest supplier of biomass. In this study the effects on climate impact from heat and power generation using biomass from the agricultural sector were studied.

Short rotation coppice (SRC) willow is a well-established woody energy crop that has received particular attention over the last 30 years for its high potential dry matter (DM) yield and suitability for use in conventional CHP plants. It is often used for co-firing with other feedstock in large- or medium-scale CHP plants.

An alternative way of generating electricity and heat is through gas engines. For instance, the majority of the biogas produced in Germany is used in small-scale CHP units that feed into the electricity grid. Farm-scale biogas is still a marginal bioenergy producer in Sweden [2]. It does however have a large potential, especially if manure and energy crops are used as feedstock for the digestion process [3]. Digesting manure alone in an anaerobic digestion process is expensive due to its high water content which lowers the effective output per unit volume of the digester. One way of increasing the output of the digester is to increase the DM and carbon (C) content of the substrate by co-digestion with a drier substrate [4].

Converting biomass to biogas enables the recycling of nutrients and C back to the field with the digestate, which can affect the soil organic carbon (SOC) levels [5, 6], and, ultimately, the climate impact of the electricity generated. To our knowledge, no studies have been published quantifying how large this impact on the climate might be relative to those from the other parts of the bioenergy production system and how it may vary over time.

When evaluating the climate impact of electricity generated from biomass, one has to consider both greenhouse gas (GHG) emissions and the energy efficiency of the system used to generate the electricity. Life cycle assessment (LCA) methodology [7, 8] is commonly used to achieve this. Several authors have investigated the energy efficiency and greenhouse gas emissions from electricity generating systems using SRC willow as feedstock [9, 10, 11, 12, 13, 14, 15, 16]. Energy production from other SRC crops, such as poplar [17] and eucalyptus [18], have also been studied from a life cycle persective. These can be cropped similar to SRC willow and often show similar energy and GHG performances [19, 18]. Several studies have considered SOC changes when estimating the climate impact from SRC systems [11, 20, 13, 14, 16, 21]. We are however not aware of any published LCA studies investigating the importance of timing of emissions in SRC willow systems and the effects of the digestate on SOC changes.

The most common way of characterizing the climate impact in LCA is to determine the global warming potential (GWP) [22]. However, this metric has been criticized, among other things, for not being able to capture the climate effects of C stock changes in biomass used for bioenergy when the life cycle net C balance is zero [23, 24]. When a land use change occurs, the impacts on climate may also change over time due to SOC dynamics [25, 26]. The inclusion of soil carbon changes and timing of GHG emissions in bioenergy LCA's of electricity and heat generation has been argued for in order to avoid false assumptions about the long and short term climate impact [27]. To capture and interpret these dynamic effects in an LCA is a challenge that requires a different impact indicator [28]. One such indicator is the global mean surface temperature change (ΔT_S) [29, 16], which was used in this study.

The aim of this study was to compare the energy efficiency and climate impact of two ways of generating electricity and heat from SRC willow. The two energy conversion pathways investigated were 1) direct combustion in a central CHP plant and 2) conversion of the willow feedstock to biogas through co-digestion with liquid manure before burning the biogas in a small scale gas engine CHP. A trade-off between energy production and carbon sequestration similar to that of biochar systems [30] was expected. This paper serves the dual purpose of quantifying the time-dependent climate impact of different bioenergy systems as well as studying the trade-off between energy generation and climate impact mitigation through carbon sequestration that can be expected in the biogas scenario as digestate is added to the soil.

2. Methodology

Life cycle assessment methodology was used to assess the climate impact and effect on the energy efficiency from all relevant GHG and energy flows taking place throughout all life cycle stages of electricity and heat generation [7, 8]. The study took the form of a comparative LCA with a cradle-to-gate perspective, starting with the extraction of resources and ending with delivery of the electricity generated to the grid. The timing of GHG fluxes was determined to assess the time-dependent climate impact [16](see section 2.7).

A model of a bioenergy production system using willow established on fallow land was set up. A dairy farm with 300 cows and with existing infrastructure for anaerobic digestion of the liquid manure and generation of electricity and heat from the biogas was assumed. Emissions and energy requirements related to construction and decomissioning of the infrastructure was excluded from the LCA for both scenarios.

In the biogas scenario, the willow was used within the current infrastructure on the farm, i.e. the willow biomass was co-digested with manure in the anaerobic digester and the biogas was combusted in a gas engine to generate electricity and heat (Fig. 1). In the direct combustion scenario the willow biomass was transported to a central CHP plant and incinerated in a furnace to generate electricity and heat. In both scenarios the electricity generated was fed into the Swedish electricity grid and the recoverable heat was delivered to local DH distribution systems.

2.1. System boundaries and general assumptions

The production of inputs, cultivation and harvest of willow, storage losses, transportation of biomass to the conversion facility, preparation of the biomass to be converted and return of the residues to the field were all included within the system boundaries (Fig. 1). Activities and losses taking place after the delivery of the electricity and heat, such as distribution losses, were outside of the system boundaries. The energy and mass flows affected by the introduction of the willow system in the biogas process at the dairy farm were included. Other activities on the dairy farm were outside the system boundaries.

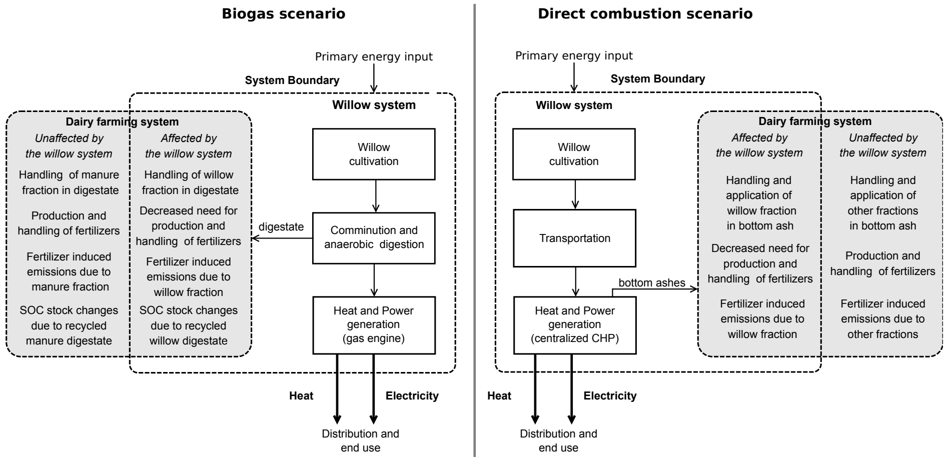

Fig. 1. System boundaries of the scenarios used in this study. Greenhouse gas fluxes in the dairy system resulting from the introduction of the willow system on the farm were included within the system boundaries.

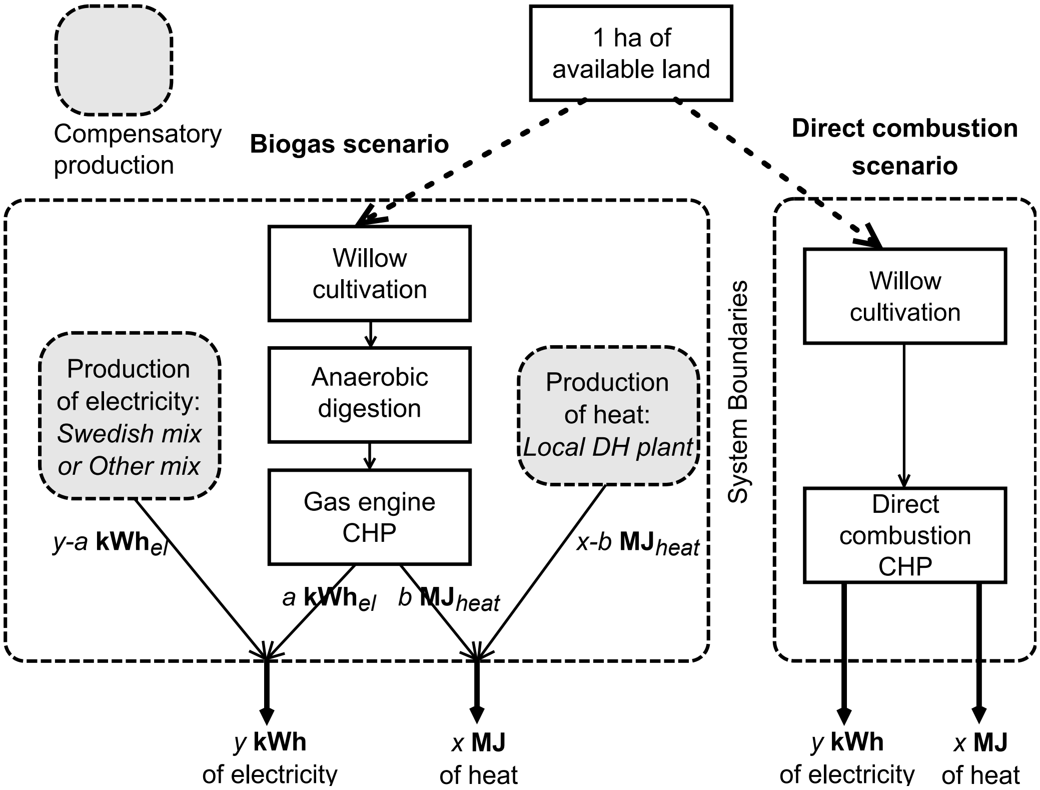

Fig. 2. Adjustment of the reference flow of the biogas system to give equal output in both scenarios. External production of heat and electricity was added to the biogas scenario. The magnitude of the reference flow in the direct combustion scenario was determined by the amount of land available for willow production.

