GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2017) **9**, 973–985, doi: 10.1111/gcbb.12399

Climate impact assessment of willow energy from a landscape perspective: a Swedish case study

TORUN HAMMAR[1], PER-ANDERS HANSSON[1] and CECILIA SUNDBERG[1,2]

[1]*Department of Energy and Technology, Swedish University of Agricultural Sciences (SLU), SE-750 07, Uppsala, Sweden,* [2]*Division of Industrial Ecology, Department of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of Technology, SE-100 44, Stockholm, Sweden*

Abstract

Locally produced bioenergy can decrease the dependency on imported fossil fuels in a region, while also being valuable for climate change mitigation. Short-rotation coppice willow is a potentially high-yielding energy crop that can be grown to supply a local energy facility. This study assessed the energy performance and climate impacts when establishing willow on current fallow land in a Swedish region with the purpose of supplying a bio-based combined heat and power plant. Time-dependent life cycle assessment (LCA) was combined with geographic information system (GIS) mapping to include spatial variation in terms of transport distance, initial soil organic carbon content, soil texture and yield. Two climate metrics were used [global warming potential (GWP) and absolute global temperature change potential (AGTP)], and the energy performance was determined by calculating the energy ratio (energy produced per unit of energy used). The results showed that when current fallow land in a Swedish region was used for willow energy, an average energy ratio of 30 MJ MJ^{-1} (including heat, power and flue gas condensation) was obtained and on average 84.3 Mg carbon per ha was sequestered in the soil during a 100-year time frame (compared with the reference land use). The processes contributing most to the energy use during one willow rotation were the production and application of fertilizers (~40%), followed by harvest (~35%) and transport (~20%). The temperature response after 100 years of willow cultivation was $-6{\cdot}10^{-16}$ K MJ^{-1} heat, which is much lower compared with fossil coal and natural gas ($70{\cdot}10^{-16}$ K MJ^{-1} heat and $35{\cdot}10^{-16}$ K MJ^{-1} heat, respectively). The combined GIS and time-dependent LCA approach developed here can be a useful tool in systematic analysis of bioenergy production systems and related land use effects.

Keywords: bioenergy, geographic information system, global warming, land use, life cycle assessment, Salix, soil organic carbon, spatial variation

Received 31 May 2016; revised version received 18 August 2016 and accepted 23 August 2016

Introduction

The high consumption of fossil fuels during the past century has generated large emissions of greenhouse gases (GHGs), which have contributed to global warming. Several climate change mitigation targets have been adopted worldwide, most recently in the Paris Agreement signed by the member countries of the United Nations Framework Convention on Climate Change (UNFCCC, 2015). One strategy to reduce GHG emissions and mitigate climate change is to move towards a more bio-based economy, by replacing fossil energy with bioenergy. In addition to climate change mitigation, bioenergy can play an important role in securing the energy supply in a region when locally produced biomass is utilized. However, there are concerns about shifting problems from one area to another, especially regarding potential negative land use effects (both direct and indirect) when increasing utilization of biomass for energy purposes, which may alter carbon stocks or displace land use for food production (Fargione *et al*., 2008; Searchinger *et al*., 2008).

One energy crop that has shown potential to generate bioenergy while increasing soil organic carbon (SOC) is short-rotation coppice willow (Rytter, 2012; Ericsson *et al*., 2013; Zetterberg & Chen, 2015). Willow is a potentially high-yielding crop that can be harvested after only a few years due to its high growth rate (Karp & Shield, 2008; Djomo *et al*., 2011). The productivity has high importance for both the energy return and the SOC content, because a higher carbon input from leaf litter and root turnover can build up the carbon stock. Growing willow on available agricultural land can be one strategy to provide a local community with a continuous supply of bioenergy. Climate impact assessments of willow are usually performed on stand level (e.g. Ericsson *et al*. (2014); Hammar *et al*. (2014); Porsö & Hansson

Correspondence: Torun Hammar, tel. +46 (0)18 67 18 30, fax +46 (0)18 67 31 56, e-mail: torun.hammar@slu.se

(2014)), but assessments of the climate impact of this strategy need to consider the variation within a landscape, as soil texture and water availability are important for willow productivity (Krzyżaniak *et al.*, 2015). Field size and transport distance also vary within regions, affecting the energy return.

In this study, a life cycle assessment (LCA) of willow establishment on current fallow land in a Swedish region was carried out. Only fallow land according to Swedish statistics was selected (which is around 5% of total crop land in Sweden) to avoid possible indirect land use effect of displaced land (Statistics Sweden, 2015). LCA is a standardized method for assessing the environmental impacts of a product or service during its whole lifespan (ISO 14040, 2006; ISO 14044, 2006). The climate metric most commonly used for assessing climate impact in LCA is global warming potential (GWP) (Cherubini & Strømman, 2011; Hauschild *et al.*, 2012), which converts GHG emissions into CO_2 equivalents (IPCC, 2007). When applying this metric to bioenergy systems, the biogenic carbon fluxes are usually set to zero; that is, bioenergy is considered carbon neutral, because the CO_2 released from bioenergy utilization has previously been captured from the atmosphere and/or will be recaptured again during regrowth.

While GWP has some benefits (e.g. enabling comparisons with previous studies), the metric also has limitations; for example, it does not consider the timing of the GHG fluxes, including temporal SOC changes, which have been shown to be of major importance for the overall climate impact of bioenergy (Brandão *et al.*, 2011; Zetterberg & Chen, 2015). The climate metric absolute global temperature change potential (AGTP), also referred to as ΔT, considers the yearly emissions of GHGs and their specific effect on the radiative balance, which affects the global mean surface temperature (Ericsson *et al.*, 2013; Myhre *et al.*, 2013a). The AGTP metric was applied in this study, because it captures the dynamics of biogenic carbon (i.e. fluxes of carbon between the atmosphere, biomass and soil).

Geographic information system (GIS) was used to identify available land and soil properties in the study region. The GIS methodology has been used previously to assess different aspects of bioenergy, for example to determine optimal placement of bioenergy facilities (Ekman *et al.*, 2013; Thomas *et al.*, 2013), assess land availability for short-rotation woody crops (Aust *et al.*, 2014; Abolina *et al.*, 2015) and calculate biomass potential at different spatial scales (Castellano *et al.*, 2009; Fiorese & Guariso, 2010; Wightman *et al.*, 2015). GIS modelling has also been incorporated into LCA to assess the GWP of bioenergy systems (Gasol *et al.*, 2011), with some studies including changes in soil carbon stocks (van der Hilst *et al.*, 2012; Humpenöder *et al.*, 2013; Monteleone *et al.*, 2015), commonly using IPCC emissions factors for direct land use change (Goglio *et al.*, 2015). However, to our knowledge, the time-dependent LCA method has not previously been combined with the landscape dynamic approach for energy forestry.

The overall aim of this study was to assess the climate effects of increased production of willow energy in a specific region, considering existing land use, soil conditions and geographical location of the region. Specific objectives were to determine:

1. the climate impact per unit of produced energy that can be expected from increased production of biomass in the form of willow grown on existing fallow, given the conditions in a larger area of land
2. the energy balance achieved in different willow systems
3. the effects on climate impact and energy balance of choosing particular fields for willow (due to spatial variations in terms of initial carbon content, transport distance, yield).

The county of Uppsala (located in east-central Sweden; Fig. 1) was chosen as the study region, as in a Swedish perspective, it has a relatively high share of energy forestry [about 1800 ha (Statistics Sweden, 2015)]. There is also potential to increase this amount, as around 10% of the arable land in the region is currently under fallow (Statistics Sweden, 2015), of which about 70% is perennial (i.e. minimum 3 years) (SCB, 2015). In addition, a new bio-based combined heat and power (CHP) plant is planned for the region, making it suitable as a case study area.

Materials and methods

An LCA was performed to determine the climate impact and energy performance of the willow system. The climate impact was assessed in terms of temperature response over time, to capture the temporal dynamics of GHGs. The soil carbon balance was modelled by the ICBM model, a carbon balance model adapted for agricultural soils (Andrén & Kätterer, 1997). ArcGIS was used to identify available land (which was defined as fallow land in this study) and soil properties in the study region and to map transport routes. All fluxes of the three major GHGs (CO_2, N_2O and CH_4) and use of primary energy for the willow procurement chains were included in the LCA, which was performed using the software MATLAB (version R2012b, The MathWorks, Inc., Natick, MA, USA). The energy performance of the willow systems was assessed by calculating the energy ratio (ER), which measures the energy output per unit energy input (Djomo *et al.*, 2011).

