# Climate impact of willow grown for bioenergy in Sweden

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## Abstract

Short rotation coppice willow (SRCW) is a fast-growing and potentially high-yielding energy crop. Transition to bioenergy has been identified in Sweden as one strategy to mitigate climate change and decrease the current dependency on fossil fuel. In this study, life cycle assessment was used to evaluate and compare the climate impacts of SRCW systems, for the purpose to evaluate key factors influencing the climate change mitigation potential of SRCW grown on agricultural land in Sweden. Seven different scenarios were defined and analysed to identify the factors most influencing the climate. A carbon balance model was used to model carbon fluxes between soil, biomass and atmosphere under Swedish growing conditions. The results indicated that SRCW can act as a temporary carbon sink and therefore has a mitigating effect on climate change. The most important factor in obtaining a high climate change mitigating effect was shown to be high yield. Low yield gave the worst mitigating effect of the seven scenarios but it was still better than the effect of the reference systems, district heating produced from coal or natural gas.

*Keywords: short rotation coppice willow (SRCW), life cycle assessment (LCA), soil organic carbon (SOC), greenhouse gas (GHG), Salix*

## 1 Introduction

There is now consensus amongst most scientists that climate change is a human-induced problem that needs to be dealt with immediately, but the question is *how*. In December 2010, the United Nations Framework Convention on Climate Change (UNFCCC) formulated the Cancun Agreements, which stated that clear mitigation goals are needed to limit the global surface temperature rise to 2 °C [1]. In Europe, the European Union (EU) has agreed joint mitigation goals for all member states, referred to as the “20-20-20” targets, with the objective of reducing the level of greenhouse gases (GHGs), increasing the proportion of renewable energy and improving energy efficiency, all by 20% by 2020 compared with the base year 1990 [2]. To meet these targets, bioenergy has been identified as an alternative to fossil fuel for producing heat and electricity. One possible way to increase the proportion of bioenergy used and simultaneously reduce GHG emissions compared with fossil energy is to grow short rotation forestry on former arable soils, due to the potential this provides to store carbon in the soil [3,4], decreasing the concentration of GHGs in the atmosphere.

In Sweden, the area used for energy forestry was around 0.5% of the total arable land in 2010 [5]. In the same year, about 6.7% of the arable land was under fallow [5], which indicates a potential to increase the proportion of energy forestry without claiming land currently used for food or feed production. About 12,000 hectares of land are currently cropped with short rotation coppice willow (SRCW), the most common type of energy forestry in Sweden [6]. SRCW is a fast-growing, high-yielding energy crop that can be burnt or gasified to produce heat and power [7]. It was introduced into Sweden during the early 1990s, with good prospects of high yield levels. However, the practical results did not live up to the high expectations due to inefficient management, unsuitable willow clones and use of low productivity land [8,9]. This, in combination with high transportation costs and low prices due to inefficient establishment strategies, resulted in poor profitability for willow farmers [6]. Since the 1990s, new clones that are better adapted to Swedish growing conditions have been developed and this, together with an increased demand for renewable energy sources, is likely to increase the interest in SRCW [6]. The production of willow biomass depends on climate conditions and soil quality, as well as management regime, fertilisation, pest control, rotation interval and planting density [10]. The soil type is important for achieving high productivity, and low clay content has been shown to reduce SRCW yield [9].

A common method for evaluating the climate impacts of energy crops is life cycle assessment (LCA) [11], a standardised method (ISO 14040, 14044) for evaluating potential effects and impacts of a product or service. The method considers all flows of energy and all emissions during the whole lifespan of the product or service, including the production and usage phase. LCAs of SRCW have been performed before [3,4,7,12-14], commonly by using the climate impact metric global warming potential (GWP), which expresses the integrated radiative forcing over a chosen period. However, the relationship between GWP and other metrics (e.g. temperature response) is complex and its use has been questioned. The results may be misinterpreted, with policymakers assuming that emissions with equal GWP have the same impact on the global temperature, although the relationship may be non-linear [15]. Impulse emissions of a strong GHG with a short lifetime and a weak GHG with a longer lifetime could have the same GWP, but still lead to different climate impacts [16]. To avoid some uncertainties associated with GWP and capture how the climate impact varies over time, an absolute climate metric can be used [17]. Climate metrics that consider the temporal variations in GHG emissions have been used previously in LCAs [3,18,19].

Bioenergy can be considered carbon neutral in the sense that the carbon emitted from the combustion process will be recaptured once again in new plant tissue, but there is however a time difference between carbon uptake and carbon release. This is important to consider when assessing the climate impact, since for a certain period there will be a change in the GHG concentration in the atmosphere, affecting the climate. Another important factor to consider when performing LCAs of bioenergy systems is the change in soil organic carbon (SOC). Carbon can be captured in the soil by growing perennial crops, and therefore carbon fluxes between soil, biomass and atmosphere should be included in LCAs. A new method that considers temporal fluctuations and SOC changes was recently developed by Ericsson *et al*. [3]. Application of the method to an SRCW system to study the climate impacts revealed that such systems have the potential to sequester carbon and counteract global warming. However, that analysis was limited to one production system under two previous land use regimes. For a deeper understanding of the climate impact of willow grown in Sweden, more aspects of the land and management need to be included in LCAs. The potential of SRCW systems under different growing conditions also needs to be examined, in order to provide a better understanding of how marginal land can be used for bioenergy and identify the key elements determining the climate impact. The aims of this study were therefore to evaluate: (1) key factors influencing the climate change mitigation potential of SRCW grown on agricultural land in Sweden; (2) the potential to store soil organic carbon and create a carbon sink; and (3) the sensitivity of the models used to calculate carbon and climate effects.

# 2 Method

## 2.1 Goal and scope

The energy balance and climate impact from using agricultural land to produce SRCW under Swedish conditions were analysed using process-based LCA methodology [20,21]. The functional unit was set to one hectare of arable land and the impact categories were climate impact and energy use. Two methods were used to analyse climate impact; global warming potential ($GWP_{100}$) and the time-dependent climate impact methodology developed by Ericsson *et al*. [3], which accounts for the dynamic impacts related to timing of emissions and uptake of GHGs. The three major GHGs carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) were used for calculating the GWP and temperature response. A carbon balance model referred to as the Introductory Carbon Balance Model (ICBM) was used for calculating carbon flows between soil, biomass and atmosphere [22]. Seven different scenarios were studied to assess the climate impact under various conditions. A sensitivity analysis was compiled to address the effects of model assumptions and data uncertainties.

