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Research paper

Climate impact and energy efficiency of woody bioenergy systems from a landscape perspective

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ABSTRACT

The climate impact of bioenergy is debated, especially due to potential land use change effects and biogenic carbon fluxes. This study assessed the climate impact and energy efficiency of conventional long-rotation forest residues (branches, tops and stumps) and short-rotation forestry (willow) from a landscape perspective. A time-dependent life cycle assessment method, which considers the timing of biogenic carbon fluxes and the impact on global temperature over time, was combined with GIS mapping to assess the impact for a specific Swedish region (Uppsala County), *i.e.* a 'real' landscape. The results showed that harvesting forest residues decreased the forest carbon stocks over the landscape, while growing willow on previous fallow land increased the total carbon stocks. On average, energy ratios of 49 $MJ\,MJ^{-1}$ for branches and tops, and 30 $MJ\,MJ^{-1}$ for stumps and willow was found. Harvesting forest residues from the studied landscape resulted in climate impacts of around $0.8{\cdot}10^{-15}\,K\,MJ^{-1}$ heat for branches and tops, and $1.3{\cdot}10^{-15}\,K\,MJ^{-1}$ heat for stumps. Willow energy gave the lowest climate impact of about $-0.6{\cdot}10^{-15}\,K\,MJ^{-1}$ heat. The landscape analysis showed that spatial variations in the region had an effect on energy efficiency and climate impact, but that this effect was relatively small. A more important factor was the time frame chosen for the analysis, especially for long-rotation forest systems. Methodological choices such as spatial scale (stand or landscape perspective), allocation method and functional unit also influenced the results.

1. Introduction

Regionally produced biomass can be used for supplying energy as a strategy to mitigate climate change and increase energy security in a region by reducing the dependency on imported fossil fuels. Biomass can be derived from many sources, *e.g.* dedicated energy crops, residues from forestry and agriculture or industrial residues. The end use of biomass is wide, with the most established energy use being direct combustion for heat and power, but biomass can also be processed into other types of biofuels and materials.

To determine the climate benefit of producing biomass for energy purposes, the whole value chain from cultivation to processing, transport and end use should be considered. This can be done by performing a life cycle assessment (LCA), which is a standardised method for evaluating environmental impacts of a product or service [1,2]. Including greenhouse gas (GHG) fluxes from living biomass and soil has been shown to be highly important in previous LCA studies [3,4]. Furthermore, perennial crops have been shown to have greater carbon sequestration potential than annual crops, due to the higher carbon inputs to the soil from litter and root turnover [5,6]. Biomass productivity is thus important for both soil carbon content and energy and economic return.

Forests contain large fractions of carbon, both in standing biomass and in dead wood and soil [7]. How forest is managed is thus important for the GHG balance. Previous studies have described the effect of harvesting forest residues for energy and how the release of carbon dioxide (CO_2) through combustion affects the climate compared with the slower release via decomposition [8–11]. Such studies commonly use a single stand perspective, where a single energy outtake is considered and spatial variations in a landscape are overlooked. However, site-specific properties can affect biomass productivity and decomposition, which influences soil carbon development over time.

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Life cycle assessment is continually evolving and its application to bioenergy systems has been a driving factor for development of the method during recent years [12]. Spatial and temporal factors have been increasingly recognised as important [13], and a distinction between stand and landscape has been made in some bioenergy assessments to separate the dynamics of *e.g.* a forest stand and a forest landscape [14]. A landscape can be defined in multiple ways depending on scientific discipline, and the size and properties of a landscape can vary greatly within similar research areas [15]. In the field of bioenergy, a further division has been made between a theoretical landscape and a 'real' or 'true' landscape, where a theoretical landscape refers to a number of identical stands, but of different ages [16]. Real landscape analysis requires more knowledge of the specific area studied and is thus more complex [17].

This study examined a real landscape, which was defined based on administrative borders for a Swedish region. Properties of forest and agricultural land in the region were mapped by geographic information system (GIS) and used as input in simulations of GHG fluxes of the bioenergy production system. The combined use of LCA and GIS, which is referred to as "spatial LCA" by Hiloidhari, Baruah, Singh, Kataki, Medhi, Kumari, Ramachandra, Jenkins and Thakur [18], can be useful for a number of reasons, *e.g.* for assessing biomass potential in a region, logistical analysis and improving environmental impact assessment results by including spatial variations.

The overall goal of this study was to extend existing knowledge on the climate effects and energy performance of increased use of solid biomass for heat and power production in a region, considering spatial variations and temporal dynamics. This work is a continuation of a previous study in which a time-dependent LCA method was combined with GIS mapping to examine spatial variations in willow energy [17]. To include temporal dynamics, the combined method uses a time-dependent climate metric, denoted absolute global temperature change potential (AGTP) [19] or ΔT_s [20], which shows the temperature change over time as a response to GHG emissions. The method was modified in this study to include conventional forest residues (tops, branches and stumps) in addition to short-rotation coppice willow.