System boundaries

Only fields in the study region of Uppsala currently under fallow on mineral soils were included in the study. The time

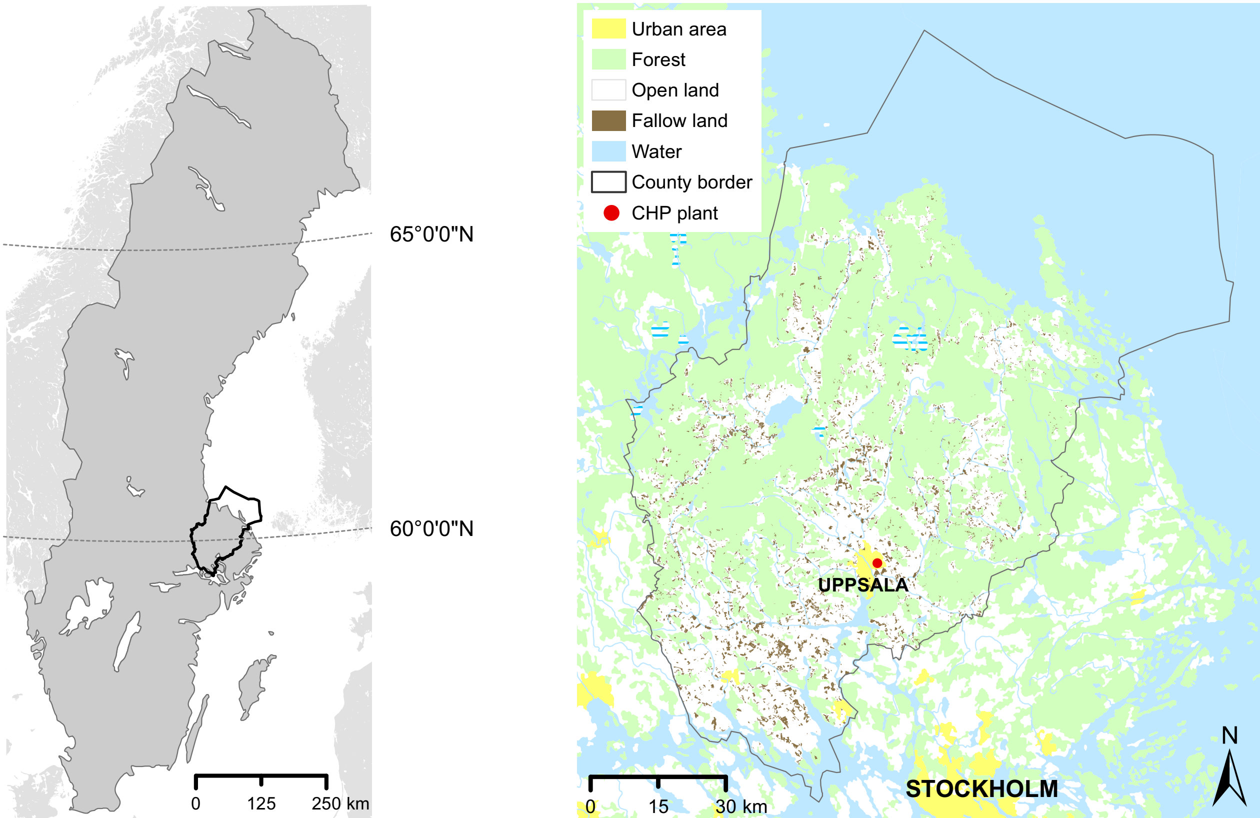

Fig. 1 Left figure: map of Sweden indicating the study region (Uppsala County). Background map © Lantmäteriet. Right figure: distribution of fallow land (brown dots) in Uppsala County. Crop and field information © Swedish Board of Agriculture; background map: overview map 1:1 000 000 © Lantmäteriet.

frame for the study was 100 years, which corresponds to four willow coppice cycles.

The system boundaries included processes related to the willow procurement chain, land use and energy conversion at a CHP plant (Fig. 2). The impact of a one unit increase in energy produced from willow was assessed and only direct land use effects were included as the land was assumed to be initially unused (i.e. fallow). Direct land use effects were defined as the impact of land transformation from the existing land use green fallow to willow cultivation and the continuous effect of altered land use. The climate impact was allocated between heat and power (see Impact allocation). To provide a continuous biomass supply to the CHP plant, all fields were randomly divided into three groups, which were harvested at one-year time steps (within a three-year cutting cycle).

Two functional units were used: (1) 1 hectare (ha) of land, and (2) average heat (MJ) generated at the CHP plant. The per hectare unit was used in the inventory analysis to show the land use change effect on carbon stocks. The heat functional unit was used in the climate impact assessment to show the temperature response when continuously generating heat from willow biomass. A sensitivity analysis was performed where effect of transport distance, yield level and initial SOC content was studied (Table 1).

System description

Procurement chain. The willow plantations were assumed to have a cutting cycle of three years; that is, the willow was harvested and chipped directly at the site every three years. The willow was then regrown and harvested every three years for 25 years, after which the stumps were broken up and new seedlings were planted. The willow procurement chain included the processes site preparation, planting, application of herbicides and pesticides, fertilization, harvesting, chipping, transportation and storage, after which the willow chips were combusted at a CHP plant located in Uppsala.

The yield level in the base scenario was set to 20 Mg dry matter (DM) ha^{-1} for the first harvest and 30 Mg DM ha^{-1} for subsequent harvests in the rotation for all fields (Hollsten *et al.*, 2013). The willow chips were stored for 30 days before combustion with a DM loss of 3%. The production of inputs (seedlings, herbicides, pesticides and fertilizers) was included in the analysis. The willow system was as defined by Hammar *et al.* (2014), which is based on previous studies of willow production in Sweden (Börjesson, 2006; Nilsson & Bernesson, 2008). Updated data were used for the production of mineral fertilizers (Fossum, 2014). For more details on used input data, see Table S2.

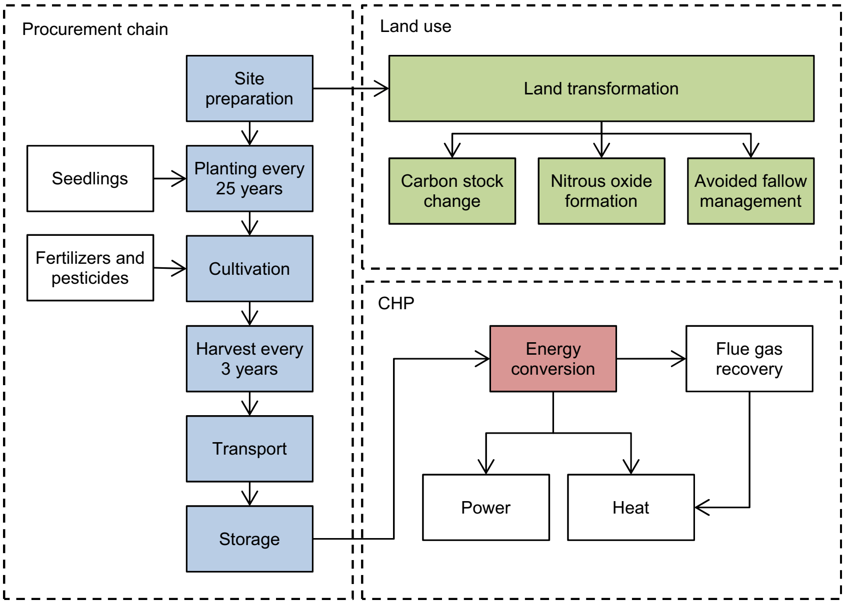

Fig. 2 System boundaries of the study showing processes included in the willow procurement chain, energy conversion at a combined heat and power (CHP) plant and direct land use change effects.

Table 1 Description of sensitivity analysis

Scenario	Description
Base scenario	See System description
Transport ≤60 km	Only including fields located 0–60 km from the CHP plant
Transport ≤30 km	Only including fields located 0–30 km from the CHP plant
Yield −25%	Yield decreased by 25% for all fields and years
Yield +25%	Yield increased by 25% for all fields and years
Yield rand.	Random yield for all fields, ±20% with the same average as the base scenario (i.e. 20 Mg DM first harvest, 30 Mg DM subsequent harvest)
Yield rand. top10%	The top 10% of fields (with random yield) giving the lowest climate impact
Low SOC	Fields with initial SOC content <150 Mg carbon per ha
High SOC	Fields with initial SOC content ≥150 Mg carbon per ha

CHP, combined heat and power; SOC, soil organic carbon; DM, dry matter.