All energy and GHG fluxes were recorded in a time-distributed life cycle inventory [16] as individual net emission impulses with a time resolution of one year. All upstream activities were accounted for in the year in which the activity that gave rise to them occurred. The fluxes of the three major GHG contributing to global warming, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), were determined for both scenarios.

Results were calculated on a per hectare basis for heat and electricity and converted to per kWh of electricity delivered. The climate impact was calculated as global mean surface temperature change (ΔT_S) per kWh of electricity delivered by dividing the temperature effect for each year by the expected total output of electricity to the grid from each of the two scenarios. This restricted the validity of the interpretation to the average climate impact of two full rotations of willow.

Allocation of emissions and primary energy was done using the alternative generation method [31], also known as the efficiency method [32]. Harmonized reference values [33, 34] for the separate production of electricity and heat from biogas and wood fuel were used for the two scenarios. Total emissions and primary energy allocation factor for electricity used in the biogas and direct combustion scenarios was 0.60 and 0.54, respectively.

2.2. System description

2.2.1. Common characteristics

Mean annual temperature at the willow plantation was 5.5 °C and mean annual precipitation 600 mm. The soil was a typical clay soil. The study period covered two subsequent SRC willow rotations, spanning 25 years each. The coppicing cycle was 3 years. The first harvest of each rotation yielded two-thirds of the harvest at full capacity, which was 30 t of DM per ha (10 t of DM per (ha yr)).

To ensure a constant supply of willow to the biogas process, one-third of the total area needed was established each year over a period of three years. The willow contributed a 50 % share of the volatile solids (VS) to the substrate mixture entering the anaerobic digestion process.

The management of the willow plantation followed established guidelines [35], such as soil preparation in year 0, mechanical weed control, planting, application of pesticides, fertilization and harvesting, and cutting up the roots and stools in spring after the last harvest of each rotation. Harvest took place in winter using a whole stem harvester. Delivery to the biogas plant or direct combustion CHP took place continuously. Stems were stored at the field side until delivery. The stems were chipped before transportation using a mobile wood chipper. The wood chips were then loaded on container trucks. Each truck carried 36 t of wet biomass [36] and had an empty return trip to the field.

2.2.2. Biogas scenario

At the biogas plant, the willow chips were comminuted to a particle geometric length of 2 mm before being mixed with the liquid manure and pumped into the digester.

Electricity and heat were generated in a gas engine and 20 % of the heat generated [37] and 8 % of the electricity [38] were used for heating and operating the biogas process and CHP auxiliary equipment. An additional 15 % of the generated heat was lost in the form of low-grade heat which could not be recovered for DH purposes [37]. The specific energy needed for comminution of the biomass was calculated to be 79 kWh per t of DM [39]. This represented an additional internal energy consumption of 23 % of the generated electricity in the biogas scenario. The remaining 68 % of the electricity and 65 % of the heat generated were delivered to the electric grid and the local DH distribution system (Table 1). The net electric and thermal efficiency in relation to the energy content of the biogas lower heating value (LHV_{biogas}: 9.8 kWh per nm^3) was 0.24 and 0.27, respectively. Total net electric and thermal efficiency of the willow in the biogas scenario were 4.9 % and 5.5 %, respectively, in relation to the energy content of the feedstock (higher heating value, HHV) entering the biogas process.

The digestate was stored in covered tanks at ambient temperature before being spread on annual crops on the dairy farm. The average one-way transportation distance to the field was calculated to 3.7 km using the method in [40] (equation A.1), derived from [41]. A winding factor of 2, a share of arable land of 0.5 and the part of land used for application was assumed to be 0.3.

Modeling of the biogas process. The biogas process was set up as a mass balance model using data from laboratory-scale experiments on anaerobic co-digestion of willow and liquid manure at the Department of Microbiology, Swedish University of Agricultural Sciences (SLU) (unpublished) (Table 2). The composition and volumes of the biogas and digestate were calculated taking into account the biogas yield, CH_4 concentration and elementary composition of the individual feedstock as well as the water removed with the biogas produced. The digestate was assumed to have a density of 1 t per m^3.

The organic loading rate (OLR) of the manure fraction before and after the establishment of the willow was set to 1.5 g of VS per (dm^3 d). The first willow harvest of each rotation contributed an additional 1 g of VS per (dm^3 d). Subse-

Table 1. Gas engine - combined heat and power unit capacity and performance in the biogas scenario at full production.

Parameter	Value			Unit
Electrical power rating		64		$\mathrm{kW}_{\mathrm{el}}^{\mathrm{engine}}$
Electrical efficiency		0.36		$\eta_{\mathrm{el}}^{\mathrm{engine}}$
Thermal efficiency		0.42		$\eta_{\mathrm{th}}^{\mathrm{engine}}$
Energy input	*Codigestion*	*Manure fraction* [b]	*Willow fraction* [c]	
biogas	4838	3290	1547	$\mathrm{MJ\,yr^{-1}}$
Energy output - CHP				
electricity	1742	1184	557	$\mathrm{MJ\,yr^{-1}}$
heat	2037	1385	652	$\mathrm{MJ\,yr^{-1}}$
Energy delivered [a]				
electricity	1473	1090	383	$\mathrm{MJ\,yr^{-1}}$
heat	1324	900	424	$\mathrm{MJ\,yr^{-1}}$

[a] Energy delivered to the electric grid and district heating distribution system.

[b] The manure fraction was calculated by setting the willow input to 0.

[c] The willow fraction was calculated as the difference in output from co-digestion and digesting only the manure fraction.

Table 2. Biogas process, substrate and digestate parameters at full production.

Parameter	Value					Unit
Process specific	Willow	Manure	Mixture	Digestate		
OLR	1.5	1.5	3			$\mathrm{g_{VS}\,dm^{-3}\,d^{-1}}$
CH_4 yield	0.103	0.219	0.159			$\mathrm{nm^3\,kg_{VS}^{-1}}$
CH_4 content	53	65	61			%of biogas
Feedstock specific				Total	Willow	
Wet weight	921	6420	7341	7029	798	t per yr
DM	47.7	8.2	13.2	9.9	41.6	%of wet weight
VS/TS	0.98	0.82	0.89	0.85	0.97	g per g
Tot-N	0.5	5.5	3.2	4.5	0.7	%of DM
min-N[a]	0	53	50	68	42	%of Tot–N
Tot-P	0.03	0.62	0.35	0.49	0.04	%of DM
K	0.1	5.1	2.8	3.9	0.1	%of DM
C	37.6	55.5	45.8	46.3	60.2	%of DM

[a] The amount of min−N returned to the field was reduced by 10 % of the min-N content in the digestate to account for ammonia (NH_3) lost during storage and application of digestate [42].

quent harvests of willow contributed 1.5 g of VS per (dm^3 d).The active digester volume was 869 m^3 giving a hydraulic retention time (HRT_{in}) of 39 days when co-digesting at full capacity.

Eighteen percent of the C in the willow substrate was converted to gas, yielding 83×10^3 nm^3 of biogas annually at full capacity.

2.2.3. Combustion scenario

The willow chips were transported 30 km to the central CHP plant. At the CHP plant, the willow chips were mixed with biomass of forest origin and incinerated in a grate furnace with a steam boiler. The net electric efficiency was set to 28 % and the amount of heat delivered to the DH distribution system was set to 62 % of the energy content of the biomass entering the furnace (HHV).

The amount and composition of the bottom ash was based on Swedish CHP plants using similar fuels and technology (wood fuel and grate furnace) [43]. The bottom ash fraction contained 50 % of the feedstock ash content. The energy and emissions from transport of the bottom ash back to the field were included, but field application was excluded since the ash was mixed with digested manure and applied to the field.

2.3. Energy balance and emissions from operations

Primary energy and emissions from operations were based on the primary energy factors and life cycle emissions of the energy carriers used [44]. An additional energy input of 20 % and 8 % of the energy content of the diesel used, as well as the emissions related to the production of this energy, were added for the manufacturing and maintenance of tractors and trucks, respectively [45]. Emissions and direct energy input for machine operations was determined using operation-specific data (Table B.1).

The energy efficiency was calculated as the energy ratio (ER) between the energy delivered and the primary energy input. The HHV of the willow was set to 17.64 MJ per t of DM, based on the elementary composition of the feedstock used in the biogas laboratory-scale experiments at the Department of Microbiology, SLU.

Dry matter losses during storage were based on a 0.8 % DM reduction for every month of storage [36], assuming that 25 % of the annual harvest was delivered at the beginning of every three-month period. This resulted in a DM loss of 3.6 % of the total yield. The moisture content (MC) used when calculating transported volumes was 52 %, 31 %, 19 % and 20 % at 0, 3, 6 and 9 months after harvest [36].

CH_4 losses from biogas production were set to 2 % of the biogas produced, with 1 % coming from the biogas production phase and 1 % from the digestate storage phase [46, 47].

Both systems were assumed to recycle part of the nutrients exported from the field with the harvested willow back to the dairy farm. These nutrients reduced the need for inorganic fertilizers, affecting GHG emissions and the energy balance of each scenario through avoided production. The reduction was calculated based on the primary energy consumption and emissions from the production of mineral fertilizer [48].