The main aim of this study was to evaluate the climate impact and energy efficiency of woody bioenergy produced in a region. Specific objectives were to analyse:

- How climate impact and energy balances are affected by the raw material prioritised
- Whether climate change mitigation potential and energy efficiency can be optimised by selecting certain willow fields or forest stands for producing bioenergy
- Whether the biomass potential in the study region is sufficient to fulfil the regional energy demand
- How methodological choices (spatial scale, time perspective and allocation method) affect the results.

2. Materials and methods

In our previous work (Hammar, Hansson and Sundberg [17], a spatial LCA method was developed and applied to a willow energy system. In the present study, this method was applied to a forest landscape where residues (tops, branches and stumps) from conventional forests were harvested for energy. The LCA was performed using the software MATLAB (version R2017b, The MathWorks, Inc., Natick, MA, USA) and GIS programme ArcGIS (ARCMAP version 10.3, ESRI, Redlands, CA, USA). The Introductory Carbon Balance Model (ICBM) was used for agricultural land, while the Heureka forestry decision support system and Q model were used for modelling the forest landscape (see section 2.4 *Biogenic carbon modelling*).

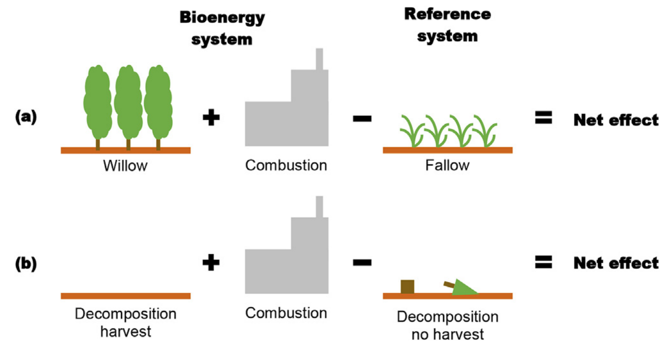

Fig. 1. System boundaries for biogenic carbon fluxes for: a) willow energy and b) energy from forest residues. In (a), the net effect is the difference between willow and an alternative land use (fallow). In (b), the net effect is the difference between harvesting and not harvesting forest residues at final forest felling.

2.1. System boundaries

The LCA included processes in the supply chain, energy conversion and land use of bioenergy produced from forest residues (branches, tops and stumps) and willow grown on agricultural land. Yearly fluxes of CO_2, nitrous oxide (N_2O) and methane (CH_4) were calculated, as were primary energy use and energy generated at a combined heat and power (CHP) plant. The Swedish county of Uppsala was chosen as the study site and the biomass was assumed to be transported to a CHP plant located in the city of Uppsala (Fig. 2). Emissions and losses occurring downstream from the energy plant were not included (*e.g.* losses in the district heating grid).

There are different approaches to model land use in LCA [21]. In this study, the consequence of an increased biomass extraction for energy was assessed, referred to as net land use effect (Fig. 1). Since

Fig. 2. Map of forest stands (N = 11015) and willow fields (N = 2083) in Uppsala County included in this case study. Forest stand information ©kNN Sweden; Crop and field information ©Swedish Board of Agriculture; background map © Lantmäteriet.

willow is a dedicated energy crop, the land use change effect was defined as the difference between willow cultivation and an alternative land use, in this case green fallow. The net effect included changes in biogenic carbon (both living biomass and soil organic carbon (SOC)), N_2O emissions from soil (due to application of fertiliser and litter input) and avoided management of the alternative land use. A large proportion of forest residues will release CO_2 irrespective of whether the biomass is harvested or not, either by combustion or through decomposition over time. Biogenic carbon fluxes for the forest system were therefore defined as the yearly difference between biomass harvest (combustion) and no biomass harvest (decomposition). The initial SOC content in the forest floor was assumed to be unaffected by biomass removal (*i.e.* net emissions were zero), which was also assumed for soil N_2O emissions and future forest productivity.

Two impact categories, climate impact and energy performance, were assessed in the study. The climate metrics global warming potential in a 100-year perspective (GWP_{100}) and AGTP were used for assessing climate impact, while energy ratio (ER) was used for assessing energy performance (see section 2.7 *Impact assessment methods*). The life cycle inventory results were expressed using the functional unit hectare of land (ha), which is useful for describing carbon balances, while the life cycle impact assessment results were expressed using the functional unit MJ of heat produced per year. The impact was allocated between the two outputs heat and power using energy allocation. The time frame for the assessment was 75 years (to restrict the analysis to one harvest per forest stand), with new forest stands harvested each year (depending on forest age). Since willow is harvested every third year, all fields were randomly divided into three groups harvested sequentially (one group per year). Use of bioenergy from the systems was compared with use of two fossil fuel alternatives, hard coal and natural gas.

2.2. Biomass scenarios

Four different biomass scenarios were studied:

1) Harvesting tops and branches (70% of spruce and pine) at final felling of conventional forestry.
2) Harvesting tops and branches (70% of spruce and pine) and stumps (80% of spruce and pine, with stump diameter 15–60 cm) in spruce-dominated stands (> 70% spruce) at final felling of conventional forestry.
3) Growing willow for energy on fallow land (≥ 2 ha).
4) Using a biomass mix of forest residues (as in scenarios 1,2) and willow (as in scenario 3).