Land use. The direct land use effect of willow cultivation was expressed in two ways: (1) by only considering the willow carbon stock development over time, or (2) by counting the net effect compared with the reference land use, that is the yearly difference between willow and green fallow. The reason for using two forms of expression was to clarify the impact of willow cultivation alone and the impact of the chosen reference land use. Avoided use of fossil fuel from cutting the fallow once every year was included in the net land use effect (Table S3). The fallow biomass was assumed to be left in the field after cutting and emissions of CO_2 and N_2O due to the change in land use were included. To assess soil carbon flux for the willow plantations, yearly net primary production (NPP) of the willow stands was calculated based on Rytter (2001) to determine yearly carbon uptake in living biomass and yearly carbon input to the soil via leaf litter and root turnover (Hammar *et al.*, 2014). Direct and indirect N_2O soil emissions from application of fertilizers and biomass input were calculated using IPCC emissions factors (for both willow and fallow) (IPCC, 2006; Ahlgren *et al.*, 2009).

Energy conversion. The bio-based CHP plant was assumed to be located in the same area as the current energy facility in Uppsala and to generate the same amount of heat and electricity as the existing facility, that is 1600 GWh (5760 TJ) heat and 225 GWh (810 TJ) electricity per year (Vattenfall, 2016). A higher heating value (HHV) of 19.9 GJ Mg^{-1} DM (dry and ash free) was used for calculating the lower heating value (LHV) for the willow biomass (Strömberg & Herstad Svärd, 2012), which was adjusted for the specific moisture content (MC) by:

$$\mathrm{LHV_{MC}} = (\mathrm{HHV} - 2.45 \cdot 0.09 \cdot H_2) \cdot \left(1 - \frac{A}{100}\right) - 2.45 \cdot \frac{\mathrm{MC}}{100 - \mathrm{MC}} \quad (\mathrm{MJ\,kg^{-1}\,DM}) \qquad (1)$$

where $\mathrm{LHV_{MC}}$ is the theoretical heat gained from wood chips excluding water condensation heat, and 2.45 is the latent heat of water vaporization at 20 °C (MJ kg^{-1}), A is the ash content, 0.09 represents one part hydrogen and eight parts oxygen in water, and H_2 is the hydrogen content (6% assumed) (Lehtikangas, 1999). An ash content of 1.5% and a moisture content of

50% gave an LHV_{MC} of 15.8 GJ Mg^{-1} DM. Emissions of CH_4 and N_2O from combusting willow chips were set to 11 and 6 g GJ^{-1} fuel, respectively (Paulrud *et al.*, 2010).

Heat produced from hard coal or natural gas was used as reference. Emissions factors from Gode *et al.* (2011), which include production, distribution and combustion of the fuels, were used. Conversion efficiency for willow and natural gas was adjusted to account for flue gas condensation (Table 2). Flue gas condensation increases the conversion efficiency (for heat) by 15–35% for woody biomass and 10–15% for natural gas (Swedish EPA, 2005), which can give conversion efficiency values of over 100% when using the lower heating value.

Impact allocation. The climate impact was allocated between heat and power using an efficiency allocation method (also called benefit-sharing method; Martinsson *et al.*, 2012; Olsson *et al.*, 2015). The method allocates emissions between power and heat based on the corresponding amount of power and heat that would have been produced in separate production facilities. The allocation factor for heat (α_h) is calculated as:

$$\alpha_h = \frac{\frac{Q_h}{\eta_h}}{\frac{Q_h}{\eta_h} + \frac{Q_p}{p_h}} \tag{2}$$

where Q is the energy produced from heat (h) or power (p) and η is the conversion efficiency for separate production (excluding flue gas recovery). The allocation factor for power is calculated in the same way. The conversion efficiency for separate heat and power production was set according to EU (2011) (Table 3).

GIS model

The ARCGIS product (ARCMAP version 10.3, ESRI, Redlands, CA, USA) was used for mapping land use in the study region and to link soil data with specific fields. Information regarding land use, soil texture and soil organic matter (SOM) was obtained from the Swedish Board of Agriculture. Initial SOM data were available for 880 measurement points in the Uppsala region. The SOM for each field was defined as the SOM value at the closest measurement point. The specific soil properties at each site were used as the base for the carbon balance modelling. Fields smaller than 2 ha in area were excluded from the study according to Swedish management recommendations (Hollsten *et al.*, 2013). Distances between fields and the CHP plant were also calculated using ARCGIS, based on road network data from the Swedish Transport Administration (Trafikverket, 2016).

Table 2 Conversion efficiency (%) for willow, hard coal and natural gas when combusted in a combined heat and power plant (Börjesson *et al.*, 2010), including increase due to assumed flue gas recovery

	Willow	Hard coal	Natural gas
Heat	55	55	45
Power	30	30	40
Flue gas recovery	20	0	10
Total efficiency	105	85	95

Soil carbon model

Soil carbon balances were calculated using the ICBM (Introductory Carbon Balance Model; Andrén *et al.*, 2004). The model assumes two soil pools, one young (Y) and one old (O), where the carbon input (i) from litter and roots first enters the young pool. A fraction then returns to the atmosphere by oxidation to CO_2, while the rest is transferred to the old pool. This fraction, described by the humification coefficient (h), varies with aboveground (a) and belowground (b) biomass. The carbon input for willow was calculated based on the net primary production from Rytter (2001), and the input from fallow was calculated based on Andrén *et al.* (2004) and an assumed productivity of 4.8 Mg ha^{-1} (including all biomass) (Aronsson *et al.*, 2009). Carbon in coarse roots and stumps entered the soil pool at the end of each rotation (Table 4).

The relationship between the young and old pool is described by:

$$\begin{aligned} O(t) = &\left(O_{t-1} - \left(\frac{h_a \cdot k_Y}{(k_O - k_Y)} \cdot (Y_{a_{t-1}} + i_{a_{t-1}}) + \frac{h_b \cdot k_Y}{(k_O - k_Y)} \cdot (Y_{b_{t-1}} + i_{b_{t-1}})\right)\right) \\ &\cdot \exp^{-k_O \cdot r_e} + \left(\frac{h_a \cdot k_Y}{(k_O - k_Y)} \cdot (Y_{a_{t-1}} + i_{a_{t-1}}) + \frac{h_b \cdot k_Y}{(k_O - k_Y)} \cdot (Y_{b_{t-1}} + i_{b_{t-1}})\right) \\ &\cdot \exp^{-k_y \cdot r_e} \end{aligned} \tag{3}$$

where the young pool is described by:

$$Y_{[a,b]}(t) = \left(Y_{[a,b]_{t-1}} + i_{[a,b]_{t-1}}\right) \cdot \exp^{-k_Y \cdot r_e} \tag{4}$$

and where k_Y and k_O are constants representing the decay rate of the two pools (Andrén & Kätterer, 1997; Andrén *et al.*, 2004). The r_e parameter describes external factors such as soil temperature and water-holding capacity (Karlsson, 2012). The r_e parameter was altered to adjust the model for differences in soil texture (Table S1). The total SOC content each year is the sum of the two pools. The SOM content was converted to SOC

Table 3 Conversion efficiencies for separate heat and power production (excluding flue gas recovery; EU, 2011), and allocation factors of emissions and climate impact between heat (α_h) and power (α_p) production for willow and the two reference fuels hard coal and natural gas

	Conversion efficiencies (%)			Allocation factors (%)		
	Willow	Hard coal	Natural gas	Willow	Hard coal	Natural gas
Heat	78	80	82	44	50	42
Power	33	44	53	56	50	58

Table 4 Annual carbon input (i) to the soil from willow (in base scenario) and green fallow (Mg C per year and ha; Hammar *et al.*, 2014)

	Aboveground (i_a)	Belowground (i_b)
Green fallow	0.7	1.4
Willow		
1st cycle (year 1–3)	0.6, 1.2, 0.9	1.5, 2.8, 2.5
2nd–8th cycle (year 4–24)	1.2, 1.9, 1.6	2.6, 4.1, 3.6
Year 25		2.1

by division by a factor of 1.7 (60% of SOM is SOC). The SOC content was converted from fraction to mass by:

$$\mathrm{SOC}(\mathrm{Mg\,C\,ha^{-1}}) = \frac{\mathrm{SOC}(\%)}{100} \cdot \rho \cdot V \tag{5}$$

where ρ is the specific bulk density for each soil texture, and V is the volume of topsoil (25 cm depth) in 1 ha (10 000 m^2). The bulk density values for the different soil textures were set according to Kätterer *et al.* (2006).