2.4. Nutrient balances and associated emissions

The amount and timing of fertilizer application was taken into account when generating the life cycle inventory (Table B.2).

All nutrients present in the feedstock of the biogas scenario were assumed to end up in the digestate. In the direct combustion scenario, all of the N present in the feedstock was assumed to be lost, while 51 % and 45 % of the P and K present in the feedstock was assumed to be returned to the field with the bottom ash [43]. The mineral nitrogen (min−N), total phosphorous (tot−P) and potassium (K) content of the digestate and bottom ashes replaced equivalent masses of mineral fertilizer (Table 2).

Fertilizer-induced N_2O emissions were calculated applying a conversion factor of 1 % to the applied N. 30 % of the applied N was leached. A conversion factor of 0.75 % was applied to the N in the leached fraction [49]. N_2O emissions from above-ground and below-ground organic matter decomposition was included, using the same conversion factors as above. A N content of 2.5 % in the litter and 0.43 % in the stems was assumed [50], with fine roots having the same N content as the stems.

2.5. Carbon fluxes in soil and standing biomass

The net CO_2 flux between the atmosphere and the biosphere due to the establishment of the willow plantation was calculated as the difference between each scenario and a reference case where no land use change took place. Annual CO_2 fluxes were modeled as in [16] (equation (C.1) & (C.2)). A modified two-compartment C pool model was used (ICBM) [51, 52] that enabled the use of variable yearly input.

The above-ground humification factors (*h* values) and other parameters used in the ICBM model are found in table C.1. The *h* value for below-ground input was multiplied by 2.3 [53].

Annual net C flux in the standing biomass was calculated assuming a 45 % C content in willow DM and a 50 % C content in the DM of other crops.

In this study, SOC pool changes refer to the entire soil profile, since C allocation to different depths varies between crop types. The C input throughout the entire soil profile was calculated as in [16].

Land use prior to establishing the willow was assumed to have been green fallow for a period of 20 years, preceded by annual crops long enough to achieve steady state SOC.

Annual net C flux due to the digestate was determined as the difference in SOC change between applying co-digestion digestate and applying manure only digestate to the same area of application. The C input and initial SOC values of the green fallow and the digestate application area are found in table B.3.

The h value of the digestate (h_{dig}) was calculated as follows: The h values of the manure and willow digestate were estimated ($h_{[m,w]}$) using equation (1), where h_{in} is the h value of the substrate entering the biogas process and $C_{out} \cdot C_{in}^{-1}$ represents the C fraction remaining in the digestate for each substrate:

$$h_{[m,w]} = \frac{h_{in}}{C_{out} \cdot C_{in}^{-1}} \tag{1}$$

The manure and willow h values ($h_m \& h_w$) were then weighted according to their relative share of C in the digestate ($a_{[m,w]}$) using equation (2).

$$h_{dig} = h_m \cdot a_m + h_w(1 - a_m) \tag{2}$$

The resulting h_{dig} was calculated to be 0.48.

2.6. Consideration of conversion efficiency

Converting biomass to biogas before generating electricity inevitably leads to lower energy efficiency compared with direct combustion in a large-scale CHP. Since the biomass output per hectare of land was identical in both scenarios a strict comparison of the climate impact per energy service becomes biased. One approach used in LCA to overcome this problem is to make the reference flows of both systems equal [8]. This is achieved by including the environmental burdens associated with external processes that fulfill equivalent functions to those lacking in one of the systems studied.

Table 3. Emission values for 1 kWh of electricity delivered to the grid for the Swedish mix in 2008, a fictional mix (Other mix) and heat in a local DH distribution network. Emissions and primary energy values are based on [44].

Electricity source	CO_2 $\frac{g}{kWh}$	CH_4 $\frac{mg}{kWh}$	N_2O $\frac{mg}{kWh}$	GWP_{100} $\frac{g_{CO_2\text{-eq}}}{kWh}$
Swedish Mix [a]	20	13	1	21
Other Mix [b]	317	565	6	333
Heat Source				
Local DH [c]	62	8	3	63

[a] The values for the Swedish mix are approximations based on the composition of the energy production from official statistics, the categorization of which does not necessarily coincide with that of [44].

[b] The other mix is composed of 30% nuclear, 30% natural gas generated in a CC-CHP, 30% hard coal generated in a back pressure steam turbine CHP, and 10% wind power. All CHPs are assumed to have a conversion efficiency of 85%. The default power to heat ratio and harmonized efficiency reference values for separate production of electricity and heat of the EU energy efficiency directive were used for allocation of emissions and primary energy calculations [33, 34].

[c] The fuel mixture used for the DH plant was made up of 90% biomass, 5% exhaust gas condensation, 4% auxiliary electricity and 1% oil

Here, the outputs of heat and electricity were equal in both scenarios in relation to the area used. The lower energy efficiency of the biogas system was compensated for by adding the emissions and primary energy input from the production of other heat and electricity sources (Table 3), making the energy output of the biogas scenario equal to that of the direct combustion scenario (Fig. 2).

Two cases for compensation of energy were modeled. The electricity used was either the Swedish electricity mix or a fictional mix (here after referred to as the 'other mix'). The Swedish mix represented electricity with a high share of renewables, while the energy source in the 'other mix' was 30 % nuclear, 30 % natural gas, 30 % hard coal and 10 % wind. In both cases the heat used represented a typical biomass-fired DH system.

2.7. Climate impact

In order to understand the effect of each system on climate over time, the time-dependent climate impact [16] was determined for both scenarios, using the contribution to global mean surface temperature change (ΔT_S) as the indicator. Since ΔT_S is an instantaneous indicator, only temperature effects realized during the evaluation period are included, making the timing of emissions relative to the time of evaluation important.

In order to investigate how the system affected ΔT_S after the study period (year 53), the temperature change was evaluated until year 100, without making any assumptions on future land use (after year 53). Hence, it was assumed that no GHG fluxes affecting ΔT_S took place between the end of the study period and year 100.

The contribution to ΔT_S in the n^{th} year of the evaluation period (ΔT_S(n), equation 3) was calculated as the sum of all individual temperature response functions ($\Delta T_S^{CO_{2i}}$) having their origin in individual emission impulses (E_{x_i}) taking place prior to year n. E_{x_i} is the emission impulse, E, of gas x emitted in year i of the study period. The magnitude of the individual temperature response functions was determined by entering the emission impulses from the time-distributed life cycle inventory into equation 4, where RE_x is the radiative efficiency of GHG x:

$$\Delta T_s(n) = \sum_{x=1}^{3} \sum_{i=1}^{n} \Delta T_s^{x_i}(t) \qquad [\mathrm{K}] \tag{3}$$

$$\begin{cases} \Delta T_s^{CO_{2i}}(t) = E_{CO_{2i}} \cdot RE_{CO_2} \cdot \left(k_0 + \sum_{j=1}^{5} k_i \exp^{\left(-\frac{t}{\tau_j^{CO_2}} \right)} \right) & [\mathrm{K}] \\ \Delta T_s^{CH_{4i}}(t) = E_{CH_{4i}} \cdot RE_{CH_4} \cdot \left(\sum_{i=1}^{3} m_j \exp^{\left(-\frac{t}{\tau_j^{CH_4}} \right)} \right) & [\mathrm{K}] \\ \Delta T_s^{N_2O_i}(t) = E_{N_2O_i} \cdot RE_{N_2O} \cdot \left(\sum_{i=1}^{3} n_j \exp^{\left(-\frac{t}{\tau_j^{N_2O}} \right)} \right) & [\mathrm{K}] \end{cases} \tag{4}$$

Parameters used in equation 4 were the same as in [16].

3. Results

3.1. Energy efficiency

Both the biogas and direct combustion scenarios were net producers of energy, having an ER of three-fold and 19-fold, respectively.

The average amount of energy delivered over the study period was 16 GJ per (ha yr) from the biogas scenario and 141 GJ per (ha yr) from the direct combustion scenario. The electricity to heat ratio for the biogas and direct combustion scenarios was 0.91 and 0.45, respectively. As a result, the direct combustion scenario delivered six-fold more electricity and 11-fold more heat than the biogas scenario.

The ER between the electricity delivered and primary energy input allocated to electricity was 11 in the direct combustion scenario and 2.3 in the biogas scenario. When the reference flows were forced to be equal by adding heat and electricity to the biogas scenario, the ER dropped to 0.7.

3.2. Greenhouse gas fluxes

The willow biomass was carbon-neutral over each rotation, as the amount of C emitted when generating energy was the same as that taken up by the willow during its growth. The net CO_2 flux from the biomass to the atmosphere (Table 4) was positive due to the difference in biomass present before establishing the willow and after the final harvest of the last rotation (Fig. 3a,b).

Differences in total GHG emissions between the scenarios were mainly due to SOC stock changes induced by willow C returned with the digestate and CH_4 losses in the biogas scenario (Fig. 3a-d).

The introduction of willow in the biogas process gave rise to additional digestate, increasing the SOC pool of the digestate application area by 11 t of C per ha (325 ha) over 53 years.

The average sequestration rate was 432 kg of C per (ha yr) in the willow plantation (45 ha) and 236 kg of C per (ha yr) in the digestate application area (325 ha). The latter was a larger C sink due to its greater extension compared with the willow plantation (Table 4).

CH_4 losses from the anaerobic digestion process and storage of the digestate were large sources of CH_4 emissions in the biogas scenario, explaining almost the entire difference in CH_4 emissions between the two scenarios (Fig. 3c,d).