#### 2.1.1 System boundaries

The SRCW system studied covered every process from the production of seedlings to the production of heat at a district heating (DH) plant. This included flows of energy and emissions from field operations, production of inputs, transportation and the combustion process. Management practices and technologies used were assumed to be constant during the whole lifespan and no improvements were considered. Losses occurring downstream from the DH plant were not included within the system boundaries. Reference systems were defined to represent business-as-usual (BAU) scenarios. The reference systems consisted of an alternative land use and production of equivalent amounts of DH from fossil fuels [7,23].

### 2.2 System description

The hypothetical SRCW systems were based on recommendations for conventional willow cultivation in south-eastern Sweden (Fig. 1). A 3-year or 4-year coppice cycle and a 25-year rotation period were assumed, meaning that harvesting took place every 3-4 years for 25 years. After one rotation period, the willow stool was assumed to be removed and new seedlings planted. The fossil reference systems included an alternative land use, which was the land management had there been no SRCW cultivation. The time frame for all scenarios was set to 100 years.

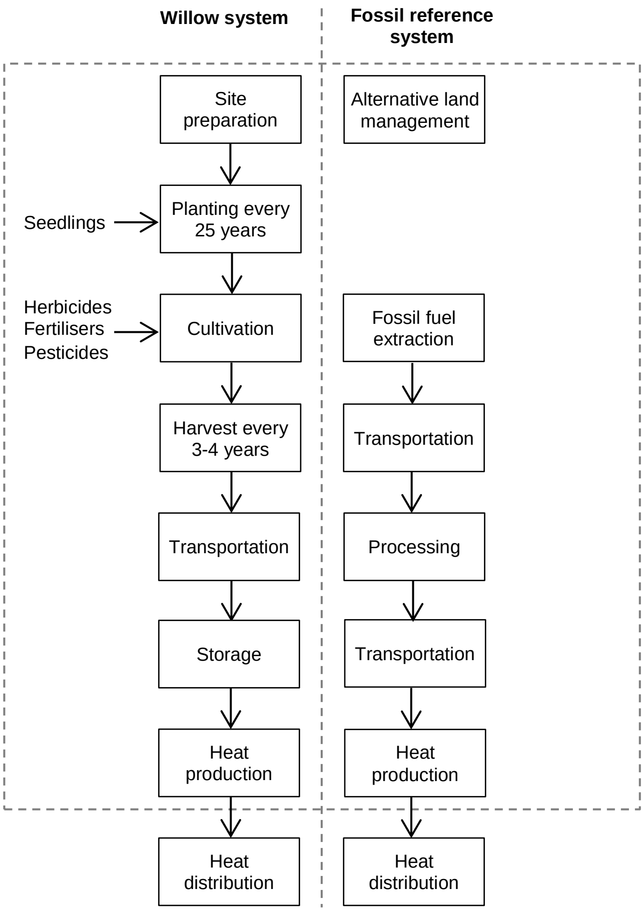


**Fig. 1** Flowchart describing the SRCW systems and fossil reference systems for producing heat at a DH plant. Both include production of inputs, use of fossil fuel for machinery and transportation, and flows of GHG for each step. Dotted line indicates system boundaries

#### 2.2.1 Scenario descriptions

Seven different scenarios of SRCW were studied (Table 1). The parameters varied were previous land use, willow yield, coppice cycle, time frame and succeeding land use. Two previous land use scenarios (nos. 2-3) were defined to analyse the impact of different initial SOC contents. One scenario (no. 4) was defined to analyse the impact on the SOC content of ending SRCW cultivation after one rotation period (25 years). Three scenarios (nos. 5-7) were defined to analyse the impact of different yield levels.

**Table 1** Description of short rotation coppice willow (SRCW) scenarios 1-7 and the parameter values used in these scenarios. (LU = land use)

| Scenario | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Description | Base scenario | Previous LU1 | Previous LU2 | Ended cultivation | Improved clone | Low yield | High yield |
| Previous land use | Green fallow | Ley | Annual crops | Green fallow | Green fallow | Green fallow | Green fallow |
| Yield (1st, subsequent harvest) (odt ha$^{-1}$) | 20, 30[a] | 20, 30[a] | 20, 30[a] | 20, 30[a] | 20, 30 with 10% increase every 25th yr. | 10, 17[b] | 30[c], 42[d] |
| Coppice cycle (yr, no. of cycles in rotation) | 3, 8 | 3, 8 | 3, 8 | 3, 8 | 3, 8 | 4, 6 | 3, 8 |
| Time frame SRCW system (yr) | 100 | 100 | 100 | 25 | 100 | 100 | 100 |
| Succeeding land use | - | - | - | Green fallow | - | - | - |
| Fossil reference system | (a) Coal, (b) natural gas | Coal | Coal | Coal | Coal | Coal | Coal |

[a][6]. [b][24]. [c][25]. [d][4].

### 2.2.2 Yield

The yield in the base scenario was assumed to be 20 oven dry tonnes (odt) ha$^{-1}$ at the first harvest and 30 odt ha$^{-1}$ at subsequent harvests [6]. SRCW gives about 40% higher yield in subsequent harvests due to the greater efficiency of the established root system [8]. One low-yield scenario (no. 6), one high-yield scenario (no. 7) and one improved clone scenario (no. 5) were also studied. In the low-yield scenario, a longer coppice cycle was assumed as a result of the low SRCW productivity. A new clone with 10% higher yield was assumed in each rotation period in the improved clone scenario. The distribution of stem growth for the 3-year coppice cycles during both the first and subsequent cycles were assumed to be 25%, 40% and 35% for years 1, 2 and 3 [3]. An equal stem growth distribution of 25% per year was assumed for the 4-year coppice. By using the distribution of annual net primary production (NPP) [26], the quantity of leaves, fine roots and coarse roots was calculated (Table 2).