In addition, the impact of methodological choices was assessed, in particular the choice of a stand or landscape perspective, the time frame used for interpretation of results and the choice of allocation method.

2.3. GIS mapping and landscape modelling

The forest landscape model was created from a rasterised forest map of Sweden (kNN Sweden; Fig. 2), created based on remote sensing in combination with a national forest inventory [22]. The rasterised forest map was divided into homogeneous treatment units through spatial segmentation [23]. The forest landscape studied comprised about 446 000 ha of productive forest land (11 015 stands), with forest residues harvested from about 60% of these stands during the study period (6856 stands, 290 500 ha) (Fig. 2).

Willow was assumed to be grown on agricultural fields defined as fallow land according to Swedish statistics in 2014, with mineral soil and a minimum size of 2 ha, which resulted in about 9800 ha (2083 fields). Information regarding land use, soil texture and soil organic matter (SOM) content for the agricultural land was obtained from the Swedish Board of Agriculture and linked to the specific field by GIS mapping. Initial SOM data were available for 880 measurement points in the study region and the SOM value for each field was defined as that at the closest of these measurement points. The specific soil properties at each site were used as the base for carbon balance modelling.

Table 1
Area and transport distance for willow fields (N = 2083) and forest stands (N = 11015) in Uppsala County included in this case study.

	Area (ha)		Distance (km, one-way trip)	
	Field	Forest	Field	Forest
Min	2.0	7.3	3.1	3.2
Max	28.3	120.0	95.8	107.8
Average	4.7	40.5	43.4	53.1

Since the modelled forest stands were generated from a rasterised map, their average size was larger than actual average stand area in the region (Table 1). Average forest productivity was 8.15 $m^3\,ha^{-1}\,year^{-1}$, standing volume 170 $m^3\,ha^{-1}$ and stand age 52 years. Most forest soils were mesic (99.6%) (subsoil water depth = 1–2 m) and the remaining area was mesic-moist (subsoil water depth < 1 m).

To simulate the management of the forest systems (*e.g.* harvest levels and interval), the stand-wise version of the Heureka forestry decision support system (Heureka) was used. Heureka is a series of programmes used for forest analysis that are based on empirical relationships between forest production and management, climate and soil conditions [24]. The most common tree species in the forest landscape studied were Norway spruce (*Picea abies*) (42%) and pine (*Pinus silvestris*) (40%) (Fig. 3).

2.4. Biogenic carbon modelling

Biogenic carbon fluxes for willow were divided into standing biomass (carbon in stems, leaves, roots and stumps) and SOC (carbon in litter, root turnover and old carbon pool). The standing biomass was modelled based on a set yield level (20 Mg dry matter (DM) yr^{-1} first harvest and 30 Mg DM yr^{-1} subsequent harvests) and yearly net primary production (NPP) based on Rytter [25]. Carbon in litter and root turnover was assumed to enter the soil pool with one-year time steps. The development of the SOC pool was modelled by the ICBM, which is designed for agricultural soils [26].

The model consists of two soil pools, where the carbon input (i) from residual biomass first enters a young (Y) soil pool. A fraction then returns to the atmosphere by oxidation to CO_2, while the rest is transferred to an old (O) soil pool. This fraction varies with aboveground (a) and belowground (b) biomass and is described by the humification coefficient (h). The relationship between the young and old pool is described by:

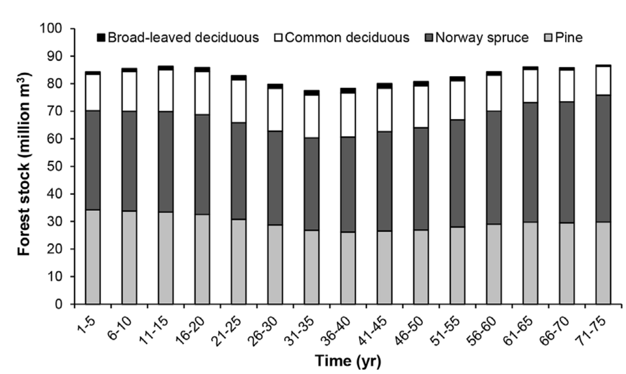

Fig. 3. Tree species distributions (in forest cubic metres, *i.e.* total volume over bark, from stump to tip) in the forest landscape studied.

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

where the young pool is described by:

$$Y_{[a,b]}(t) = \left(Y_{[a,b]_{t-1}} + i_{[a,b]_{t-1}}\right) \cdot exp^{-k_Y \cdot r_e} \quad (2)$$

where k_Y and k_O are constants representing the decay rate of the two pools and the r_e parameter describes external factors such as soil temperature and water-holding capacity (Andrén et al., 2004; Andrén & Kätterer, 1997). A detailed description of the NPP and SOC model and parameters used can be found in Hammar, Hansson and Sundberg [17].