Longer transport distance to the CHP plant gave higher CO_2 emissions from operations in the direct combustion scenario.

Biomass and fertilizer-induced emissions were the main sources of N_2O in the system (Fig. 3e,f). Emissions from the manufacturing of mineral fertilizer were slightly lower in the biogas scenario due to a higher recycling rate, leading to more mineral fertilizers being replaced.

Table 4. Total accumulated emissions per hectare for the biogas and direct combustion scenarios over the entire study period, displayed in sources and sinks.

	Biogas			Direct combustion		
	CO_2 t	CH_4 kg	N_2O kg	CO_2 t	CH_4 kg	N_2O kg
Sources						
Energy production [a]	180	7	18	25	11	28
CH_4leakage [b]		632				
Fertilizer induced N_2O [c]			50			50
Biomass induced N_2O [d]			70			70
Live biomass - C [e]	4			4		
Sinks						
Soil C - SRC willow	−79			−79		
Soil C - Digestate	−310					
Total	**367**	**639**	**138**	**–51**	**11**	**148**
GWP_{100} [t (CO_2-eq)	−367	16	41	−51	0	44

[a] Energy production includes all machine operations, such as willow production, transport and handling of the residues.

[b] CH_4 losses from the digestion process and during storage are included.

[c] Fertilizer-induced emissions refer to those attributed to fertilizers applied to the willow.

[d] Biomass-induced emissions refer to those attributed to biomass broken down in the field.

[e] The live biomass can act as both a sink and a source. Positive emissions are due to the difference in standing biomass prior to the establishment of the willow and after the final harvest of the willow. The willow biomass in itself is carbon-neutral over a complete life cycle.

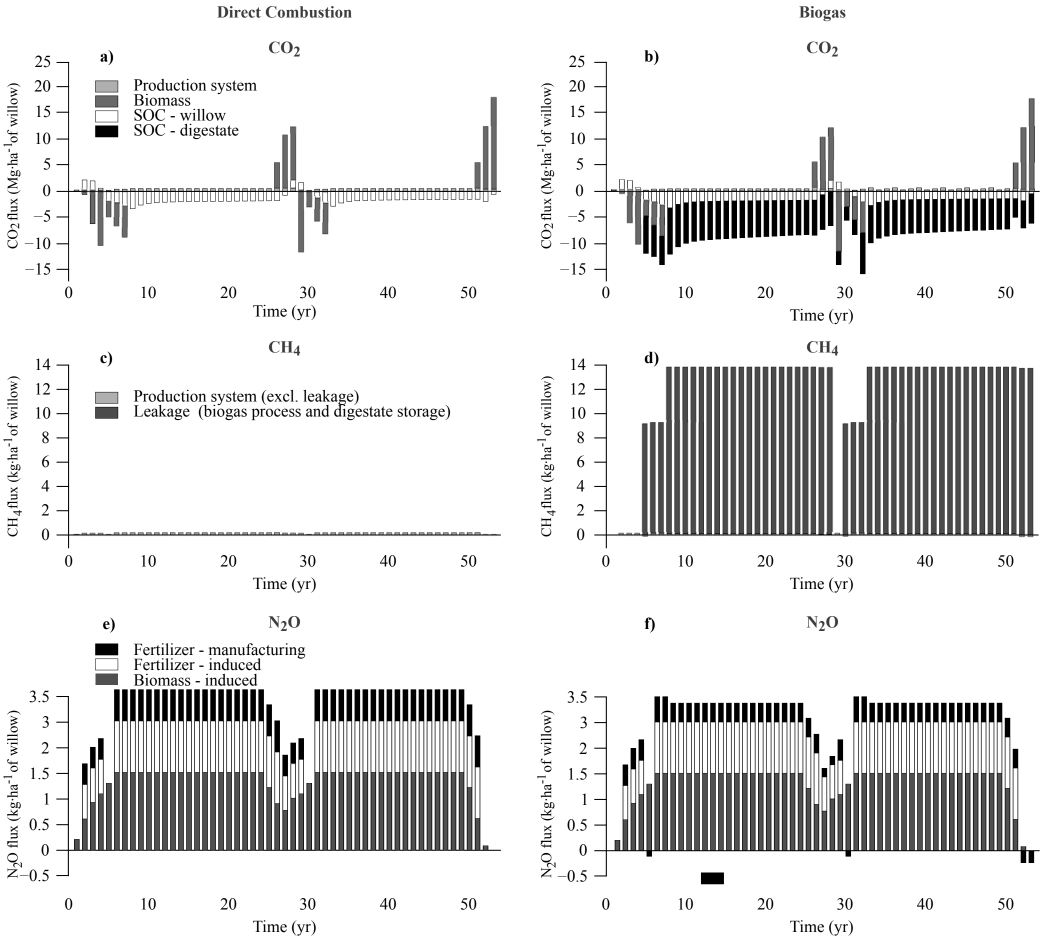

Fig. 3. Time-distributed life cycle inventory of the direct combustion and biogas scenarios. Greenhouse gas (GHG) fluxes from the main sources and sinks of each scenario are shown stacked. Soil organic carbon (SOC) stock changes, CH_4 losses from the biogas process and digestate storage, and reduced mineral fertilizer requirements due to higher recycling rates of nutrients in the biogas system were the principal differences between the two scenarios.

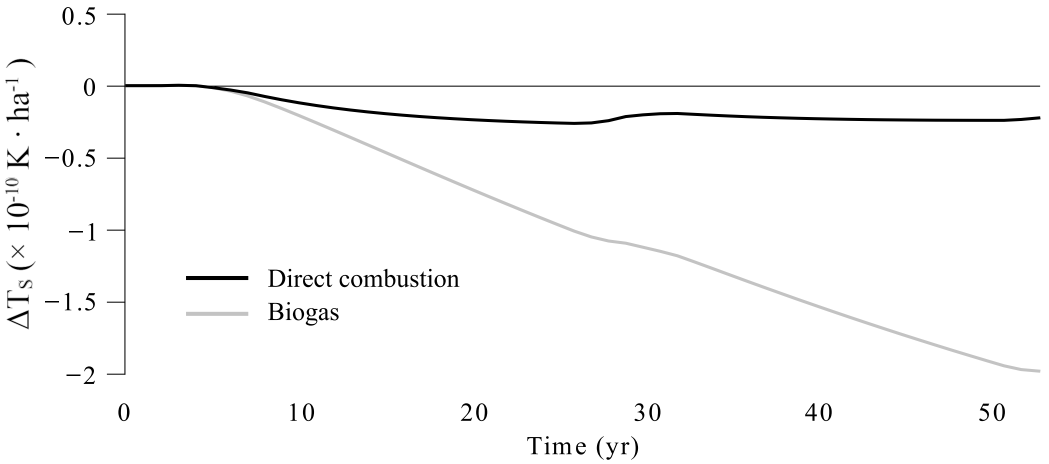

Fig. 4. Contribution to ΔT_S from willow grown for 50 years on 1 hectare of land for heat and power generation using either a biogas engine or direct combustion.

3.3. Climate impact

Both scenarios made a negative contribution to ΔT_S, counteracting global warming. The cooling effect per hectare of willow was nine-fold greater in the biogas scenario than in the direct combustion scenario at the end of the study period (Biogas: -1.98×10^{-10} K per ha; Direct combustion: -0.22×10^{-10} K per ha in year 53). Almost all of the decrease in ΔT_S took place during the first rotation of the direct combustion scenario (Fig. 4). In the biogas scenario ΔT_S continued to decrease throughout the entire study period, increasing the difference between the scenarios over time. The main contributing factor to this difference was the SOC stock changes induced by the C returned to the field with the digestate.

The effect of the biogas system on ΔT_S after the reference flows had been adjusted for its lower energy efficiency depended on the composition of the compensating electricity mix used. When the Swedish mix was used, the cooling contribution to ΔT_S in the biogas scenario was six-fold that of the direct combustion scenario at the end of the study period (Fig. 5). Using the other mix resulted in a warming contribution to ΔT_S from the biogas scenario at the end of the study period.

All three scenarios counteracted global warming the first 18 years (Fig. 5). This effect was due to the rapid and substantial biomass increase changing cropping system (Figs. 3a,b and 6). The cooling effect from the increased C stock in the biomass dominated the short term trend in ΔT_S, while the SOC stock changes dominated the long term trend.