**Table 2** Annual net primary production (NPP) for the first and subsequent coppice cycles (% of annual stem growth), based on Rytter [26]

| | Leaves | | | | Fine roots | | | | Coarse roots | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| 1st cycle | 25 | 30 | 27 | 27 | 60 | 71 | 70 | 70 | 39 | 19 | 12 | 12 |
| 2nd-8th cycle | 31 | 31 | 31 | 31 | 69 | 69 | 69 | 69 | 0 | 0 | 0 | 0 |

### 2.2.3 Mineral fertiliser

Mineral fertiliser can cause both direct and indirect emissions of $N_2O$ through nitrification and denitrification. Negatively charged nitrate ions that are created through nitrification can be leached by drainage water [27]. In the present study, the amount of mineral fertiliser applied was based on yield and losses, so that the amounts of nutrients leaving the system equalled the amounts added to maintain an unchanged mass balance. The nitrogen content in stems was assumed to be 0.43% [3]. The direct and indirect emissions from the fertilisers applied ($N_{applied}$) were calculated by:

$$N_2O_{direct} = EF_N \cdot (N_{applied} + N_{litter} + N_{fine\ roots}) \cdot \frac{44}{28} \tag{1}$$

$$N_2O_{indirect} = N_{applied} \cdot (F_A \cdot EF_D + N_{leached} \cdot EF_L) \cdot \frac{44}{28} \tag{2}$$

where $N_{leached}$ is the nitrogen lost by leaching, and $N_{litter}$ and $N_{fine\ roots}$ are the amount of nitrogen contained in aboveground litter and fine roots. Default values were used as emission factors due to lack of specific data (Table 3). The fraction $\frac{44}{28}$ converts N into $N_2O$ [28].

**Table 3** Parameters used for calculating $N_2O$ emissions by equation (1) and (2)

| Parameter | Description | Value | Unit |
|---|---|---|---|
| $N_{leached}$ | N lost by leaching | 0.30[c] | kg N $kg^{-1}$ applied N |
| $N_{fine\ roots}$ | N content in fine roots | 0.43[a] | % |
| $N_{litter}$ | N content in litter | 2.5[a] | % |
| $EF_N$ | Direct emissions from applied N | 0.01[b,c] | kg $N_2O$-N $kg^{-1}$ N |
| $EF_L$ | $N_2O$ emissions due to N leaching | 0.0075[b,c] | kg $N_2O$-N $kg^{-1}$ leached N |
| $EF_D$ | Emissions from volatilisation and re-deposition | 0.01[b,c] | kg $N_2O$-N $kg^{-1}$ $NH_3$-N |
| $F_A$ | Fraction of applied N emitted as ammonia | 0.012[b] | kg $NH_3$-N + $NO_x$-N $kg^{-1}$ applied N |

[a][3], [b][29], [c][28].

The recommendation that fertilisers should not be spread during the first coppicing cycle but during subsequent cycles was followed [30,31]. The assumed amounts of phosphorus (P) and potassium (K) applied were based on values from Börjesson [12].

### 2.2.4 Harvest and combustion

SRCW is usually harvested during the winter when the plant is dormant, the water content is low and the frozen soil has a high carrying capacity for machinery [32]. The willow was assumed to be harvested by direct chipping, after which it was stored in containers and thereafter transported to the DH plant located 30 km from the site. The willow chips were assumed to be stored at an average daytime temperature of maximum 5 °C and combusted within 30 days, leading to a dry matter loss of 3% [33]. The efficiency rate of the DH plant was assumed to be 85% and a high heating value was used. $CO_2$ emissions due to the combustion were calculated based on the carbon content of the biomass, while emission factors of 0.006 respectively 0.011 kg $GJ^{-1}$ were used for calculating $N_2O$ and $CH_4$ emissions [34].

### 2.2.5 Land use

In order to determine the SOC sequestering potential of willow cultivation, initial soil conditions were calculated by defining a previous land use for each scenario. For the base scenario, the previous land use was set to a 20-year old green fallow that had formerly been used to grow annual crops. Green fallow was defined as land set aside and topped annually to prevent tree growth. The green biomass was assumed to be left in the field to decompose, which gave a carbon input to the soil. Two additional land uses were also considered; annual crops (LU1) and ley (LU2) (scenarios 2 and 3). Ley was defined as unfertilised land harvested for hay or green fodder. Annual crops were modelled using data for spring and winter cereals.

### 2.2.6 Fossil reference system

Two types of fossil reference systems were analysed in this study; heat production from coal at a DH plant and heat production from natural gas (Table 4).

**Table 4** Emission factors for district heating from coal and natural gas (kg $GJ^{-1}$)

| Reference system | $CO_2$ | $CH_4$ | $N_2O$ |
|---|---|---|---|
| (a) Coal[a] | 94.2 | 1.1005 | 0.012 |
| (b) Natural gas[a] | 59.1 | 0.0075 | 0.00105 |

[a]Production, distribution and usage at heating plant [35].

The fossil reference system was assumed to produce the same amount of heat in the same year as the SRCW system. Green fallow was assumed as the alternative land use in the reference systems. Use of fossil fuel for topping the land once every year was included in the LCA.

## 2.3 Soil organic carbon

ICBMr is a soil carbon balance model adapted for variable annual input due to regional differences. The model calculates carbon fluxes due to changes in soil organic carbon (SOC). ICBM has two assumed soil carbon pools, one young (*Y*) and one old (*O*), the relationship between which is calculated by:

$$Y_{[a,b]}(t) = \left(Y_{[a,b]_{t-1}} + i_{[a,b]_{t-1}}\right) \cdot exp^{-k_Y \cdot r_e} \tag{3}$$

$$O(t) = \left(O_{t-1} - \left(\frac{h_a \cdot k_Y}{(k_O - k_Y)} \cdot \left(Y_{a_{t-1}} + i_{a_{t-1}}\right) + \frac{h_b \cdot k_Y}{(k_O - k_Y)} \cdot \left(Y_{b_{t-1}} + i_{b_{t-1}}\right)\right)\right) \cdot exp^{-k_O \cdot r_e} +$$