Climate model

The climate impact was assessed using AGTP, as defined by the IPCC (Myhre *et al.*, 2013a). This climate metric considers the temperature change resulting from a radiative imbalance of the globe, that is radiative forcing (RF), due to a pulse emission of a GHG. Each GHG has a specific radiative efficiency, meaning that the gases have different abilities to change the balance between the incoming solar radiation and the outgoing terrestrial radiation. The GHGs also remain in the atmosphere for varying lengths of time before they decay. N_2O and CH_4 have an average perturbation lifetime of 121 and 12.4 years, respectively. CO_2 remains in the atmosphere until it is taken up by oceans or the biosphere, while about one-third remains airborne. The perturbation lifetime of CO_2 was modelled using the Bern carbon cycle model (Joos *et al.*, 2001, 2013). The indirect effect of CH_4 oxidation was included in the climate model. The AGTP (referred to as 'temperature response' in the Results section) is described by:

$$\mathrm{AGTP}_x(H) = \int_0^H RF_x(t) R_T(H-t)\,\mathrm{d}t \tag{6}$$

which is a convolution between the radiative forcing (RF) and the climate response function (R_T) due to a unit change in the RF from a pulse emission of gas x. The temperature metric considers the timing of the GHG emissions and their perturbation lifetime and is therefore a very useful metric for displaying time-dependent climate change, unlike the more common GWP metric, which describes the cumulative RF of one gas relative to the cumulative RF of CO_2 during a set time frame (Joos *et al.*, 2013). However, GWP in a 100-year perspective (GWP_{100}) was also applied in this study to enable comparisons with previous studies. According to Myhre *et al.* (2013b), the GWP_{100} of CH_4 and N_2O is 28-fold (fossil methane) and 265-fold larger, respectively, than that of CO_2 in a 100-year time frame.

Results

Inventory analysis

Field properties. In Uppsala County, about 7200 fields of varying size were reported as being under fallow in 2014, giving a total fallow area of around 14 000 ha (Fig. 1). Of these, about 2100 fields exceeded the cut-off size of 2 ha applied in this study, giving a total area of about 9800 ha. The transport distance between the fields and the CHP plant varied from 3 to 96 km, with an average distance of 43 km (Table 5).

The most common soil texture in the selected fields was clay (26%), followed by clay loam (21%), loam (14%) and loamy sand (12%) (Fig. 3). The area of each soil texture was decreased by around 30% for most soils on only selecting fields ≥2 ha.

Soil carbon balance. The initial SOC content for all fields varied between 19.5 and 447 Mg C ha^{-1}, with an average of 114 Mg C ha^{-1} (Fig. 4). The initial SOC pool was not in steady-state, and the content had a strong influence on changes in carbon stocks (Fig. 5). Soils with an initially high SOC content released carbon both when willow was established (Fig. 5a) and when the land remained as green fallow (Fig. 5b). Fields with initially low SOC content sequestered carbon over time, particularly when willow was established rather than leaving green fallow in place. Thus, the net land use effect of establishing willow on fallow land was net uptake of carbon (Fig. 5c). This effect showed almost no variation between fields due to the assumption of constant willow and fallow productivity. The final net effect on SOC after 100 years varied between 83.1 and 85.2 Mg C ha^{-1}, with an average of 84.3 Mg C ha^{-1}.

Energy balance. The energy supplied by willow biomass each year (from all fields ≥2 ha) was on average 1040 TJ heat and 420 TJ power, which corresponds to ~20% of the heat and ~50% of the power produced at the existing energy facility. This corresponds to around

Table 5 Properties of fields ≥2 ha in Uppsala County (N = 2083)

	Area (ha)	Distance* (km)	Initial SOC (%)	Initial SOC (Mg C ha^{-1})
Max	28.3	95.8	12.1	447.0
Min	2.0	3.1	0.6	19.5
Median	3.6	44.0	2.6	88.9
Average	4.7	43.4	3.4	114.1

SOC, soil organic carbon.
*Distances are for one-way transport.

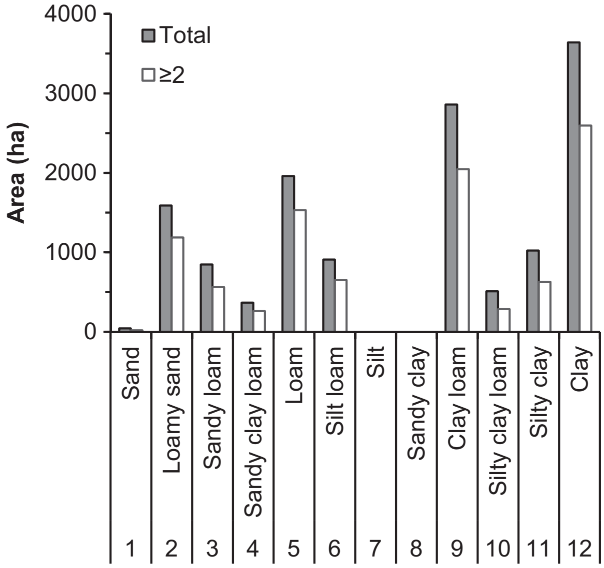

Fig. 3 Distribution of soil texture in all fields in Uppsala County (Total) and in fields ≥2 ha.

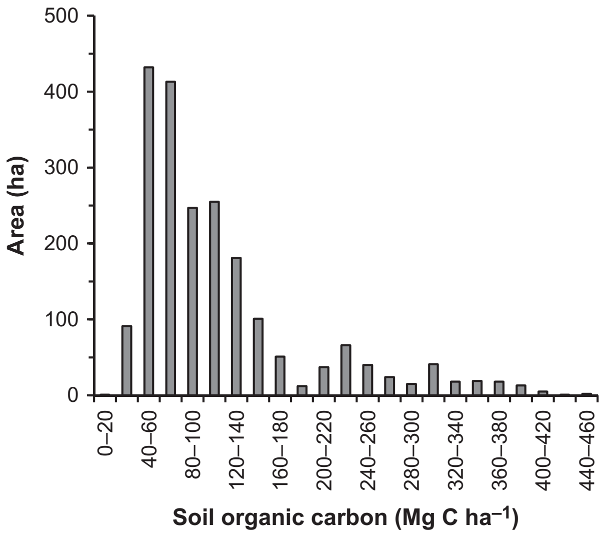

Fig. 4 Frequency distribution of initial soil organic carbon content.

150 GJ ha^{-1} and yr (including heat, power and flue gas condensation). The average primary energy use per hectare and year ranged between 4 to 6.1 GJ, with an average of about 4.9 GJ (including all processes). This resulted in an average energy ratio (ER) ranging from 24 to 36, with an average of 30 MJ MJ^{-1} (including heat, power and flue gas condensation). The production and application of fertilizers gave the highest primary energy use during one rotation period, followed by the processes harvest and chipping, forwarding and transport (Fig. 6).

Climate impact assessment

Global warming potential (GWP). The average GWP_{100} was 7.2 g CO_2-eq per MJ heat for the willow procurement chains in the different fields (excluding biogenic carbon) (Table 6). The GWP_{100} varied mainly due to differences in transportation distance between field and energy facility. Production and use of fertilizers (including soil N_2O emissions) gave the highest GWP_{100}, followed by emissions of N_2O and CH_4 from incomplete combustion (Fig. 6). Including biogenic carbon for the willow cultivation gave large variations in GWP_{100} (as shown in Fig. 5a), with an average of −2.3 g CO_2-eq per MJ heat. When the net land use effect was included (Fig. 5c), the variation was small, with an average GWP_{100} of −8.2 g CO_2-eq per MJ heat. The GWP was thus smaller when accounting for avoided emissions from the reference land use of green fallow. In comparison, the GWP_{100} for fossil coal and natural gas was 116 and 59.7 g CO_2-eq per MJ heat, respectively (no land use emissions included).

Temperature response. The climate impact of willow energy, in terms of temperature response over time, varied greatly when only including SOC changes for the willow cultivation (and no comparison with green fallow) (Fig. 7a). Fields with high initial SOC content released carbon from the soil when willow was established (Fig. 5a), which gave a positive temperature response (i.e. warming effect). However, the reference land use green fallow would release even more carbon from those fields, which means that the net effect of growing willow was a negative temperature response for all fields (i.e. a cooling effect) (Fig. 7b). On harvesting all fields in the landscape to continuously supply the local CHP plant, the temperature response was negative (cooling effect) (Fig. 7c). The final temperature response after 100 years was $-6{\cdot}10^{-16}$ K MJ^{-1} heat (including the net land use effect).