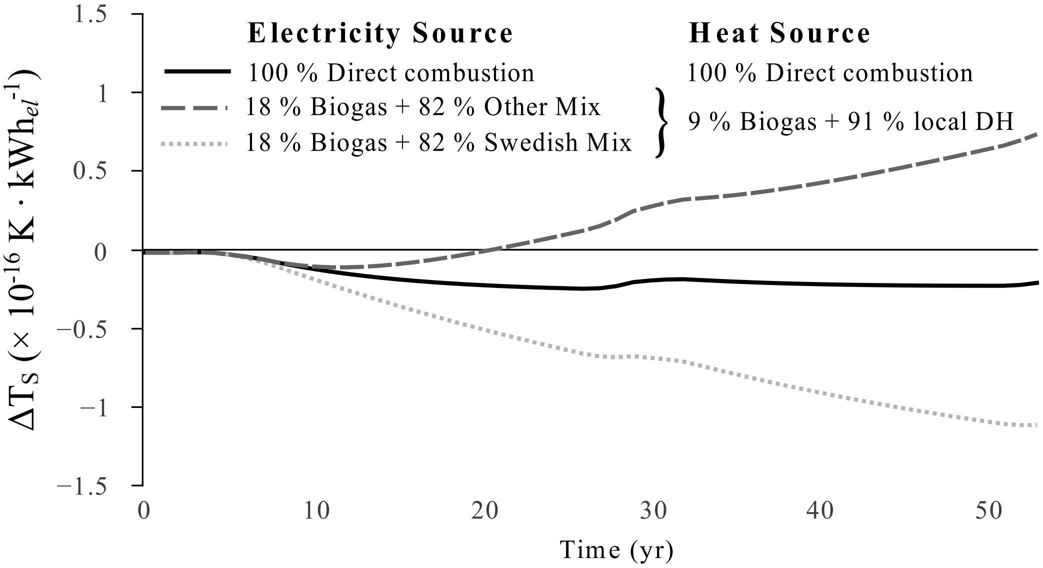

Fig. 5. Contribution to ΔT_S from the electricity of both systems after adjusting the reference flow in the biogas system. The electricity used to compensate for the lower electric output of the biogas scenario was either the Swedish mix or other mix (30 % nuclear, 30 % natural gas, 30 % hard coal and 10 % wind). The heat used to compensate for the lower heat output was assumed to be that of a local DH distribution system, using mainly biomass as the fuel source.

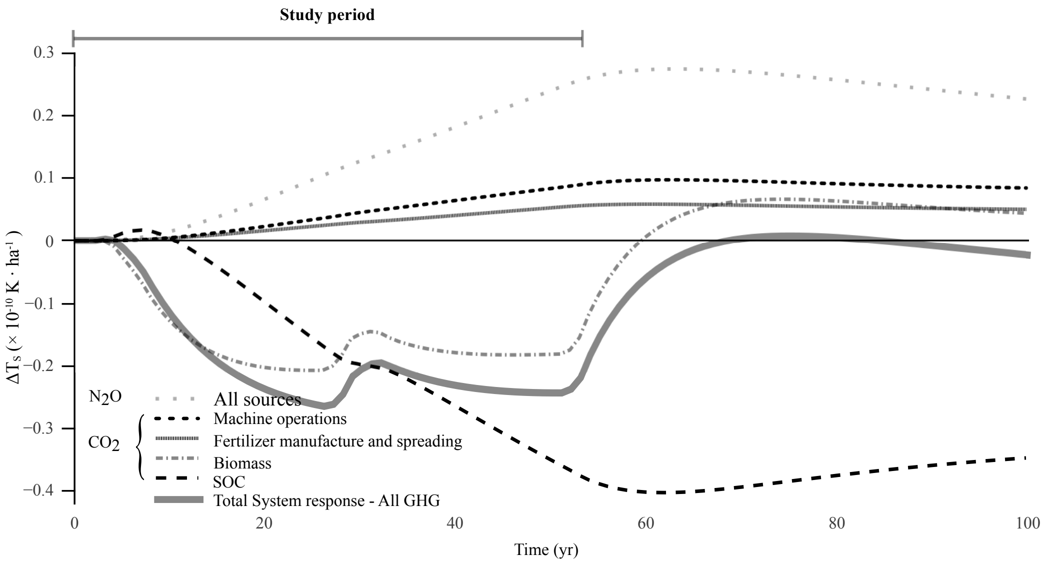

Fig. 6. Effect of emissions produced in year 0 to 53 in the combustion scenario on ΔT_S during and after the study period. The effect on ΔT_S after year 53 is that from GHG emitted in the study period. No assumptions were made on land use after year 53 and no GHG fluxes affecting the temperature response occurred after this year. The thick gray line represents the total system impact.

The effect of all activities taking place in the direct combustion scenario during the study period on ΔT_S after the end of the study period was evaluated. No assumptions were made on what the land was used for after the final harvest. This revealed the effect of returning the C in the live biomass to the atmosphere (Fig. 6). The temperature cooling effect became a warming contribution to ΔT_S within ten years after the final harvest. This occurred because the relative contribution of the biomass to the total contribution to ΔT_S was high and the total biomass at the site after final harvest was lower than before establishing the willow (Table 4). It is important to consider this effect when evaluating subsequent systems if C stock changes take place. The total temperature response will be the combined effect of the not yet realized temperature response from the previous system and the future temperature response from the new system.

3.4. Sensitivity analysis

The sensitivity of ER and ΔT_S to changes in some of the input parameters was tested in a sensitivity analysis. The humification coefficient (*h* value) of the digestate and the CH_4 yield of the willow fraction were varied since they influenced the final result of the biogas scenario. The initial SOC level of the willow plantation

Table 5. Primary energy input in the Biogas and Combustion energy production scenarios (MJ/ha/yr).

	Biogas	Combustion
Willow cultivation		
- *establishment*	349	349
- *fertilization* [a]	1550	2438
- *harvest*	3206	3206
- *termination*	144	144
Transport [b]	98	1355
Handling of residues [c]	233	4
Total	**5580**	**7496**

[a] Primary energy input into production of fertilizers for the willow plantation was reduced by the amount of primary energy saved through increased recycling of nutrients on the dairy farm.

[b] Transport is from field side to the digester or CHP-plant.

[c] Handling of residues includes loading, transport to the field and application of recycled digestate and ashes.

was also varied since it affected the final results of both scenarios. The parameters were varied in steps of 20 % between 20 % and 200 % of the value in the base scenarios. The effect on the impact indicator values was calculated and recorded as % of base scenario.

The effect of the CH_4 yield on ΔT_S expressed per kWh of electricity delivered increased exponentially with a decreasing yield (Fig. 7c), up to the point where net electric output became negative (which happened at a CH_4 yield of 16 % of the base scenario) (Fig. 7b,c). This effect is explained by two factors. First, the recycling rate of C with the digestate increased as CH_4 yield decreased, leading to a higher sequestration rate of C on the dairy farm. This amplified the climate impact of the system. Secondly, the energy efficiency of the system decreased with decreasing CH_4 yield, increasing the sensitivity of the climate impact indicator.

The CH_4 yield was the only parameter that affected the ER (Fig. 7b). Apart from the climate impact per kWh of electricity delivered, the ER was the indicator most affected by a change in the parameters in the biogas scenario (Fig. 7a,b,d and e).

The h value of the digestate and the initial SOC level of the willow plantation affected ΔT_S identically on a per hectare and per kWh basis, since they did not affect the ER of the biogas scenario, leaving the allocation factor unaltered (Fig. 7d,e and f).

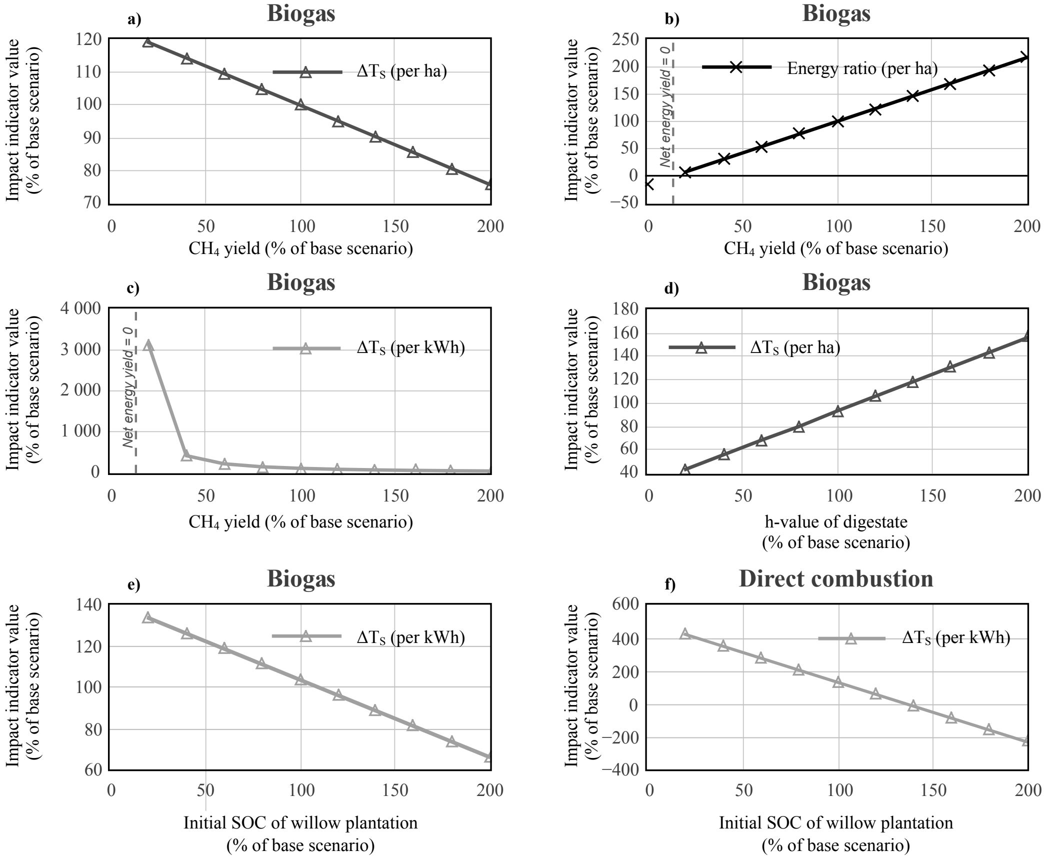

Fig. 7. Sensitivity analysis of the indicators ER and ΔT_S to changes in the CH_4 yield, h value of the digestate and initial SOC content in the willow plantation. Parameters that did not affect the energy ratio had an identical impact on the indicators, expressed per hectare and per kWh.