$$\left(\frac{h_a \cdot k_Y}{(k_O - k_Y)} \cdot \left(Y_{a_{t-1}} + i_{a_{t-1}}\right) + \frac{h_b \cdot k_Y}{(k_O - k_Y)} \cdot \left(Y_{b_{t-1}} + i_{b_{t-1}}\right)\right) \cdot exp^{-k_y \cdot r_e} \tag{4}$$

where $k_Y$ and $k_O$ are constants. External factors (e.g. weather, soil type) affecting the decomposition rate are described by $r_e$ [22]. The humification coefficient $h$ describes the magnitude of the fraction of the young pool that enters the old pool. The suffixes $a$ and $b$ represent aboveground biomass (leaves) and belowground biomass (roots, stumps), respectively. The relationship between the aboveground and belowground humification coefficients is described by:

$$h_b = 2.3 \cdot h_a \tag{5}$$

[22], and the annual aboveground carbon input to the soil $i_a$ (Table 5) is calculated by:

$$i_a = A + s \cdot H \tag{6}$$

where $A$ and $s$ are empirically based parameters that differ between straw, stubble, roots and different crops. $H$ is the carbon content of the biomass [22], in this study set to 50% for all parts of the biomass. The belowground input $i_b$ (Table 5) from fine root turnover and accumulated coarse roots and stumps can be described by:

$$i_b = \frac{H \cdot R_m \cdot R_{RE}}{1 - R_{RE}/0.85} \tag{7}$$

where $R_m$ is the root mass fraction and $R_{RE}$ is the relative carbon fraction allocated to roots, including rhizodeposition [22]. The total SOC content in the topsoil (0-25 cm) is calculated by adding the pools:

$$SOC(t) = Y_a(t) + Y_b(t) + O(t) \tag{8}$$

Here, $k_Y$ and $k_O$ (0.8 and 0.0085 [3]) were calibrated using values from the Ultuna long-term soil experiment [36]. $r_e$ was set to 1.0, which represents the annual mean conditions for fertilised cereal crops grown on clay soil in Ultuna, Sweden [37].

**Table 5** Annual carbon input to the soil due to different land uses (Mg C yr$^{-1}$ and ha$^{-1}$), calculated using equations (6) and (7)

| | Aboveground ($i_a$) | Belowground ($i_b$) |
|---|---|---|
| Green fallow[a] | 0.7 | 1.4 |
| Annual crops[a] | 3.3 | 0.7 |
| Ley[b] | 1.1 | 1.5 |
| Willow[c] | | |
| 1st cycle (yrs. 1-3) | 0.6, 1.2, 0.9 | 1.5, 2.8, 2.5 |
| 2nd-8th cycle (yrs. 4-24) | 1.2, 1.9, 1.6 | 2.6, 4.1, 3.6 |

[a]Based on Andrén et al. [22] and Aronsson et al. [38]. [b]Based on Andrén et al. [22]. [c]Base scenario, based on Rytter [26].

The SOC content was converted into proportion (g C g$^{-1}$) of the topsoil (0-25 cm) by:

$$SOC = \frac{\rho_{bulk}}{\rho_{particle}} \tag{9}$$

where $\rho_{bulk}$ is the SOC bulk density measured in g C cm$^{-3}$ and $\rho_{particle}$ is the soil particle density measured in g cm$^{-3}$. The particle density was assumed to be 2.65 g cm$^{-3}$ [39] and $\rho_{bulk}$ was calculated by dividing the SOC mass (Mg C ha$^{-1}$) by the soil volume (1 ha x 25 cm). The belowground annual carbon input ($i_b$) was recalculated by setting $R_m$ to 0.7 to only account for the topsoil and not the entire soil profile [39].

## 2.4 Energy indicators

Two different energy indicators were used to quantify the energy performance. The first one, referred to as the life cycle efficiency (LCE), was defined as net energy output divided by biomass energy:

$$LCE = \frac{E_{out} - E_{in}}{E_{bio}} \tag{10}$$

where $E_{out}$ is the energy produced at the DH plant, $E_{in}$ the total energy input in the upstream processes, and $E_{bio}$ the energy contained in the willow biomass. LCE is an indicator of the overall efficiency of the SRCW system [7]. The second energy indicator used was the energy ratio (ER), which is the ratio between the energy produced at the DH plant and the total energy input:

$$ER = \frac{E_{out}}{E_{in}} \tag{11}$$

ER is a commonly used energy efficiency indicator that describes the overall energy output per unit energy input [7]. Contrary to LCE, it does not explicitly consider the efficiency of biomass utilisation. There is no standardised method for calculating ER and the concept can be referred to in other ways, e.g. Energy Return On Energy Investment (EROI) [40].

## 2.5 Climate impact

Global warming potential ($GWP_{100}$) and global mean surface temperature change were used as climate impact indicators. $GWP_{100}$ indicates the cumulative radiative effect of a given substance relative to another, over a 100 year time horizon [41]. $CH_4$ and $N_2O$ are stronger GHGs than $CO_2$, with, respectively, a 25-fold and 298-fold stronger $GWP_{100}$ [42]. Multiplying the net emissions of $CH_4$ and $N_2O$ by their specific $GWP_{100}$ characterisation factor converts the emissions into carbon dioxide equivalents ($CO_2$-eq). The $CO_2$-eqs for all three GHGs were summed up to calculate the total $GWP_{100}$. GWP does not consider the timing of the emissions. Therefore the time-dependent LCA method developed by Ericsson *et al*. [3] was used for calculating the temporal global mean surface temperature change, referred to as $\Delta T_s$. When GHGs are released, the atmospheric concentration is altered, which disturbs the energy balance on Earth. To model this process, an impulse response function (IRF) can be used (e.g. Bern CC model [43]). The change in concentration leads to a change in radiative forcing (RF), which describes the perturbation of the energy balance of Earth in Wm$^{-2}$ [44]. RF can be either positive or negative, leading to either warming or cooling $\Delta T_s$. For a detailed explanation, see Ericsson *et al*. [3]. Indirect effects of $CH_4$ were included by adding the fraction of gas oxidised into $CO_2$ during the preceding year.