Biogenic carbon fluxes for the forest systems were defined as the CO_2 released from tops and branches or stumps, either by combustion or decomposition. The net effect of harvesting forest residues was calculated as the yearly difference between biomass harvest (combustion) and the reference case of no harvest (decomposition). The fate of the carbon stored in the biomass when left in the forest was modelled using the Q model, which is a process-based model that simulates decomposition of organic material with different qualities and decomposition rates [27]. The average harvest level was 22.1 Mg DM ha^{-1} for tops and branches and 32.4 for Mg DM ha^{-1} stumps. Due to an uneven age distribution in the forest landscape, larger fractions of biomass were harvested in the beginning of the study period (Fig. 4).

2.5. Supply chains

The supply chain for the willow fields was set according to Hammar, Hansson and Sundberg [17]. All processes from production of seedlings and field preparation to combustion of willow chips at a CHP plant were included in the system boundaries. The supply chains for tops and branches was based on Hammar, Ortiz, Stendahl, Ahlgren and Hansson [8] and that for stumps on Ortiz, Hammar, Ahlgren, Hansson and Stendahl [9]. The system boundaries were drawn after final felling, with emissions occurring previously allocated to timber and pulpwood production (Fig. 5).

2.5.1. Field operations

Before willow seedlings were planted, it was assumed that the fields were prepared by weed harrowing and application of pesticides. The willow biomass was harvested every third year by direct chipping. After 25 years, the plantation was assumed to be broken up and new seedlings planted. Nitrogen (N) fertiliser was applied in years 3–25, in amounts based on yield levels, so that equal amounts of N were applied as were removed by harvest (and N losses). Energy use and emissions

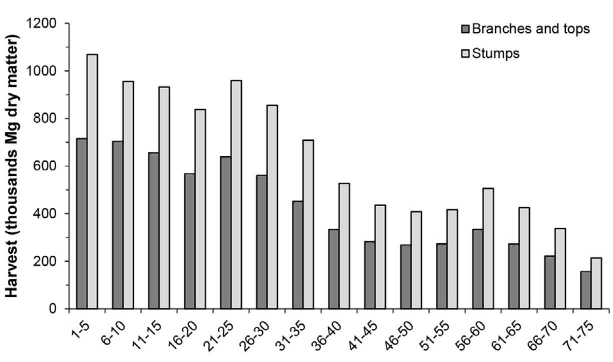

Fig. 4. Biomass outtake of branches, tops and stumps from the forest landscape studied.

from production of N fertiliser were according to Fossum [28]. Application of N (from fertilisers and biomass residues) gives rise to both direct and indirect N_2O emissions, which were calculated according to IPCC [29]. Phosphorus (P) and potassium (K) were applied every third year according to Nilsson and Bernesson [30]. The biomass was assumed to be transported to the CHP plant after harvest and stored for 30 days before combustion, with a dry matter loss of 3%.

2.5.2. Forest operations

It was assumed that, after final felling, the tops and branches were forwarded to the roadside, where they were stored for eight months with a DM loss of 1% per month [31]. An average forwarder (136 kW) was assumed, with fuel consumption of 10.8 L per effective hour, including delays shorter than 15 min [32], and a total forwarding time of 8.4 min per Mg DM [33]. The biomass was chipped directly at the roadside by a truck-mounted grinder with fuel consumption of 3.05 L per Mg DM [34], and then transported to the energy plant. A 3.6% chipping loss was assumed and the lubricating oil use for forest machines was set to 6% of the diesel consumption [35]. The moisture content for the fresh biomass was assumed to be 50%, which was lowered to 45% on a wet basis for the chipping, transportation and combustion [36,37].

The stumps were excavated and forwarded to the roadside for storage. An excavator equipped with a dedicated stump harvesting head was assumed, with fuel consumption of 20.2 L per hour and productivity of 2.9 Mg DM per hour [35]. After eight months of storage with a storage loss of 0.1% per month, the stumps were transported to the energy plant, where they were assumed to be crushed by a stationary crusher with 3.6% comminution loss [35]. The diesel consumption for loading and unloading the stumps was set at 4.7 and 1.7 L diesel per load, respectively [35]. Electricity consumption was assumed to 3.6 MJ per Mg on a wet basis and a moisture content of 30% on a wet basis was assumed for the stumps.

2.5.3. Transport

Transport was modelled using ArcGIS, with data for transport routes from the fields and forest stands to the energy plant retrieved from the Swedish Transport Administration [38] (Table 1). Consumption of fuel was set to 0.58 L diesel per km, which is the average consumption for a vehicle with a full loading rate for 54% of the distance and a load weight of 34 Mg [39]. For the stumps, a basic density of 0.43 Mg per DM m^3 and a load space of 145 m^3 were assumed [40].

2.5.4. Energy conversion

The combined heat and power plant was assumed to be equipped with flue gas recovery, which recovers heat lost by water vaporisation. This can increase the energy efficiency for biomass and natural gas (for heat) and give total conversion efficiencies over 100% (Table 2).