The climate impact and energy return of the individual fields varied due to varying field properties. Prioritizing the best performing fields (in terms of lowest climate impact) improved the climate change mitigation potential per MJ heat (Fig. 8). However, this meant that the total heat production was also lower. There was no trade-off between maximizing total heat production and lowering the climate impact, as all fields (including net land use effect) showed negative climate impacts (i.e. cooling effect) (Fig. 8b). When fields giving the highest climate impact were utilized (bottom 10% or 50%), the temperature response was positive (i.e. warming effect) when considering the willow SOC only (Fig. 8a). This means that the choice of field plays a greater role when

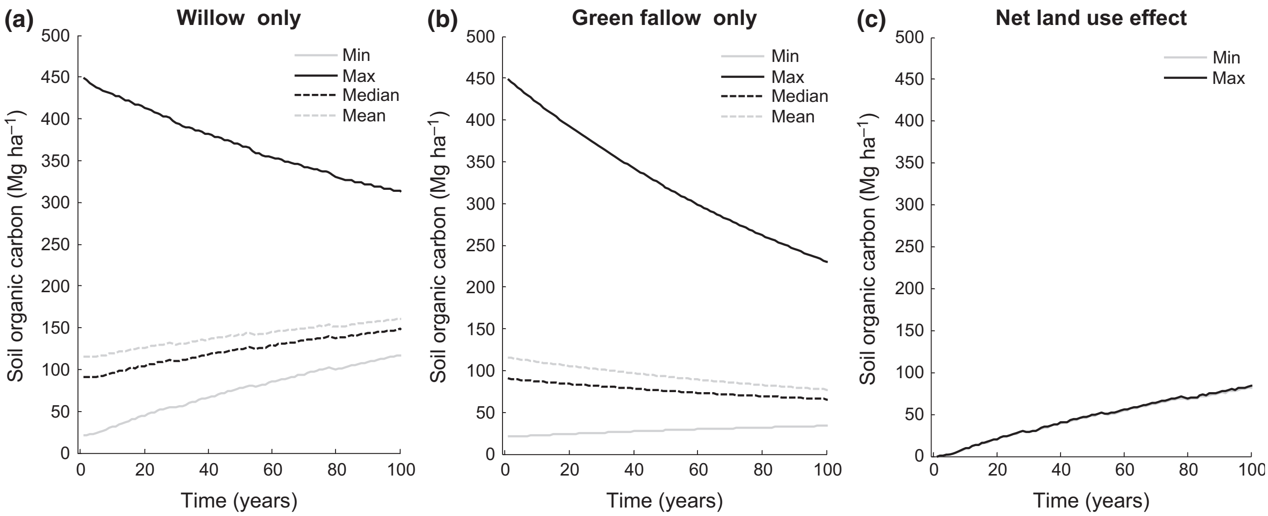

Fig. 5 Changes in soil organic carbon (SOC) content for all fields (N = 2083) when including (a) willow cultivation only and (b) reference land use only (continued green fallow); and (c) the net effect of transforming green fallow into willow cultivation and the continuing effect over time.

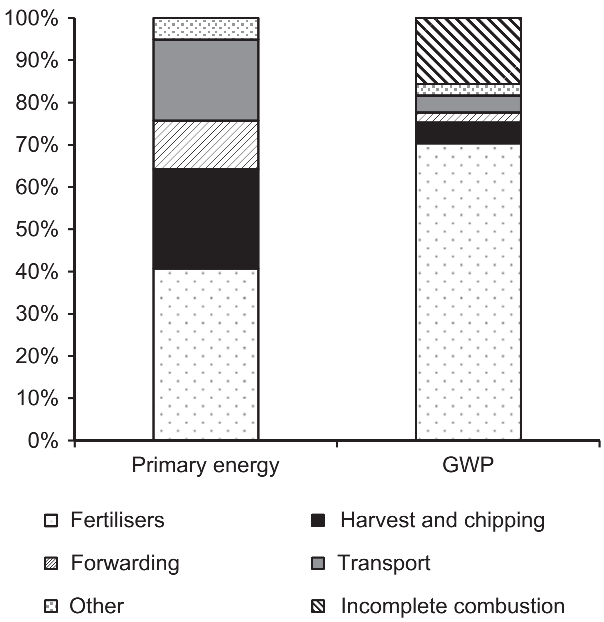

Fig. 6 Distribution of primary energy use during one willow rotation (MJ ha^{-1}) and global warming potential (GWP_{100}) from procurement chain (g MJ^{-1} heat), based on average transport distance (43 km). Other includes field preparation, production and planting of seedlings, production and application of pesticides and stump removal. Incomplete combustion includes emissions of nitrous oxide and methane. No soil organic carbon changes are included.

excluding the impact of avoided carbon emissions from the reference land use green fallow and might have an even larger impact if another alternative land use were considered.

Table 6 Global warming potential (GWP_{100}, g CO_2-eq per MJ heat) for willow systems during 100 years of cultivation on different fields (N = 2083). The procurement chain included fossil greenhouse gas emissions and nitrous oxide emissions from the soil

	Procurement chain (excluding SOC)	Procurement chain including SOC (willow only)	Procurement chain including SOC (net land use effect)
Min	6.9	−10.4	−8.6
Max	7.6	25.2	−7.8
Average	7.2	−2.3	−8.2

SOC, soil organic carbon

Continuously growing willow for energy over a landscape gave a much smaller climate impact than using fossil coal or natural gas (~$70{\cdot}10^{-16}$ K MJ^{-1} heat and ~$35{\cdot}10^{-16}$ K MJ^{-1} heat after 100 years, respectively) (Fig. 9).

Sensitivity analysis

The sensitivity analysis showed that willow yield level had the largest influence on the temperature response over the whole landscape, while initial SOC content and transport distance made a minimal difference when considering the average effect over the whole landscape (Table 7). However, yearly heat production was highly affected by initial SOC content and transport distance, as fewer fields were assumed to be cultivated in these scenarios. When fields were assumed to be located within 60 or 30 km from the energy facility (compared

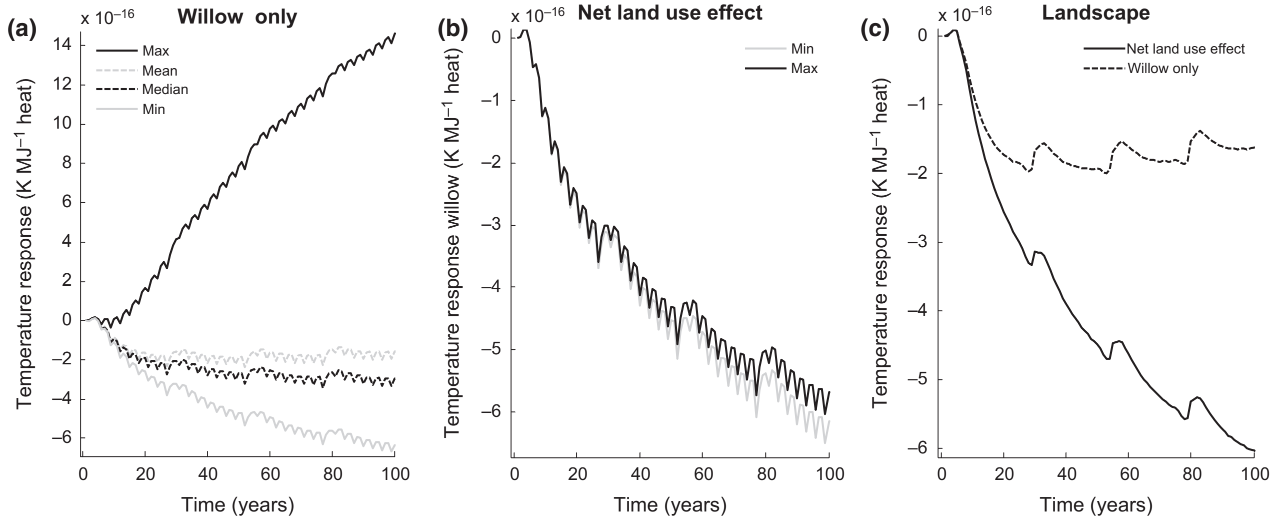

Fig. 7 Temperature response of all fields (N = 2083) including (a) willow procurement chains and soil organic carbon (SOC) changes for willow cultivation only; (b) willow procurement chains and net land use effect (i.e. difference between willow and green fallow); and (c) the combined effect of willow cultivation over a landscape (considering willow SOC only or the net land use effect), where the willow stands were harvested in groups of three with one-year time steps.