## 2.6 Sensitivity analysis

According to Huijbregts [45], there are six different types of uncertainty and variability associated with the general framework of LCA: (1) parameter uncertainty; (2) model uncertainty; (3) uncertainty due to choices; (4) spatial variability; (5) temporal variability; and (6) variability between objects and sources. Even if data are collected carefully and standardised methods are followed, uncertainties cannot be avoided completely. By performing a sensitivity analysis, it is possible to determine the degree of uncertainty different factors impose on the final results [46]. Sensitivity is the influence that one independent input parameter has on one other dependent parameter, and consequently on the final results [47].

As the scenario analysis in the present study captured variability and uncertainty due to choices, the sensitivity analysis focused on parameter and model uncertainty. In the sensitivity analysis, one input parameter was varied at a time while all other parameters were kept constant. The purpose was to see how much the selected parameter affected the results. To address the uncertainties related to SOC modelling, the external factor ($r_e$) and the humification parameter ($h$) in the ICBM model were analysed. The net primary production (NPP) for leaves and fine roots influences the SOC and for that reason it was also analysed. Default values for nitrogen leakage ($N_{leached}$) and emissions due to applied fertilisers ($EF_N$) are also uncertain and were therefore evaluated in the sensitivity analysis. All six parameters were varied one at a time by ±20% relative to the base scenario.

# 3 Results and discussion

## 3.1 Greenhouse gases and soil organic carbon

The inventory analysis showed that the base scenario had the potential to capture 50 Mg C ha$^{-1}$ in the soil during four rotation periods (100 years), leading to a total SOC content of 1.7% in the topsoil (Table 6). The high yield scenario (no. 7) showed the greatest potential to sequester carbon, capturing 92 Mg C ha$^{-1}$. The low yield scenario (no. 6), on the other hand, gave a reduced SOC level and emitted 12 Mg C ha$^{-1}$. This indicates that with a very low yield, a SRCW plantation will not work as a carbon sink. Among the previous land uses, green fallow was shown to give the lowest initial SOC level, followed by ley (LU1) and annual crops (LU2), but the differences in SOC due to previous land use were small. The scenario where the cultivation ended after one rotation period (no. 4) showed a larger sequestering potential than the low yield scenario (no. 6), which was a result of lower annual carbon input from aboveground and belowground willow biomass in the low yield scenario compared with the green fallow biomass in the ended cultivation scenario.

**Table 6** Initial, total and net soil organic carbon (SOC) after 100 years. Total SOC (% C) was calculated for the topsoil (0-25 cm), while the other figures represent the entire soil profile

| Scenario | Initial SOC (yr. 0) | Total SOC (yr. 100) | Net SOC uptake (yrs. 0-100) | Total SOC in topsoil (yr. 100) |
|---|---|---|---|---|
| | Mg C ha$^{-1}$ | Mg C ha$^{-1}$ | Mg C ha$^{-1}$ | % C |
| 1. Base scenario | 96 | 146 | 50 | 1.7 |
| 2. Previous LU1 | 98 | 147 | 48 | 1.8 |
| 3. Previous LU2 | 100 | 147 | 47 | 1.8 |
| 4. Ended cultivation | 96 | 98 | 2 | 1.2 |
| 5. Improved clone | 96 | 166 | 70 | 2.0 |
| 6. Low yield | 96 | 84 | -12 | 1.0 |
| 7. High yield | 96 | 188 | 92 | 2.2 |

The high yield scenario gave the largest emissions of all three GHGs (Table 7). The inventory analysis showed that a high yield (scenario nos. 5 and 7) gave higher $N_2O$ emissions due to an increased fertilisation rate. The low yield scenario gave the lowest emission of all GHGs.

**Table 7** Net greenhouse gas emissions from willow cultivation and heat produced at a district heating (DH) plant (years 0-100). In unit Mg $ha^{-1}$

| Scenario | $CO_2$ | $N_2O$ | $CH_4$ |
|---|---|---|---|
| 1. Base scenario | 45 | 0.38 | 0.23 |
| 2. Previous LU1 | 45 | 0.38 | 0.23 |
| 3. Previous LU2 | 45 | 0.38 | 0.23 |
| 4. Ended cultivation[a] | 11 | 0.10 | 0.06 |
| 5. Improved clone | 50 | 0.44 | 0.27 |
| 6. Low yield | 24 | 0.16 | 0.10 |
| 7. High yield | 59 | 0.54 | 0.33 |

[a]First rotation period only.

## 3.2 Energy use and efficiency

The life cycle inventory showed that the base scenario gave an average annual energy output of 150 GJ $ha^{-1}$ $yr^{-1}$. The high yield scenario gave the highest annual energy output (210 GJ $ha^{-1}$ $yr^{-1}$), followed by the improved clone scenario (170 GJ $ha^{-1}$ $yr^{-1}$) (Table 8). The high yield scenario also gave the highest energy ratio (ER), 27.1 MJ DH produced per MJ input energy in the production chain. The life cycle efficiency (LCE) was 0.79 for all scenarios except the low yield scenario, which resulted in a slightly lower LCE of 0.78. The increased use of fossil fuel for machinery and production of fertilisers in the high yield scenario contributed to the almost unchanged energy ratio.

**Table 8** Energy use and efficiency for short rotation coppice willow (SRCW) systems during four rotation periods (years 0-100)

| Scenario | Annual average energy input (GJ $ha^{-1}$ $yr^{-1}$) | Annual average energy output (GJ $ha^{-1}$ $yr^{-1}$) | Life cycle efficiency (LCE) | Energy ratio (ER) |
|---|---|---|---|---|
| 1. Base scenario | 5.9 | 150 | 0.79 | 25.5 |
| 2. Previous LU1 | 5.9 | 150 | 0.79 | 25.5 |
| 3. Previous LU2 | 5.9 | 150 | 0.79 | 25.5 |
| 4. Ended cultivation[a] | 5.8 | 150 | 0.79 | 25.2 |
| 5. Improved clone | 6.6 | 170 | 0.79 | 26.3 |
| 6. Low yield | 3.0 | 61 | 0.78 | 20.4 |
| 7. High yield | 7.8 | 210 | 0.79 | 27.1 |

[a]First rotation period only.