Besides conversion efficiency, the heating value and moisture content of biomass influence the energy output (Table 3). The higher heating value (HHV), which expresses the total energy content in the biomass, was recalculated to the lower heating value (LHV) and adjusted for specific moisture, ash and carbon content as:

$$LHV_{MC} = (HHV - 2.45 \times 0.09 \times H_2) \times \left(1 - \frac{AC}{100}\right) - 2.45 \times \frac{MC}{100 - MC}\,(\mathrm{MJ{\times}kg^{-1}{\times}DM}) \quad (3)$$

where LHV_{MC} is the theoretical heat gain from wood chips excluding water condensation heat, 2.45 is the latent heat of water vaporisation at 20 °C (MJ kg^{-1}), AC 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) [42].

Emissions of N_2O and CH_4 as a result of incomplete combustion were set to 0.006 and 0.011 g MJ_{fuel}^{-1}, respectively, for all biomass fractions [37]. Ash was assumed to be recycled to the forest stands to

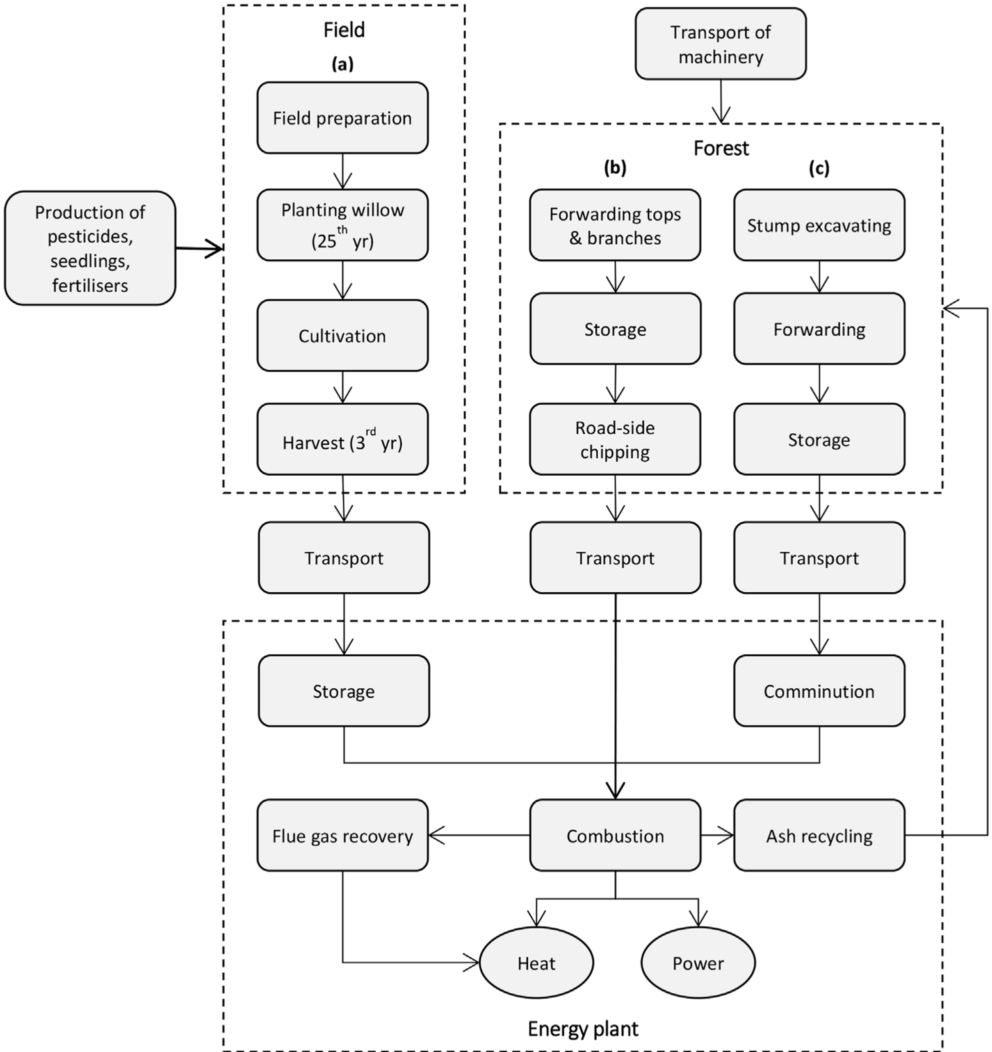

Fig. 5. Flowchart describing the supply chain of: a) willow, b) tops and branches and c) stump harvesting for producing heat and power at an energy plant.

Table 2
Conversion efficiency (%) for biomass (willow and forest biomass), hard coal and natural gas when combusted in a combined heat and power plant [41], including increase due to assumed flue gas recovery.

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

avoid nutrient deficiency. The energy requirement for returning and spreading 2 Mg ash per ha was divided between the supply chain of branches and tops and stumps. The ash was assumed to be spread using a converted forwarder [45,46].

2.6. Fossil reference situation

Natural gas and hard coal were included in this study as reference energy systems. Emission factors for production, distribution and combustion of the two fuels were used (Table 4). No land use change was included for the reference fuels (*i.e.* the net land use change was zero).