ΔT_S was more sensitive to changes in the initial SOC level in the direct combustion scenario than in the biogas scenario, since the relative contribution to the climate impact was higher in in the former scenario (Fig. 7e and f).

4. Discussion

Growing SRC willow to generate electricity and heat can be energy-efficient and counteract the current trend in global warming. The direct combustion and biogas scenarios studied were both net energy producers and had a cooling effect on ΔT_S. The cooling effect was stronger in the biogas scenario due to the recycling of C with the digestate, resulting in increased SOC stocks. The ratio of the primary energy input to the energy in the biogas produced corresponded to results of other life cycle studies of biogas production from manure, grasses, straw and silage crops [45, 54, 55]. However, the biogas yield from the willow used in this study was very low compared with that from other energy crops used for biogas production. A different pretreatment or added post digestion step would most likely affect the biogas yield and the comparison between the two systems studied.

Climate impact from the SOC and biomass stock changes in the biogas scenario was several-fold higher and of an opposing sign to the impacts from the fossil inputs and fertilizers used. This came at the cost of net energy output since there was a clear trade-off between maximizing energy efficiency and sequestering C.

The biogas conversion step enabled a high recycling rate of nutrients and C back to the soil. This higher recycling rate of nutrients may be important for closing the loops in agriculture, but had little impact on the energy efficiency and climate impact in this study. However, the effect of recycling C was very large for both the energy efficiency and climate impact of the system. The biogas system was shown to offer a sustained cooling contribution to ΔT_S due to the long term accumulation of SOC. This differentiated it from the direct combustion scenario,which only offered a short-term mitigation effect when it came to counteracting global warming. The importance of considering SOC whenever a land use change occur is also evident from the CH_4 losses in the biogas system. This would have had a much larger relative climate impact if the SOC had not been considered.

The energy sources used to compensate for the lower ER of the biogas scenario proved to be critical. After adjusting the reference flow of the biogas scenario to be equal to the direct combustion scenario, the external production source of electricity and heat chosen effectively determined whether the biogas scenario had a cooling or a warming influence on ΔT_S. In all cases the biogas system contributes to lower the climate impact of the electricity mix.

If the lower output in the biogas scenario could be compensated for by expanding the area of willow cultivation on existing fallow and marginal land which would otherwise not be used for forestry or food production the beneficial climate effects would be very large since more C could be sequestered.

If the demand for bioenergy sector products increases, it is possible that the profitability of bioenergy plantations might surpass those of conventional crops on primary farmland. If that is the case, the consequences of indirect land use change (iLUC) have to be taken into account when determining the possible consequences of choosing biogas over direct combustion [56].

An important observation from this study was the long-term effects on yield in a scenario where recycling rates are high [57]. The long-term fertilization effect of organic nitrogen and SOC will most likely reduce the need for external inputs per unit of biomass yield in a biogas system. This could lead to increased competitiveness of the individual farm, which is an important aspect for the economic sustainability of bioenergy. This has to be viewed in the light of the energy efficiency of the system. If the gains from recycled nutrients can not compensate for the lower energy output there is little or no incentive for farmers to choose a less energy-efficient system, no matter what the implications are for the climate. After all, it is the the on-farm profitability of cropping that will ultimately decide the future of bioenergy crops.

From an energy security perspective it seems preferable to utilize the feedstock in the most energy efficient way, which in this case was direct combustion. If regional development and economy is in the focus of policy makers it makes more sense to support other resources for biogas production which can offer higher yields at lower costs and where techonology development needs are smaller. The most obvious advantage of the biogas system was its high mitigation effect against global warming. It is however not obvious that it would be a good policy to support biogas production from willow to mitigate global warming. There might be other systems that may provide the same benefits with higher energy efficiency, for example pyrolysis systems [58]. Unlike the biogas process, the pyrolysis process stabilises the carbon which further increases its mitigating effects.

Another important insight is that SRC willow systems have the potential to produce electricity and heat while counteracting the current trend in global warming at the same time. Whether direct combustion, optimizing the net electrical output, or prior conversion to biogas, optimizing recycling and C sequestration, is preferable is a question of societal priorities. To answer that question, factors other than the energy efficiency and climate impact of the system need to be considered. Some of the issues that need to be taken into account are the economic, social and general environmental aspects of the system, as well as how society uses energy in general.

5. Conclusions

The climate impact and energy efficiency of producing electricity and heat from SRC willow using either a biogas conversion pathway or direct combustion were compared using LCA methodology. Both systems may be net generators of electricity and heat, and may also contribute to counteracting the current trend in global warming due to potential SOC increases, providing an additional benefit to that of replacing non-renewable and fossil fuels in climate change mitigation strategies. An important temporal difference in the climate effect was shown. The cooling influence of the direct combustion system was stabilized after the first rotation of the study period, while the biogas system continued to exert a cooling influence throughout the entire study period. This offers two different options in a policy context, depending on the climate goals considered more important. A clear trade-off between C sequestration and energy efficiency was shown in the biogas scenario, where a decreasing CH_4 yield resulted in a lower energy efficiency, but increased the C recycling, the potential SOC levels and the cooling effect on ΔT_S per unit of energy produced. If the lower energy efficiency of the biogas system needs to be compensated for using energy from other sources, the climate benefit of the biogas system relative to direct combustion will depend on the external energy source used. In all cases, the SRC willow system contributes to lowering the climate impact of the energy system.

Acknowledgments

We are grateful to the STandUP for Energy program and the Swedish Research Council Formas (project number 2009-2056) for financial support as well as Anna Schnürer, Maria Eriksson and the rest of the staff at the Department of Microbiology at the Swedish University of Agricultural Sciences involved in the anaerobic digestion trials for their work and for providing us with anaerobic digestion data. We are also gratefull to Edgar Hertwich at the Norwegian University of Science and Technology and Anna Mårtensson at the Swedish University of Agricultural Sciences for contributing with helpful comments on the drafts of this manuscript.

[1] Swedish Energy Agency, Energy in sweden 2011, Report 43, Swedish Energy Agency (2011).

[2] Swedish Energy Agency, Produktion och användning av biogas år 2011, Report ES 2012:08, Energimyndigheten, Eskilstuna, Sweden (2012).

[3] T. Lönnqvist, S. Silveira, A. Sanches-Pereira, Swedish resource potential from residues and energy crops to enhance biogas generation, Renewable and Sustainable Energy Reviews 21 (0) (2013) 298 – 314. `doi:10.1016/j.rser.2012.12.024`.

[4] A. Lehtomäki, S. Huttunen, J. Rintala, Laboratory investigations on codigestion of energy crops and crop residues with cow manure for methane production: Effect of crop to manure ratio, Resources, Conservation and Recycling 51 (3) (2007) 591 – 609. `doi:http://dx.doi.org/10.1016/j.resconrec.2006.11.004`.

[5] H. Janzen, The soil carbon dilemma: Shall we hoard it or use it?, Soil Biology and Biochemistry 38 (3) (2006) 419 – 424. `doi:10.1016/j.soilbio.2005.10.008`.

[6] A. Galvez, T. Sinicco, M. Cayuela, M. Mingorance, F. Fornasier, C. Mondini, Short term effects of bioenergy by-products on soil C and N dynamics, nutrient availability and biochemical properties, Agriculture, Ecosystems & Environment 160 (0) (2012) 3 – 14. `doi:10.1016/j.agee.2011.06.015`.

[7] ISO 14040:2006, Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006), European Comittee for Standardization, rue de Stassart 36, B-1050 BRUSSELS, 1st Edition, supersedes EN ISO 14040:1997, EN ISO 14041:1998, EN ISO 14042:2000, EN ISO 14043:2000 (19 Jun. 2006).

[8] ISO 14044:2006, Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006), European Comittee for Standardization, rue de Stassart 36, B-1050 BRUSSELS, 1st Edition, supersedes EN ISO 14040:1997, EN ISO 14041:1998, EN ISO 14042:2000, EN ISO 14043:2000 (19 Jun. 2006).

[9] M. C. Heller, G. A. Keoleian, M. K. Mann, T. A. Volk, Life cycle energy and environmental benefits of generating electricity from willow biomass, Re-

newable Energy 29 (7) (2004) 1023 – 1042. `doi:DOI:10.1016/j.renene.2003.11.018`.

[10] G. A. Keoleian, T. A. Volk, Renewable energy from willow biomass crops: Life cycle energy, environmental and economic performance, Critical Reviews in Plant Sciences 24 (5-6) (2005) 385–406. `doi:10.1080/07352680500316334`.

[11] D. Styles, M. B. Jones, Energy crops in ireland: Quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity, Biomass and Bioenergy 31 (11-12) (2007) 759 – 772. `doi:DOI:10.1016/j.biombioe.2007.05.003`.

[12] P. Goglio, P. Owende, A screening lca of short rotation coppice willow (salix sp.) feedstock production system for small-scale electricity generation, Biosystems Engineering 103 (3) (2009) 389–394.

[13] M. Kimming, C. Sundberg, Å. Nordberg, A. Baky, S. Bernesson, O. Norén, P.-A. Hansson, Biomass from agriculture in small-scale combined heat and power plants – a comparative life cycle assessment, Biomass and Bioenergy 35 (4) (2011) 1572–1581. `doi:10.1016/j.biombioe.2010.12.027`.