## 3.3 Global warming potential

The life cycle impact assessment showed that the base scenario gave a total $GWP_{100}$ of -16 Mg $CO_2$-eq $ha^{-1}$, not including the effect of substituting fossil fuel. The lowest $GWP_{100}$ was obtained with the high yield scenario (-110 Mg $CO_2$-eq $ha^{-1}$), whereas the low yield scenario gave the highest global warming potential (108 Mg $CO_2$-eq $ha^{-1}$) (Table 9). This further indicates the importance of high yield for achieving a climate change mitigating effect. If coal were to be replaced by the SRCW system, a mitigating effect of -564 to -3340 Mg $CO_2$-eq $ha^{-1}$ could be obtained. The impact assessment also showed that natural gas (scenario 1b) released 1090 Mg $CO_2$-eq per MJ DH produced during the entire time frame (100 years), whereas the coal system emitted over double that amount, 2300 Mg $CO_2$-eq per MJ DH produced.

**Table 9** Global warming potential ($GWP_{100}$) for the short rotation coppice willow (SRCW) systems and fossil reference systems, and potential reduction if SRCW systems replaced the reference systems. Units are Mg $CO_2$-eq $ha^{-1}$ and g $CO_2$-eq $MJ^{-1}$ district heating (DH) for years 0-100. A positive value indicates emission to the atmosphere, a negative value reduction

| Scenario | SRCW system | | Fossil reference system | | Reduction | | |
|---|---|---|---|---|---|---|---|
| | Mg $ha^{-1}$ | g $MJ^{-1}$ | Mg $ha^{-1}$ | g $MJ^{-1}$ | Mg $ha^{-1}$ | g $MJ^{-1}$ | % |
| 1. Base scenario | | | | | | | |
| (a) Coal | -16 | -1.1 | 2300 | 152 | -2320 | -154 | -101 |
| (b) Natural gas | -16 | -1.1 | 1090 | 72 | -1100 | -73 | -101 |
| 2. Previous LU1 | -11 | -0.8 | 2280 | 151 | -2290 | -152 | -100 |
| 3. Previous LU2 | -6 | -0.4 | 2270 | 150 | -2280 | -151 | -100 |
| 4. Ended cultivation[a] | 1740 | 115 | 2300 | 152 | -564 | -37 | -25 |
| 5. Improved clone | -69 | -3.9 | 2660 | 152 | -2730 | -156 | -103 |
| 6. Low yield | 108 | 17 | 960 | 155 | -854 | -140 | -89 |
| 7. High yield | -110 | -5.2 | 3230 | 152 | -3340 | -160 | -103 |

[a]SRCW for first rotation period, followed by DH from coal.

## 3.4 Temperature response

The base scenario gave a negative temperature response, i.e. contributed to lowering of the global mean temperature (Fig. 2). The temperature response ($\Delta T_s$) stabilised around $-0.35\cdot10^{-10}$ K $ha^{-1}$, with small oscillations as a result of harvest taking place every 3-4 years and larger oscillations due to the removal of willow stool every 25 years. The low yield scenario showed a positive temperature response that contributed to raising the global mean temperature. The high yield scenario, on the other hand, had the highest cooling effect of all scenarios. The previous land use scenarios had similar, but slightly smaller, cooling effects than the base scenario.

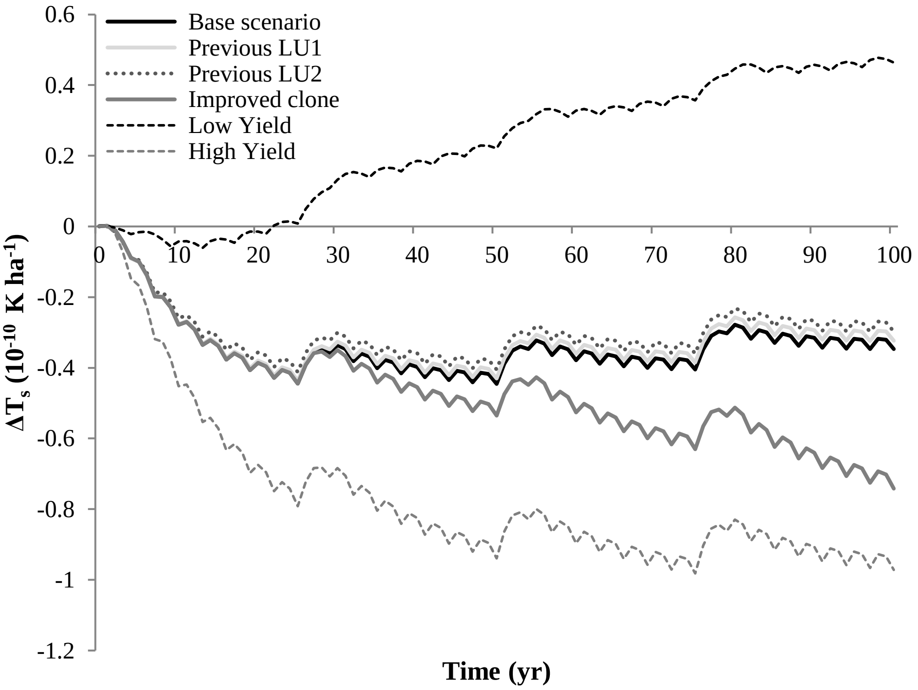


**Fig. 2** Time-dependent temperature response ($\Delta T_s$) for scenarios 1-3 and 5-6, with the fossil reference scenarios not included. The low yield scenario had a warming effect on the temperature, while all other scenarios had a cooling effect

If the SRCW cultivation were to end after one rotation period (scenario 4) and instead be replaced by green fallow, the succeeding land use would bind less carbon to the soil due to loss of living biomass and annual carbon input to the soil (Fig. 3). This indicates that the cooling effect is only short-term and that ending SRCW cultivation would lower the SOC level. The succeeding land use for the ended cultivation scenario showed a small sequestering effect (Table 6), but not enough to counteract the combustion of coal to produce DH.