Table 3
Properties of the different forms of biomass (DM = dry matter).

	Willow	Forest	
		Branches and tops	Stumps
Higher heating value (HHV)(MJ Mg^{-1} DM, ash-free)	19.9[a]	20.8[b]	20.5[c]
Ash content (AC) (%, dry basis)	1.5	1.5	3
Moisture content (MC) (%, wet basis)	50	45[a]	30
Lower heating value (LHV < SUB > MC < /SUB >) (MJ Mg^{-1} DM, dry basis)	15.8	17.2	17.6

[a] Strömberg and Herstad Svärd [36].
[b] Nilsson, Nylinder, Fryk and Nilsson [43].
[c] Eriksson, Eliasson, Hansson and Jirjis [44].

2.7. Impact assessment methods

2.7.1. Impact allocation

Since the functional unit MJ heat was used, the climate impact was allocated between the two outputs heat and power using the efficiency allocation method [48,49]. The allocation method is based on the amount of heat and power that would have been produced in separate energy plants and is described by:

Table 4
Emission factors (g MJ^{-1} fuel) for the fossil reference fuels hard coal and natural gas (European average), when combusted at a combined heat and power plant [47].

	Hard coal	Combustion	Total	Natural gas	Combustion	Total
	Production & distribution			Production & distribution		
CO_2	4.15	106	110	5.53	56.8	62.3
CH_4	0.56	0.01	0.575	0.275	0.001	0.276
N_2O	$2.35{\cdot}10^{-5}$	0.00127	0.00129	$2.59{\cdot}10^{-12}$	0.0001	0.00010

Table 5
Conversion efficiency for separate heat and power production (excluding flue gas recovery) [50], and allocation factors for emissions and climate impact between heat ($\alpha_{h</i>}$) and power ($\alpha_{<i>p}$) production for biomass, hard coal and natural gas.

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

$$\alpha_h = \frac{\frac{Q_h}{\eta_h}}{\frac{Q_h}{\eta_h} + \frac{Q_p}{\eta_p}} \tag{4}$$

where α_h is the allocation factor for heat, Q is the energy produced from heat (h) or power (p) and η is the conversion efficiency for separate production (excluding flue gas recovery). Separate conversion efficiency was set according to EU [50] (Table 5).

2.7.2. Energy performance

The bioenergy potential from utilising all studied biomass fractions in the region was assessed in the landscape analysis. The energy performance of the system was assessed by calculating the primary energy use for all processes and the energy ratio (ER), which was defined as the total energy produced (both heat and power) per unit of primary energy use (in MJ MJ^{-1}) [51].

2.7.3. Climate metrics

Several climate metrics can be used to assess the climate impact of GHG fluxes. Levasseur, Cavalett, Fuglestvedt, Gasser, Johansson, Jørgensen, Raugei, Reisinger, Schivley, Strømman, Tanaka and Cherubini [52] concluded that using more than one climate metric and/or time frame can be useful in an LCA, depending on the goal of the study. In the present study, an absolute time-dependent climate metric (AGTP) and a normative climate metric (GWP) were used. The former is valuable for describing the temperature change over time due to both fossil and biogenic GHG fluxes, while the latter is useful for validating the results, since it is the most commonly used climate metric.

Both metrics are based on radiative forcing (RF), which is a measure of the radiative balance between incoming solar radiation and outgoing terrestrial radiation, measured in W per m^2. Greenhouse gases have different abilities to absorb and re-emit longwave terrestrial radiation, which makes them unevenly strong climate agents. They also remain in the atmosphere for varying periods of time after being emitted to the atmosphere, *e.g.* N_2O and CH_4 have average perturbation lifetimes of 121 and 12.4 years, respectively, while CO_2 remains in the atmosphere until it is taken up by oceans or the biosphere, while about one-third remains airborne [53,54]. These two aspects are considered when using GWP, which is the cumulative RF of one gas relative to the cumulative RF of CO_2, during a set time frame (usually 100 years). During a 100-year time frame, the GWP_{100} for biogenic CH_4 and N_2O is 28-fold and 265-fold larger than that for CO_2, according to the latest IPCC report [55].

However, GWP does not consider the year in which emissions/uptake take place and fluxes occurring during *e.g.* the first year of the study period are handled similarly to fluxes occurring during the last year. Therefore when GWP is used for bioenergy systems, net CO_2 from biomass use is usually set at zero. When studying the temporal dynamics of biogenic CO_2 AGTP is more suitable, since it considers the perturbation time for each emission of each GHG. It also goes one step further down the cause-effect chain and expresses the climate impact as temperature response:

$$AGTP_x(H) = \int_0^H RF_x(t) R_T(H-t) dt \tag{5}$$

which is a convolution between the RF and the climate response function (R_T) due to a unit change in the RF from a pulse emission of gas x. Each AGTP of each gas and year is summed up for the total temperature response, also referred to as ΔT [20].