[14] S. González-García, D. Iribarren, A. Susmozas, J. Dufour, R. J. Murphy, Life cycle assessment of two alternative bioenergy systems involving salix spp. biomass: Bioethanol production and power generation, Applied Energy 95 (0) (2012) 111 – 122. `doi:http://dx.doi.org/10.1016/j.apenergy.2012.02.022`.

[15] S. Njakou Djomo, O. El Kasmioui, T. De Groote, L. Broeckx, M. Verlinden, G. Berhongaray, R. Fichot, D. Zona, S. Dillen, J. King, I. Janssens, R. Ceulemans, Energy and climate benefits of bioelectricity from low-input short rotation woody crops on agricultural land over a two-year rotation, Applied Energy 111 (2013) 862–870.

[16] N. Ericsson, C. Porsö, S. Ahlgren, Å. Nordberg, C. Sundberg, P.-A. Hansson, Time-dependent climate impact of a bioenergy system - methodology development and application to swedish conditions, GCB Bioenergy 5 (5) (2013) 580–590. `doi:10.1111/gcbb.12031`.

[17] A. Roedl, Production and energetic utilization of wood from short rotation coppice-a life cycle assessment, International Journal of Life Cycle Assessment 15 (6) (2010) 567–578.

[18] B. Gabrielle, N. Nguyen The, P. Maupu, E. Vial, Life cycle assessment of eucalyptus short rotation coppices for bioenergy production in southern france, GCB Bioenergy 5 (1) (2013) 30–42. `doi:10.1111/gcbb.12008`.

[19] S. N. DJOMO, O. E. KASMIOUI, R. CEULEMANS, Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review, GCB Bioenergy 3 (3) (2011) 181–197. `doi:10.1111/j.1757-1707.2010.01073.x`.

[20] A. Courchesne, V. Bécaert, R. Rosenbaum, L. Deschênes, R. Samson, Using the lashof accounting methodology to assess carbon mitigation projects with life cycle assessment, Journal of Industrial Ecology 14 (2) (2010) 309–321. `doi:10.1111/j.1530-9290.2010.00228.x`.

[21] F. Murphy, G. Devlin, K. Mcdonnell, Energy requirements and environmental impacts associated with the production of short rotation willow (salix sp.) chip in ireland, GCB BioenergyArticle in press.

[22] P. Forster, V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D. W. Fahey, J. Haywood, J. Lean, D. C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, R. van Dorland, Changes in Atmospheric Constituents and in Radiative Forcing, Vol. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2007, Ch. 2, pp. 129–234.

[23] E. Johnson, Goodbye to carbon neutral: Getting biomass footprints right, Environmental Impact Assessment Review 29 (3) (2009) 165–168. `doi:10.1016/j.eiar.2008.11.002`.

[24] M. Brandão, A. Levasseur, M. Kirschbaum, B. Weidema, A. Cowie, S. Jørgensen, M. Hauschild, D. Pennington, K. Chomkhamsri, Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting, The International Journal of Life Cycle Assessment (2012) 1–11`doi:10.1007/s11367-012-0451-6`.

[25] R. Lal, Soil carbon sequestration to mitigate climate change, Geoderma 123 (1-2) (2004) 1–22. `doi:10.1016/j.geoderma.2004.01.032`.

[26] C. Poeplau, A. Don, L. Vesterdal, J. Leifeld, B. Van Wesemael, J. Schumacher, A. Gensior, Temporal dynamics of soil organic carbon after land-use change in the temperate zone - carbon response functions as a model approach, Global Change Biology 17 (7) (2011) 2415–2427, cited By (since 1996)31. `doi:10.1111/j.1365-2486.2011.02408.x`.

[27] S. Muench, E. Guenther, A systematic review of bioenergy life cycle assessments, Applied Energy 112 (0) (2013) 257 – 273. `doi:http://dx.doi.org/10.1016/j.apenergy.2013.06.001`.

[28] K. Tanaka, G. Peters, J. Fuglestvedt, Multicomponent climate policy - why do emission metrics matter?, Carbon Management 1 (2) (2010) 191–197, cited By (since 1996) 0. `doi:10.4155/cmt.10.28`.

[29] G. Peters, B. Aamaas, M. T. Lund, C. Solli, J. Fuglestvedt, Alternative ”global warming” metrics in life cycle assessment: A case study with existing transportation data, Environmental Science and Technology 45 (20) (2011) 8633–8641, cited By (since 1996) 0. `doi:10.1021/es200627s`.

[30] J. Hammond, S. Shackley, S. Sohi, P. Brownsort, Prospective life cycle carbon abatement for pyrolysis biochar systems in the uk, Energy Policy 39 (5) (2011) 2646–2655. `doi:10.1016/j.enpol.2011.02.033`.

[31] Swedenergy, Miljövärdering 2012. Guide för allokering i kraftvärmeverk och fjärrvärmens elanvändning (2012).

[32] GHG Protocol, Allocation of GHG Emissions from a Combined Heat and Power (CHP) Plant. Guide to calculation worksheets (September 2006) v1.0 A WRI/WBCSD GHG Protocol Initiative calculation tool.

[33] EU, 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, commision implementing decision L343/91, European commision (12 2011).

[34] EU, 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 2004/8/EC and 2006/32/EC., Directive L315/1, European comission (11 2012).

[35] R. Hollsten, O. Arkelöf, G. Ingelman, Handbok för Salixodlare, KanEnergi Sverige AB (2013).

[36] A. Baky, M. Forsberg, H. Rosenqvist, N. Jonsson, M. Sundberg, Harvest and logistics for better profitability from small cultivations of short rotation willow coppice, Report 1143, Värmeforsk (2010).

[37] B. Thomas, A. Wyndorps, Efficiencies and emissions of a 192kWel otto engine chp-unit running on biogas at the research station ünterer lindenhof", Engineering in Life Sciences 12 (3) (2012) 306–312. `doi:10.1002/elsc.201100070`.

[38] H.-J. Naegele, A. Lemmer, H. Oechsner, T. Jungbluth, Electric energy consumption of the full scale research biogas plant "unterer lindenhof": Results of longterm and full detail measurements, Energies 5 (12) (2012) 5198–5214. `doi:10.3390/en5125198`.

[39] Z. Miao, T. Grift, A. Hansen, K. Ting, Energy requirement for comminution of biomass in relation to particle physical properties, Industrial Crops and Products 33 (2) (2011) 504 – 513.

[40] M. Berglund, P. Börjesson, Energianalys av biogassystem, Tech. Rep. 44, Lunds Tekniska Högskola, Lund (2003).

[41] R. Overend, The average haul distance and transportation work factors for biomass delivered to a central plant, Biomass 2 (1) (1982) 75 – 79. `doi:http://dx.doi.org/10.1016/0144-4565(82)90008-7`.

[42] M. Sundberg, W. Johansson, H. Hjortsberg, K. Hansson, H. Oostra, K. Berglund, H. Elmquist, Biogas i framtida lantbruk och kretsloppssamhällen - effekter på mark, miljö och ekonomi., Tech. Rep. 12, Jordbrukstekniska institutet, Uppsala (1997).

[43] H. Bjurström, S. Grönstedt, S. Shamsa, R. Beijer, Maintaining the database allaska 2009-2011, Tech. Rep. 1248, Värmeforsk, Stockholm (2012).

[44] J. Gode, F. Martinsson, L. Hagberg, A. Öman, J. Höglund, D. Palm, Miljöfaktaboken 2011. estimated emission factors for fuels, electricity, heat and transport in sweden, Tech. Rep. 1183, Värmeforsk, Stockholm (2011).

[45] M. Berglund, P. Börjesson, Assessment of energy performance in the life-cycle of biogas production, Biomass and Bioenergy 30 (3) (2006) 254–266. `doi:10.1016/j.biombioe.2005.11.011`.

[46] Avfall Sverige, Frivilligt åtagande kartläggning av metanförluster från biogasanläggningar 2007-2008, Rapport, Avfall Sverige, Malmö (2009).

[47] J. Liebetrau, T. Reinelt, J. Clemens, C. Hafermann, J. Friehe, P. Weiland, Analysis of greenhouse gas emissions from 10 biogas plants within the agricultural sector, Water Science & Technology 67 (6) (2013) 1370–1379. `doi:10.2166/wst.2013.005`.

[48] P. Börjesson, L. Tufvesson, M. Lantz, Life cycle assessment of biofuels in sweden, Tech. Rep. 70, Department of Environmental and Energy Systems Studies, Lund University (2010).

[49] IPCC, 2006 IPCC guidelines for national greenhouse gas inventories, prepared by the national greenhouse gas inventories programme (2006).

[50] M. Weih, N.-E. Nordh, Determinants of biomass production in hybrid willows and prediction of field performance from pot studies, Tree Physiology 25 (9) (2005) 1197–1206, cited By (since 1996) 13.

[51] O. Andrén, T. Kätterer, ICBM: The introductory carbon balance model for exploration of soil carbon balances, Ecological Applications 7 (4) (1997) 1226–1236.

[52] T. Kätterer, O. Andrén, J. Persson, The impact of altered management on long-term agricultural soil carbon stocks - a swedish case study, Nutrient Cycling in Agroecosystems 70 (2) (2004) 179–187. `doi:10.1023/B:FRES.0000048481.34439.71`.