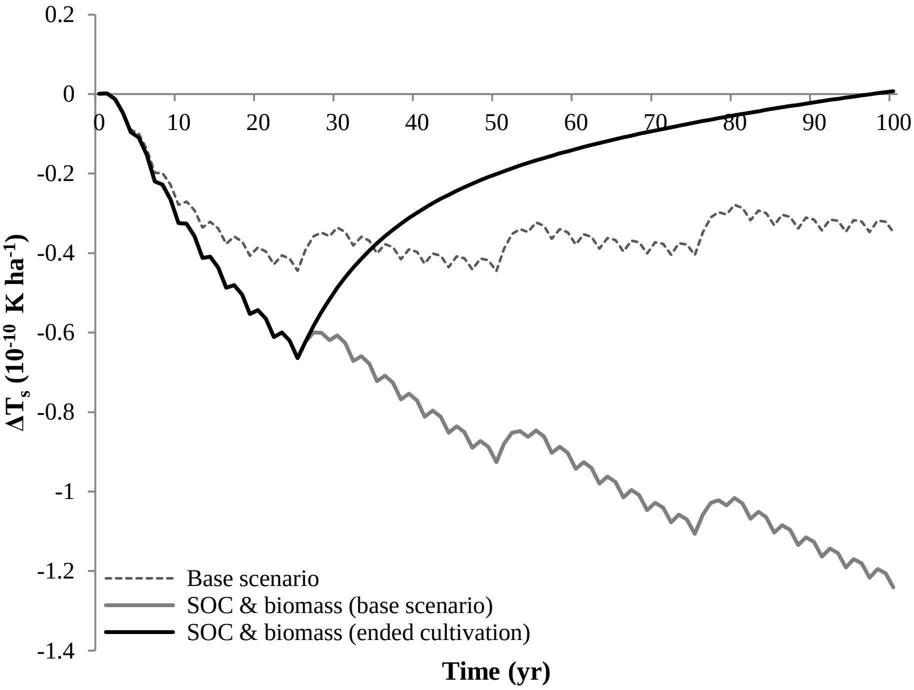


**Fig. 3** Time-dependent global mean surface temperature change ($\Delta T_S$) due to carbon fluxes between soil, biomass and atmosphere. Emissions from management operations, transportation and production of DH are not included

Compared with the reference systems (coal and natural gas), all SRCW scenarios had a mitigating climate effect. The coal reference system (scenario 1a) gave a higher temperature rise than the natural gas system (scenario 1b) (Fig. 4). The low SRCW yield scenario gave a cooling temperature response when the substitution effect was included, even if the SRCW system showed a small warming effect.

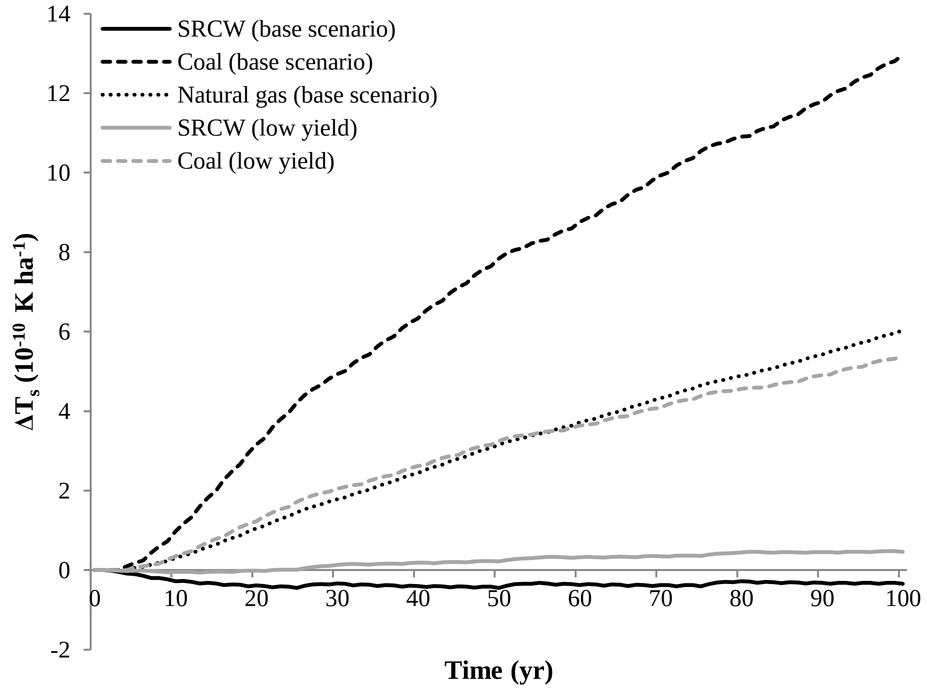


**Fig. 4** Time-dependent global mean surface temperature change ($\Delta T_s$) for the base scenario (no. 1; black lines) and the low-yield scenario (no. 6; grey lines)

## 3.5 Sensitivity analysis

The sensitivity analysis showed that of the parameters analysed, the NPP for fine roots, $r_e$ and $h$ in the soil C model had the largest impact on the temperature response $\Delta T_s$ (Table 10). High $h$ or high NPP for fine roots gave a larger cooling effect, as did low $r_e$. High $r_e$ means that C input to the soil will be decomposed faster, increasing the $CO_2$ concentration in the atmosphere and thus the temperature response. Increased NPP of fine roots also affects the amount of carbon stored in the soil. The amount of leached nitrogen ($N_{leached}$), NPP for leaves and direct emissions from nitrogen fertilisers ($EF_N$) gave a smaller impact on the results. However, even though these parameters contained large uncertainties, they contributed only a small amount to the overall sensitivity of the results.

**Table 10** Sensitivity analysis of final temperature response ($\Delta T_s$) at year 100 when different parameters were varied by ±20%. In unit $10^{-10}$ K $ha^{-1}$ and relative change to the base scenario ($-0.35 \cdot 10^{-10}$ K $ha^{-1}$) (%), where a positive change indicate a larger cooling effect

| | $r_e$ | $h$ | $N_{leached}$ | $EF_N$ | $NPP_{leaves}$ | $NPP_{fine\ roots}$ |
|---|---|---|---|---|---|---|
| +20% | -0.10 (-70) | -0.53 (54) | -0.31 (-12) | -0.29 (-18) | -0.40 (15) | -0.68 (97) |
| -20% | -0.64 (86) | -0.16 (-54) | -0.38 (10) | -0.41 (18) | -0.30 (-15) | -0.01 (-97) |

## 3.6 General discussion

This study demonstrated a clear connection between climate change mitigation potential and yield level of SRCW stand. A high yield means greater production of leaves, fine and coarse roots, which increases the annual carbon input to the soil. A low yield, on the other hand, can lead to a warming effect, by adding less C to the soil than is decomposed by soil microorganisms. To evaluate the possible significance of a longer coppice cycle related to a low SRCW productivity, the low yield scenario (no. 6) was also modelled with at 3-year coppice cycle. The outcome confirmed previous conclusions that the yield level is an important factor for obtaining a cooling effect on the temperature, and not the harvesting interval.