3. Results

3.1. Energy performance

The landscape analysis showed that the largest bioenergy potential in the study region was from stump harvesting, followed by willow biomass and forest branches and tops (Table 6). The total yearly bioenergy potential was around 3630 TJ heat (1.0 TW h) and 1450 TJ power (0.4 TW h).

Willow had higher primary energy use during one rotation period than forest residues, but willow generated energy in a much shorter interval than one conventional forest stand. The production and use of fertilisers consumed most energy in the willow system, followed by harvest, forwarding and chipping. Of the forest supply chains, harvesting and transporting stumps was more energy-intense than harvesting branches and tops. Bioenergy from branches and tops gave the highest ER (*i.e.* energy output per unit of primary energy used), on average 49 MJ MJ^{-1}. Stumps and willow both gave an energy ratio of around 30 MJ MJ^{-1} (Fig. 6). The variation in energy ratio was mainly due to different transport distances, although varying biomass outtake levels also had some effect for the forest stands.

3.2. Biogenic carbon

The biogenic carbon fluxes for willow were defined as the yearly difference between willow cultivation and the reference land use green fallow, including carbon in both standing biomass and soil. Since willow has higher biomass productivity than green fallow, the yearly input of carbon from the leaf litter and root turnover resulted in higher soil carbon build-up over time for all fields (Fig. 7).

Harvesting forest residues for bioenergy removes carbon from the

Table 6
Average yearly heat and power production from willow and forest residues (branches, tops and stumps) (TJ yr^{-1}).

	Willow	Branches and tops	Stumps	Total
Heat	1040	980	1610	3630
Power	420	390	640	1450

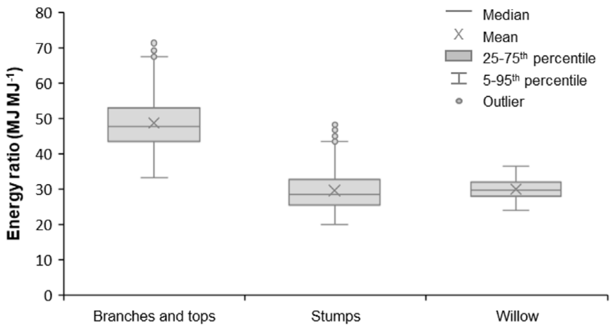

Fig. 6. Energy ratio (ER) of forest residues (branches, tops and stumps) (N = 6856) and willow (N = 2083).

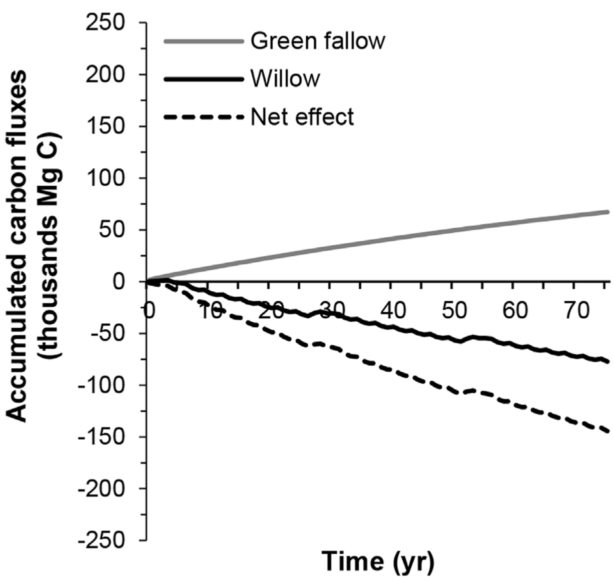

Fig. 7. Accumulated carbon fluxes from the studied landscape under willow cultivation and green fallow and the net land use effect (difference between the two land uses) for all studied fields in Uppsala County (2083 stands, 9800 ha). The values include carbon in standing biomass and soil, where negative values indicate carbon uptake.

forest floor and even though some of this carbon will eventually be released to the atmosphere through decomposition over time, its release is earlier when the residues are harvested (Fig. 8).

The net effect of harvesting forest residues from the studied landscape thus resulted in an increased atmospheric CO_2 concentration during a 75-year period, while growing willow on previous fallow land resulted in a decreased atmospheric CO_2 concentration.

3.3. Climate impact

3.3.1. Global warming potential

The average GWP_{100} was 7.2, 2.0 and 2.6 g CO_2-eq per MJ heat for willow, forest branches and tops, and forest stumps, respectively, when excluding biogenic carbon fluxes. Willow cultivation gave the largest GHG emissions, mainly due to N_2O soil emissions. However, on including biogenic carbon fluxes (SOC, standing biomass, decomposition, combustion), willow gave a negative GWP_{100} due to the uptake in biomass and soil (on average −8.2 g CO_2-eq per MJ heat, including net land use effect). Harvesting forest biomass, on the other hand, released more CO_2, which increased the GWP (on average 13.1 g CO_2-eq per MJ heat for branches and tops, and 22.4 g CO_2-eq per MJ heat for stumps). The decomposition of stumps is slower than for branches and tops, which means that stumps work as a carbon sink for a longer time when not harvested, hence the higher GWP_{100}.