[53] T. Kätterer, M. Bolinder, O. Andrén, H. Kirchmann, L. Menichetti, 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 (1-2) (2011) 184–192, cited By (since 1996) 0. `doi:10.1016/j.agee.2011.02.029`.

[54] B. Smyth, J. Murphy, C. O'Brien, What is the energy balance of grass biomethane in ireland and other temperate northern european climates?, Renewable and Sustainable Energy Reviews 13 (9) (2009) 2349–2360, cited By (since 1996)45. `doi:10.1016/j.rser.2009.04.003`.

[55] M. Pöschl, S. Ward, P. Owende, Evaluation of energy efficiency of various biogas production and utilization pathways, Applied Energy 87 (11) (2010) 3305–3321, cited By (since 1996)77. `doi:10.1016/j.apenergy.2010.05.011`.

[56] D. Lapola, R. Schaldach, J. Alcamo, A. Bondeau, J. Koch, C. Koelking, J. Priess, Indirect land-use changes can overcome carbon savings from biofuels in brazil, Proceedings of the National Academy of Sciences of the United States of America 107 (8) (2010) 3388–3393. `doi:10.1073/pnas.0907318107`.

[57] M. Odlare, V. Arthurson, M. Pell, K. Svensson, E. Nehrenheim, J. Abubaker, Land application of organic waste - effects on the soil ecosystem, Applied Energy 88 (2011) 2210–2218. `doi:10.1016/j.apenergy.2010.12.043`.

[58] E. Lugato, F. P. Vaccari, L. Genesio, S. Baronti, A. Pozzi, M. Rack, J. Woods, G. Simonetti, L. Montanarella, F. Miglietta, An energy-biochar chain involving biomass gasification and rice cultivation in northern italy, GCB Bioenergy 5 (2) (2013) 192–201. `doi:10.1111/gcbb.12028`.

[59] D. Nilsson, S. Bernesson, Pelletering och brikettering av jordbruksråvaror, Tech. Rep. 001, Sveriges lantbruksuniversitet, Institutionen för energi och teknik, Uppsala (2008).

[60] M. Lindgren, O. Pettersson, P.-A. Hansson, O. Norén, Engine load pattern and engine exhaust gas emissions from off-road vehicles and methods to reduce fuel-consumption and engine exhaust gas emissions, Tech. Rep. 308, Institutet för jordbruks och miljöteknik, Uppsala (2002).

[61] P. Börjesson, Livscykelanalys av salixproduktion, IMES/EESS Report 60, Department of Environmental and Energy Systems Studies, Lund University (2006).

[62] I. Norberg, N.-E. Nordh, Att avsluta en salixodling, Tech. Rep. 2, Institutet för jordbruks och miljöteknik, Uppsala (2012).

[63] M. Dalemo, A. Björklund, H. Oostra, U. Sonesson, Systems analysis of nutrient recycling from organic wastes, Tech. Rep. 15, Jordbrukstekniska institutet, Uppsala (1998).

[64] U. Sonesson, Modelling of the compost and transport process in the ORWARE simulation model, Tech. Rep. 214, Swedish University of Agricultural Sciences, Department of agricultural engineering, Uppsala (1996).

[65] Jordbruksverket, Föreskrifter om ändring i statens jordbruksverks föreskrifter och allmänna råd (sjvfs 2004:62) om miljöhänsyn i jordbruket vad avser växtnäring;, Föreskrift 2012:41, Swedish board of agriculture, Jönköping (2012).

[66] O. Andrén, T. Kätterer, T. Karlsson, Icbm regional model for estimations of dynamics of agricultural soil carbon pools, Nutrient Cycling in Agroecosystems 70 (2) (2004) 231–239. `doi:10.1023/B:FRES.0000048471.59164.ff`.

AppendixA. Transportation distance equation

$$Td = WF\sqrt{\frac{Ra}{200\pi \cdot n(r) \cdot PU}} \tag{A.1}$$

where

Td : average transportation distance

Ra : area required for spreading of digestate

n(r) : share of arable land as a function of the distance to the center.

WF : winding factor. Turns straight lind distance into actual road distance.

PU : part of land used for application of digestate.

AppendixB. Input data

Table B.1. Energy and emission data for machine operations over the entire study period.

Moment	primary energy MJ/ha	CO_2 kg/ha	CH_4 g/ha	N2O mg/ha
Herbicide application - establishment[a] [59]	273	17	1	25
Plowing[b] [60]	508	32	3	47
Harrowing[c] [60]	624	40	3	58
Seedling production[61]	29040	874	380	13559
Planting [59]	179	11	1	17
Weed control[d] [59]	363	23	2	34
Fertilizer application[e] [60]	714	45	4	67
Harvest[f] [59]	110652	7016	578	10308
Field transport[g] [59]	68894	4368	360	6418
Pre-transport chipping[h] [59]	141035	8942	737	13139
Road transport - scenario 1[i] [36]	9798	621	51	913
Road transport - scenario 2[j] [36]	153216	10127	588	2687
Herbicide application - termination[k] [59]	136	9	1	13
Rotary cultivator[l] [62]	8902	564	47	829
Shallow soil preparation[m][62]	3452	219	18	322
Comminution - scenario 1[n] [39]	501914	1451	957	63017
Spreading of digestate, willow only[o] [63, 60, 40]	1275060	80843	6662	118784
Loading and transport of ash[p] [60]	17	1	0	0

[a] Trailed sprayer, 3500 l, 24 m.

[b] 4-furrow reversible plough, autumn. First rotation only.

[c] Spring, 70 spikes.

[d] Weeder, 12 m.

[e] Rotina 881.

[f] Whole stem harvester, empire 2000.

[g] 3 tractors, 80kW with dumpers, 12Mg.

[h] Stationary wood chipper, 400 kW.

[i] Containertransport with semitrailer, tractor 130kW.

[j] Semitrailer, capacity max. 40 Mg, 120 m3.

[k] Trailed sprayer, 3500 l, 24 m.

[l] Shredder, Berti 250 ECF/DT-hedge mower.

[m] Disc harrow.

[n] Electrical stationary comminution.

[o] Urine spreader, Star 15 m3 tank with 12 m ramp. Speed 4,1 km/h.

[p] Volvo L50 front loader.

Table B.2. Nutrient application scheme in kg per tonne of expected DM in the yield of the SRC willow plantation

Coppicing cycle	Year	N[a]	P	K
First	1st	0	0.73	2.43
	2nd	0	0	0
	3rd	0	0	0
Subsequent	1st	0	0	0
	2nd	5	0.73	2.43
	3rd	0	0	0

[a] The digestate returned to the dairy farm was applied at a fertilizer level of 65 kg of min−N per ha [64]. The resulting area needed for spreading the digestate was 325 ha based on the min−N content of the digestate. The application rate was 21 t of digestate per (ha yr). At this level the P application rate was below the maximum permissible average of 22 kg of P per (ha yr)[65].

Table B.3. Input values used in ICBM for modelling SOC pool changes.

	Green fallow	Annual crops	Digestate application area
Initial SOC level[a]	95.6		107.2
input (above ground)[b]	1.4	3.4	
input (below ground)[b]	2.7	0.7	
input (digestate manure)			0.37
input (digestate willow$_1$)[c]			0.41
input (digestate willow$_2$)[c]			0.61

[a] The initial SOC level refers to the first year of the study period (year 0).

[b] Above- and below-ground input for annual crops was used to calculate steady state SOC level 20 years prior to year 0. Above- and below-ground input for green fallow was used to calculate the yearly changes in the green fallow SOC, leading to initial SOC in year 0.

[c] The willow fraction of the digestate from the first coppicing cycle was two-thirds of that from subsequent cycles.

AppendixC. ICBM Equations and parameters

AppendixC.1. ICBM Equations

$$Y_{[a,b]}(t) = \left(Y_{[a,b]_{t-1}} + i_{[a,b]_{t-1}}\right) \cdot \exp^{-k_y r_e} \tag{C.1}$$

$$\begin{aligned} O(t) = (O_{t-1} - (f(Y,i) + g(Y,i))) \cdot \exp^{-k_o r_e} \\ + (f(Y,i) + g(Y,i)) \cdot \exp^{-k_y r_e} \end{aligned} \tag{C.2}$$

where

$$f(Y,i) = \frac{h_a \cdot k_y}{k_o - k_y} \cdot \left(Y_{a_{t-1}} + i_{a_{t-1}}\right)$$
$$g(Y,i) = \frac{h_b \cdot k_y}{k_o - k_y} \cdot \left(Y_{b_{t-1}} + i_{b_{t-1}}\right)$$

AppendixC.2. Parameter and variable descriptions

Y : Young soil organic carbon pool
suffix a : refers to the above ground fraction of the young pool
suffix b : refers to the below ground fraction of the young pool
O : Old soil organic carbon pool
h : Humification coefficient. Determines how much of the C broken down in a time step that ends up in the old pool and how much is returned to the atmosphere as CO_2
k_Y : Decay constant of young pool.
k_O : Decay constant of old pool.
r_e : Decomposer activity factor. Affects rate of decomosition. Dependens on external factors such as soil temperature and moisture content.

For futher explanation of ICBM see [51, 66, 16]

AppendixC.3. Parameter values

Table C.1. Parameters used in ICBM for modelling SOC pool changes.

Parameter	Value
k_Y	0.8
k_O	0.009
$h_{annual\,crops\,\&\,fallow}$	0.15
$h_{willow\,residues}$	0.15
$h_{in:\,willow\,wood}$	0.34
$h_{in:\,manure}$	0.35