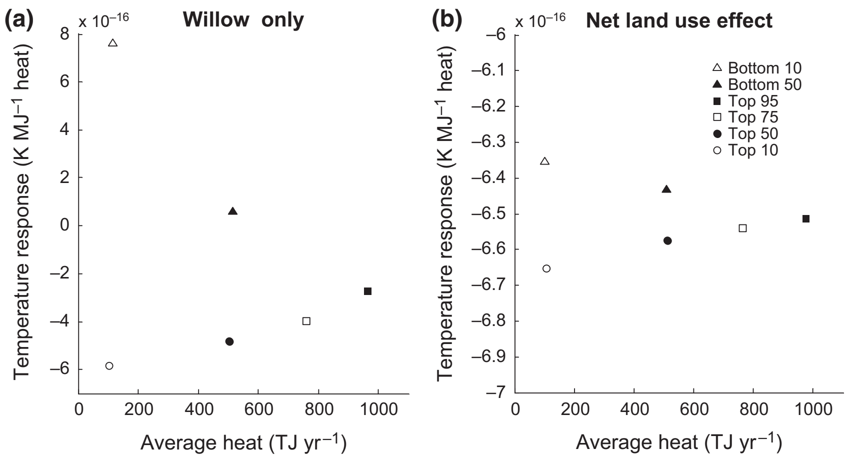

Fig. 8 Final temperature response after 100 years of utilizing willow energy harvested over a landscape and average heat produced per year when considering: (a) willow procurement chains and willow soil organic carbon (SOC) only; or (b) willow procurement chains and the net SOC effect, that is the difference between willow and the reference land use green fallow. The diagrams show the effect when selecting the best performing fields (top 10–95%) and worst performing fields (bottom 10–50%) in terms of climate impact (Note scale differences).

with 96 km in the base scenario), the average GWP_{100} (only including fossil GHGs) was lowered by 0.5–2.1% per MJ of heat compared with the base scenario, while the amount of heat produced was lowered by 17–71%. Selecting fields based on initial carbon content gave either a slightly lower climate impact (low initial SOC) or higher climate impact (high initial SOC), while the energy production was lowered by 20–80%.

Higher yield gave the largest climate benefit and energy output (Fig. 10). When the yield was set randomly, the temperature response over the landscape was slightly lower than for the base scenario and the average net SOC effect was somewhat higher. On choosing the top 10% (with random yields) of fields (with the smallest climate impact), the temperature response over the landscape was lowered by 5%, but heat production decreased by 88%.

Discussion

This study examined the climate effects of supplying a local CHP plant with willow biomass during a 100-year

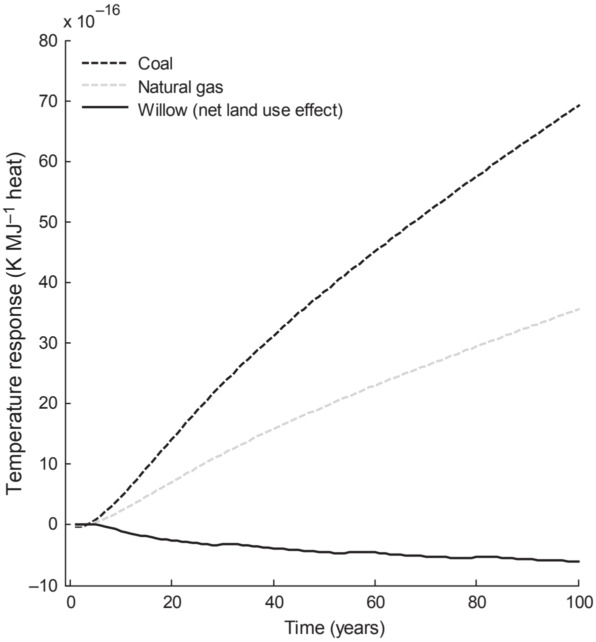

Fig. 9 Temperature response of willow energy (landscape perspective including net land use effect, i.e. difference between willow and green fallow), fossil coal and natural gas per MJ heat and year. The net effect of land use change in the fossil reference systems was zero; that is, no emissions from land use were included for coal and natural gas.

time frame, with the aim of analysing the potential effects of regionally produced energy considering spatial variations. If all fallow land (≥2 ha) in the study region were utilized for producing willow energy, ~20% and ~50% of the yearly heat and power production, respectively, at the energy facility could be produced from willow chips. The average climate impact, in terms of temperature response over the 100-year period, would be negative (i.e. a cooling effect) due to carbon sequestration in living biomass and soil. In other words, under the assumptions in this study, willow cultivation could both generate energy and mitigate climate change even when considering spatial variations in a landscape.

The major contributor to the primary energy use in the willow procurement chains was the production and use of fertilizers (~40%) followed by the willow harvest (~35%) (including chipping and forwarding), which is in line with previous studies on willow energy (Djomo *et al.*, 2011). When excluding SOC changes, the production and application of fertilizers gave the largest contribution to the GWP_{100} due to soil N_2O emissions (in total ~70%) (Fig. 6). Including SOC changes gave negative average GWP_{100} of −2.3 or −8.2 g CO_2-eq MJ^{-1} heat (depending on if only willow cultivation or net land use

Table 7 Sensitivity analysis based on net land use effect, that is the difference between willow cultivation and the reference land use green fallow

Parameter	Base scenario	Transport ≤60 km	Transport ≤30 km	Yield −25%	Yield +25%	Yield rand	Yield top 10%	SOC <150	SOC ≥150
No. of fields	2083	1705	598	2083	2083	2083	209	1668	415
Final average net SOC (Mg C ha^{-1})	84.3	+0.0%	+0.1%	−32%	+32%	+0.9%	+24%	+0.1%	−0.4%
Final temperature response landscape (K MJ^{-1} heat)	$-6 \cdot 10^{-16}$	−0.4%	−1.7%	+7.7%	−4.6%	−0.1%	−5.0%	−0.2%	+0.8%
Heat (TJ yr^{-1})	1040	−17%	−71%	−25%	+25%	+0.5%	−88%	−20%	−80%
Average GWP_{100} excluding SOC (g CO_2-eq MJ heat)	7.2	−0.5%	−2.1%	+1.1%	−1.1%	+0.0%	−1.7%	−0.1%	+0.4%

SOC, soil organic carbon; GWP, global warming potential.

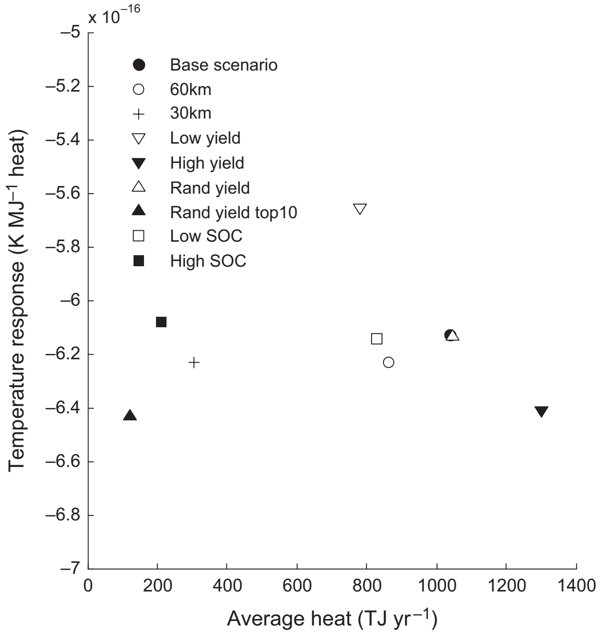

Fig. 10 Final temperature response after 100 years of willow cultivation and yearly average heat produced over a landscape in the different scenarios, including willow procurement chains and the net land use effect, that is the difference between willow cultivation and the reference land use green fallow. Rand yield, randomly allocated yield level; SOC, soil organic carbon.

effect was included). According to a literature review by Djomo *et al.* (2011), the GWP of willow energy ranged from −2.7 to −4.7 g CO_2-eq MJ^{-1} fuel (including SOC). In Zetterberg & Chen (2015), the GWP of willow was reported as −2.0 g CO_2-eq MJ^{-1} fuel and the temperature change after 100 years was estimated to $-5{\cdot}10^{-16}$ K MJ^{-1} fuel. The same value in this study was $-6{\cdot}10^{-16}$ K MJ^{-1} heat; however, the values are problematic to compare because functional units and system boundaries differ.

From a landscape perspective, growing willow on all available fields for energy purposes resulted in a negative temperature response (i.e. cooling effect) (Fig. 7c). From a single stand perspective, there was large variation when only considering willow SOC changes, which could potentially result in a positive temperature response (i.e. warming effect) if the worst fields were chosen (Fig. 8a). When including the net land use effect (i.e. avoided SOC fluxes from green fallow), a negative temperature response (i.e. cooling effect) was shown for all fields (Fig. 8b). In conclusion, the reference land use had a large influence on the results, especially when considering single stands.