Previous studies of SRCW and its effect on SOC have shown conflicting results, with some indicating a sequestering effect and others indicating the opposite [48]. One factor that may influence the results is the NPP distribution between aboveground and belowground biomass. Here, the relative distribution of NPP was assumed to be the same for all scenarios, independent of yield level, but if the NPP distribution varies due to changes in yield, it could affect the results, and would therefore be important to analyse further. The sensitivity analysis indicated that the NPP of fine roots affected the amount of SOC to a relatively large extent. However, the annual carbon input from fine root turnover ($i_b$) for all scenarios in this study lay within the range for fine root productivity and mortality estimated by Rytter [49].

The inventory analysis showed that the energy ratio (ER) ranged from 20.4 to 27.1 for the seven scenarios. This agrees with the net energy ratio of 23 calculated by González-García *et al*. [14]. The mean annual energy input for the base scenario was 5.9 GJ $ha^{-1}$ $yr^{-1}$ and the mean annual energy output was 150 GJ $ha^{-1}$ $yr^{-1}$. This is in line with the LCA results reported by Börjesson [12], of 7.3 GJ $ha^{-1}$ $yr^{-1}$ and 155 GJ $ha^{-1}$ $yr^{-1}$ for energy input and output, respectively. A literature review by Djomo et al. [7] showed that LCAs of short rotation woody crops often use different system boundaries and impact indicators for evaluating the performance of bioenergy systems, which makes comparisons between studies problematic. Those authors concluded that the main causes of differing results between studies are the assumptions made regarding fertilisers, system boundaries, emissions of $N_2O$ and handling of GHGs. Of the studies reviewed that included SOC changes, the GWP ranged from -2.7 to -4.7 g $CO_2$-eq $MJ^{-1}$ biomass. For the base scenario in the present study the value was -1.1 g $CO_2$-eq $MJ^{-1}$ DH produced, calculated for the whole time frame (years 0-100) (substitution effect not included).

Willow productivity depends on many factors, such as temperature, soil type and management. These factors are dependent on site-specific parameters that can vary from year-to-year. The sensitivity analysis showed that $r_e$ affected the sequestration potential to a great extent (Table 10). This indicates that using calibrated, site-specific data is of major importance. In this study $r_e$ was set to 1.0, which was calibrated for Ultuna soil data. According to Karlsson [37], average values for $r_e$ in Sweden in the period 1990-2004 ranged from 0.67 to 1.30, with the lowest values in the north and the highest in the south. The variations are primarily due to different climate conditions (e.g. temperature) in the regions. In the plain districts of Svealand, central Sweden, where the assumed site was located, $r_e$ was 1.04 [37], which agrees well with the value used in the present study. $r_e$ was assumed to be equal for green fallow, ley, annual crops and willow in this study, although crop type and management can affect $r_e$ [37].

Due to lack of site-specific data, a default value was used for calculating nitrogen leaching due to application of mineral fertiliser. Studies have shown that nitrogen leaching from willow is relatively low compared with that from other crops [4,50], which indicates that the default value of 30% used here might be too high to represent willow cultivation. However, the sensitivity analysis showed that the final result was not sensitive to changes in the amount of nitrogen leaching, indicating that using the default value had a very small effect on the final results.

The scenario analysis showed that the increased quantity of soil organic carbon was only temporary and that once SRCW cultivation ended, the carbon could be re-emitted back to the atmosphere (Fig. 3). Nevertheless, the advantages of creating this temporary carbon sink should not be disregarded, since it contributes to positive values in short-term climate mitigation strategies. Demonstration of this temporal variation is one of the advantages of using the time-dependent LCA methodology developed by Ericsson *et al*. [3], as it would have been overlooked if only the metric GWP had been used.

All scenarios analysed in the present study showed a GHG reduction potential of 25 to 103% compared with the fossil reference systems (Table 9). Most scenarios showed a higher reduction potential than the range (90-99%) stated in the review by Djomo et al. [7]. This larger GHG reduction potential may be the result of the present study including the SOC changes. Growing willow on marginal and low fertility land has been suggested as a good way to increase the amount of bioenergy produced without compromising food production. However, the resulting low SRCW yield may decrease the climate mitigation potential (Table 9, scenario 6). Better knowledge of how site-specific conditions affect yield is important for increasing the climate benefits of SRCW and also the economic benefits to farmers, which ultimately drives SRCW production.

# 4 Conclusions

The climate impact of producing bioenergy from SRCW over a 100-year period ranged from -110 to 108 Mg $CO_2$-eq $ha^{-1}$ when only including the willow system, or -3340 to -854 Mg $CO_2$-eq $ha^{-1}$ when the effect of substituting fossil fuels was included. SRCW has the potential to act as temporary carbon sink, which can decrease the atmospheric concentration of GHGs and thereby mitigate climate change. The magnitude of this potential depends on growing conditions, with high willow yield giving the highest potential. However, very low yield can contribute to increasing global temperature, although the SRCW system still gives a much lower climate impact than DH produced from coal or natural gas. The previous land use scenarios resulted in a slightly higher initial SOC content but otherwise showed similar results to the base scenario. The climate effect of the carbon stored in soil and willow biomass is only temporary and once the plantation is terminated the carbon may be returned to the atmosphere again. This does not mean that carbon storage by SRCW is negligible, however, since reducing GHGs in the short term would help mitigate climate change.

## Acknowledgements

This research was funded by the STandUP for Energy program and Swedish Research Council Formas (project number 2009-2056).

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