A sensitivity analysis was also performed (considering the net land use effect) to study the effect of transport distance, initial SOC content and yield level. Transport distance had the largest influence on fossil GHG emissions, which was reflected in the GWP_{100} (Table 7), but the influence of transport on the overall temperature response was low. By selecting, for example fields located close to the CHP plant, the climate mitigating potential could be improved, but this would also generate less energy (Fig. 10). Therefore, the best option from a climate mitigation perspective would be to utilize all fields to generate as much energy as possible.

The yield level is an important factor for the energy return and the climate impact of willow. When commercial willow was introduced in Sweden, high yields were expected but unfortunately were not obtained in practice (Mola-Yudego *et al.*, 2015). The reasons for the unexpectedly low yields may have been the combination of poor management practices and use of low productivity soils (Dimitriou *et al.*, 2011; Mola-Yudego, 2011). Today, new improved clones have been developed, in terms of resistance to diseases, insects and frost damage as well better stem characteristics and coppice responses (Karp & Shield, 2008). This in combination with better stand management guidelines for willow farmers increases the prospect of achieving better willow yields. Mola-Yudego (2011) studied the production trend of commercial willow plantations in Sweden (year 1986–2000) and found an annual increment of 2.06 Mg DM per yr and ha per decade. They concluded that higher yields could be expected in a near future due to the development of new willow varieties. The willow yield likely varies with soil texture and water availability in the study region (Nord-Larsen *et al.*, 2015), but since found yield models for the specific region were based on old statistic with very low yield, it was not considered to be applicable for this study where the aim was to assess the available best willow practice. Instead, the yield was kept constant for all fields in a base scenario, while yield variations were assessed in a sensitivity analysis.

The net primary production of willow also has a large influence on the soil carbon stock, as the carbon balance is affected by the initial carbon content and the carbon input from above- and belowground biomass. Moreover, the productivity of the reference land use also affects the results when the net land use effect is considered. In this study, the productivity of green fallow was kept constant for all fields and scenarios, but it would also be important to determine the influence of soil texture on the reference land use. Long-term field measurements of both willow and fallow would be useful both for validating the carbon balance model and for decreasing uncertainty in willow energy production estimates.

A landscape perspective was applied to continuously supply the bio-based CHP plant with feedstock. However, willow is harvested during the winter when the soil carrying capacity is high due to frost, so to obtain a continuous energy supply during the whole year other feedstocks are required, as it is not appropriate to store willow chips for a longer period (Strömberg & Herstad Svärd, 2012; Dimitriou & Rutz, 2015). Willow is also generally cofired with other fuels, to decrease related problems such as sintering and coating (Strömberg & Herstad Svärd, 2012). To meet the total demand of the energy facility (and the study region), additional feedstocks (and land) are therefore required.

No indirect land use changes (iLUC) were included in this study under the assumption that only fallow land was utilized. An increased demand for energy or food crops in the future may increase the pressure on land. There is, however, no agreed international accounting standard for including iLUC in LCA, but so-called iLUC factors have been developed for biofuels (Ahlgren & Di Lucia, 2014). These factors are calculated with theoretical models based on market predictions and have resulted in a wide range linked with a high degree of uncertainty. Including iLUC in LCA may according to Finkbeiner (2014) damage the reliability of natural science based LCA results.

In conclusion, this study showed that supplying an energy facility yearly with willow biomass grown on fallow land had a negative temperature response (i.e. cooling effect) when considering spatial variations in a landscape. The climate change mitigation potential was improved by selecting the best performing fields (e.g. in terms of highest SOC increase), but all fields needed to be utilized to generate as much energy as possible. Another conclusion was that the choice of reference land use played a major role for the results. Combined GIS and time-dependent LCA method proved to be a useful way to assess land use change in bioenergy systems. Moreover, the approach can be further improved with better data availability in the future and expanded to include and compare different types of biomass.

Acknowledgements

This research was funded by COMPLEX (project 308601) and the Swedish Energy Agency (project 41976-1). The authors gratefully acknowledge the contribution of Thomas Kätterer and Martin Bolinder (Dept. of Ecology, SLU) for their expertise in soil carbon dynamics and Anders Larsolle (Dept. of Energy and Technology, SLU) for his help with GIS modelling.

References

Abolina E, Volk TA, Lazdina D (2015) GIS based agricultural land availability assessment for the establishment of short rotation woody crops in Latvia. *Biomass and Bioenergy*, **72**, 263–272.

Ahlgren S, Di Lucia L (2014) Indirect land use changes of biofuel production – a review of modelling efforts and policy developments in the European Union. *Biotechnology for Biofuels*, **7**, 1–10.

Ahlgren S, Hansson P-A, Kimming M, Aronsson P, Lundkvist H (2009) *Greenhouse gas emissions from cultivation of agricultural crops for biofuels and production of biogas from manure - Implementation of the Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. Revised according to instructions for interpretation of the Directive from the European Commission 30 July 2009*. Dnr SLU ua 12-4067/08. Uppsala.

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

Andrén O, Kätterer T, Karlsson T (2004) ICBM regional model for estimations of dynamics of agricultural soil carbon pools. *Nutrient Cycling in Agroecosystems*, **70**, 231–239.

Aronsson H, Stenberg M, Rydberg T (2009) *Kväve- och Fosforutlakning Från två Växtföljder på Lerjord med Grön- och Stubbträda*. Sveriges lantbruksuniversitet (SLU), Uppsala.

Aust C, Schweier J, Brodbeck F, Sauter UH, Becker G, Schnitzler J-P (2014) Land availability and potential biomass production with poplar and willow short rotation coppices in Germany. *GCB Bioenergy*, **6**, 521–533.

Börjesson P (2006) *Livscykelanalys av Salixproduktion (Life Cycle Assessment of Willow Production, english abstract)*. Rapport nr 60. Lund: Institutionen för teknik och samhälle Avdelningen för miljö- och energisystem.

Börjesson P, Tufvesson L, Lantz M (2010) *Livscykelanalys av svenska biodrivmedel (Life Cycle Assessment of Biofuels in Sweden)*. In Swedish with English summary. 70. Lund, Sweden.: LUNDS TEKNISKA HÖGSKOLA.

Brandão M, Milà i Canals L, Clift R (2011) Soil organic carbon changes in the cultivation of energy crops: Implications for GHG balances and soil quality for use in LCA. *Biomass and Bioenergy*, **35**, 2323–2336.

Castellano PJ, Volk TA, Herrington LP (2009) Estimates of technically available woody biomass feedstock from natural forests and willow biomass crops for two locations in New York State. *Biomass and Bioenergy*, **33**, 393–406.

Cherubini F, Strømman AH (2011) Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresource Technology*, **102**, 437–451.

Dimitriou I, Rutz D (2015) *Sustainable Short Rotation Coppice – A Handbook*. WIP Renewable Energies, Munich, Germany.

Dimitriou I, Rosenqvist H, Berndes G (2011) Slow expansion and low yields of willow short rotation coppice in Sweden; implications for future strategies. *Biomass and Bioenergy*, **35**, 4613–4618.

Djomo SN, Kasmioui OE, Ceulemans R (2011) Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review. *GCB Bioenergy*, **3**, 181–197.

Ekman A, Wallberg O, Joelsson E, Börjesson P (2013) Possibilities for sustainable biorefineries based on agricultural residues - A case study of potential straw-based ethanol production in Sweden. *Applied Energy*, **102**, 299–308.

Ericsson N, Porsö C, Ahlgren S, Nordberg Å, Sundberg C, Hansson P-A (2013) Time-dependent climate impact of a bioenergy system – methodology development and application to Swedish conditions. *GCB Bioenergy*, **5**, 580–590.

Ericsson N, Nordberg Å, Sundberg C, Ahlgren S, Hansson P-A (2014) Climate impact and energy efficiency from electricity generation through anaerobic digestion or direct combustion of short rotation coppice willow. *Applied Energy*, **132**, 86–98.

EU (2011) *COMMISSION IMPLEMENTING DECISION of 19 December 2011 establishing harmonised efficiency reference values for separate production of electricity and heat in application of Directive 2004/8/EC of the European Parliament and of the Council and repealing Commission Decision 2007/74/EC*.

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. *Science*, **319**, 1235–1238.

Finkbeiner M (2014) Indirect land use change – Help beyond the hype? *Biomass and Bioenergy*, **62**, 218–221.

Fiorese G, Guariso G (2010) A GIS-based approach to evaluate biomass potential from energy crops at regional scale. *Environmental Modelling & Software*, **25**, 702–711.

Fossum J-P (2014) Calculation of Carbon Footprint of Fertilizer Production. Available at: http://yara.com/doc/122597_2013_Carbon_footprint-of_AN_Method_of_calculation.pdf (accessed 3 December 2015).

Gasol CM, Gabarrell X, Rigola M, González-García S, Rieradevall J (2011) Environmental assessment: (LCA) and spatial modelling (GIS) of energy crop implementation on local scale. *Biomass and Bioenergy*, **35**, 2975–2985.

Gode J, Martinsson F, Hagberg L, Öman A, Höglund J, Palm D (2011) *Miljöfaktaboken 2011. Uppskattade emissionsfaktorer för bränslen, el, värme och transporter (Environmental fact book 2011. Estimated emission factors for fuels, electricity, heat and transport (in Sweden with english abstract). ANLÄGGNINGS- OCH FÖRBRÄNNINGSTEKNIK 1183.). Stockholm, Sweden.*

Goglio P, Smith WN, Grant BB, Desjardins RL, McConkey BG, Campbell CA, Nemecek T (2015) Accounting for soil carbon changes in agricultural life cycle assessment (LCA): A review. *Journal of Cleaner Production*, **104**, 23–39.

Hammar T, Ericsson N, Sundberg C, Hansson P-A (2014) Climate impact of willow grown for bioenergy in Sweden. *BioEnergy Research*, **7**, 1529–1540.

Hauschild MZ, Goedkoop M, Guinée J *et al.* (2012) Identifying best existing practice for characterization modeling in life cycle impact assessment. *The International Journal of Life Cycle Assessment*, **18**, 683–697.

van der Hilst F, Lesschen JP, van Dam JMC, Riksen M, Verweij PA, Sanders JPM, Faaij APC (2012) Spatial variation of environmental impacts of regional biomass chains. *Renewable and Sustainable Energy Reviews*, **16**, 2053–2069.

Hollsten R, Arkelöv O, Ingelman G (2013) *Handbok för salixodlare (Handbook for willow growers)*. OVR250. Jordbruksverket (Swedish Board of Agriculture). Jönköping, Sweden.

Humpenöder F, Schaldach R, Cikovani Y, Schebek L (2013) Effects of land-use change on the carbon balance of 1st generation biofuels: An analysis for the European Union combining spatial modeling and LCA. *Biomass and Bioenergy*, **56**, 166–178.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*. IGES, Japan.

IPCC (2007) *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007 Cambridge*. Cambridge University Press, UK and New York, NY, USA.

ISO 14040 (2006) ISO 14040:2006. Environmental management. Life cycle assessment – Principle and Framework. Geneva.

ISO 14044 (2006) ISO 14044:2006. Environmental management - Life cycle assessment - Requirements and guidelines. Geneva.

Joos F, Prentice IC, Sitch S *et al.* (2001) Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) Emission Scenarios. *Global Biogeochemical Cycles*, **15**, 891–907.

Joos F, Roth R, Fuglestvedt JS *et al.* (2013) Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmospheric Chemistry and Physics*, **13**, 2793–2825.

Karlsson T (2012) *Carbon and Nitrogen Dynamics in Agricultural Soils. Model Applications at Different Scales in Time and Space*. Diss. Uppsala: Swedish University of Agricultural Sciences.

Karp A, Shield I (2008) Bioenergy from plants and the sustainable yield challenge. *New Phytologist*, **179**, 15–32.

Kätterer T, Andrén O, Jansson PE (2006) Pedotransfer functions for estimating plant available water and bulk density in Swedish agricultural soils. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science*, **56**, 263–276.

Krzyżaniak M, Stolarski MJ, Szczukowski S, Tworkowski J, Bieniek A, Mleczek M (2015) Willow biomass obtained from different soils as a feedstock for energy. *Industrial Crops and Products*, **75**, 114–121.

Lehtikangas P (1999) *Lagringshandbok för Trädbränslen, 2:A Upplaga (Storage Handbook for Wood Fuels)* (2nd edn). Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden.

Martinsson F, Gode J, Ekvall T (2012) *kraftvärmeallokeringar*.

Mola-Yudego B (2011) Trends and productivity improvements from commercial willow plantations in Sweden during the period 1986–2000. *Biomass and Bioenergy*, **35**, 446–453.

Mola-Yudego B, Díaz-Yáñez O, Dimitriou I (2015) How much yield should we expect from fast-growing plantations for energy? Divergences between experiments and commercial willow plantations. *BioEnergy Research*, **8**, 1769–1777.

Monteleone M, Cammerino ARB, Garofalo P, Delivand MK (2015) Straw-to-soil or straw-to-energy? An optimal trade off in a long term sustainability perspective. *Applied Energy*, **154**, 891–899.

Myhre G, Shindell D, Bréon F-M *et al.* (2013a) Anthropogenic and natural radiative forcing supplementary material. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM), pp. 1–44. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Myhre G, Shindell D, Bréon F-M *et al.* (2013b) Anthropogenic and natural radiative forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM), pp. 659–740. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Nilsson D, Bernesson S (2008) *Processing biofuels from farm raw materials – A systems study*. Report 001. Department of energy and technology, SLU, Uppsala, Sweden.

Nord-Larsen T, Sevel L, Raulund-Rasmussen K (2015) Commercially grown short rotation coppice willow in Denmark: biomass production and factors affecting production. *BioEnergy Research*, **8**, 325–339.

Olsson L, Wetterlund E, Söderström M (2015) Assessing the climate impact of district heating systems with combined heat and power production and industrial excess heat. *Resources, Conservation and Recycling*, **96**, 31–39.

Paulrud S, Fridell E, Stripple H, Gustafsson T (2010) *Uppdatering av klimatrelaterade emissionsfaktorer (Updated climate related emission factors)*. SMED 92 2010. Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, Sweden.

Porsö C, Hansson P-A (2014) Time-dependent climate impact of heat production from Swedish willow and poplar pellets – In a life cycle perspective. *Biomass and Bioenergy*, **70**, 287–301.

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

Rytter R-M (2012) The potential of willow and poplar plantations as carbon sinks in Sweden. *Biomass and Bioenergy*, **36**, 86–95.

SCB (2015) *Trädesareal 2014 fördelad på kort- och långliggande träda (Fallow land in 2014, divided into annual and perennial fallow)*. Available at: www.scb.se/sv_/Hitta-statistik/Statistik-efter-amne/Miljo/Godselmedel-och-kalk/Godselmedel-och-odlingsatgarder-i-jordbruket/21236/21243/207168/ (accessed 8 December 2012).

Searchinger T, Heimlich R, Houghton RA *et al.* (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319**, 1238–1240.

Statistics Sweden (2015) *Agricultural Statistics 2015*. Statistics Sweden, Agriculture Statistics Unit, Örebro, Sweden.

Strömberg B, Herstad Svärd S (2012) *Bränslehandboken 2012 (The fuel handbook 2012)*. Anläggnings- och förbränningsteknik VÄRMEFORSK (Thermal Engineering Research Institute). Stockholm, Sweden.

Swedish EPA (2005) *Förbränningsanläggningar för energiproduktion inklusive rökgaskondensering (Incineration plants for energy production including flue gas condensation)*.

Thomas A, Bond A, Hiscock K (2013) A GIS based assessment of bioenergy potential in England within existing energy systems. *Biomass and Bioenergy*, **55**, 107–121.

Trafikverket (2016) www.trafikverket.se/lastkajen.

UNFCCC (2015) *Adoption of the Paris Agreement. Proposal by the President. (FCCC/CP/2015/L.9/Rev.1.)*. United Nations Office at Geneva, Geneva (Switzerland).

Vattenfall (2016) Frågor och svar om nytt kraftvärmeverk i Uppsala (Questions and answers about the new CHP plant in Uppsala). Available at: www.vattenfall.se/sv/fragor-och-svar-om-nytt-kraftvarmeverk-i-uppsala.htm (accessed 13 January 2016).

Wightman J, Ahmed Z, Volk T *et al.* (2015) Assessing sustainable bioenergy feedstock production potential by integrated geospatial analysis of land use and land quality. *BioEnergy Research*, **8**, 1671–1680.

Zetterberg L, Chen D (2015) The time aspect of bioenergy – climate impacts of solid biofuels due to carbon dynamics. *GCB Bioenergy*, **7**, 785–796.

Supporting Information

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

Table S1. External factor (r_e) for different soil textures and soil organic carbon contents in Uppsala County
Table S2. Willow procurement chain
Table S3. Reference land use