The GWP of forest residues at the end of the simulation period was highly affected by the time of harvest, since a longer period of decomposition was included for forest stands harvested in the beginning of the 75-year study period (Fig. 9). For instance, forest stands harvested in year 1 included avoided emissions from decomposition during 75 years, while forest stands harvested in year 50 included avoided emissions from decomposition during 25 years. Forest stands harvested in year 75 only included emissions from combustion, which gave a larger GWP_{100} for branches and tops than for stumps since stumps have a higher heating value and thus generate more heat per unit CO_2 emitted. The GWP of coal and natural gas was 116 and 53 g CO_2-eq MJ^{-1} heat, respectively.

3.3.2. Temperature response

Growing willow on previous fallow land decreased the atmospheric concentration of GHG (due to carbon uptake in biomass and soil), which resulted in a cooling temperature response (Fig. 10a). Harvesting forest residues, on the other hand, resulted in a warming temperature effect, since biogenic carbon was released earlier in time at combustion than during decomposition. The temperature response curves of forest

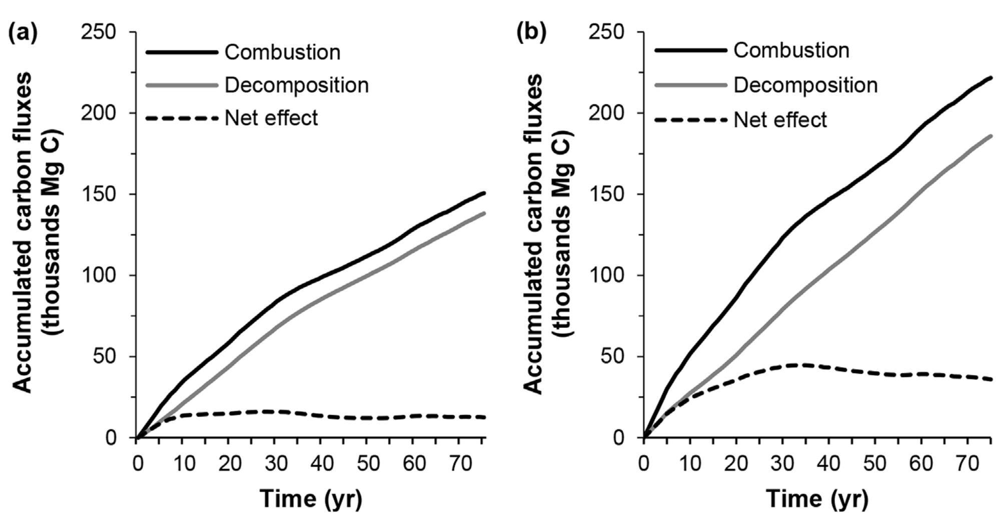

Fig. 8. Accumulated carbon fluxes from the studied forest landscape (6856 stands, 290 500 ha) through combustion (harvest), decomposition (no harvest) or net effect (difference between combustion and decomposition) of: a) branches and tops and b) stumps.

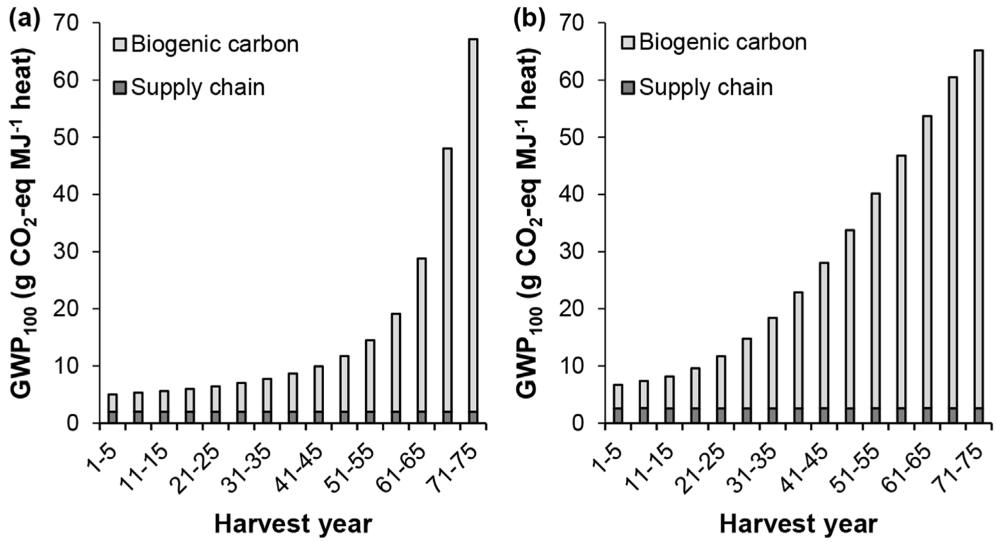

Fig. 9. Average global warming potential (GWP_{100}) of: a) branches and tops and b) stumps harvested in different years during a 75-year period, including fossil greenhouse gas emissions from supply chains and biogenic carbon fluxes (calculated as difference between combustion and decomposition) (N = 6856).

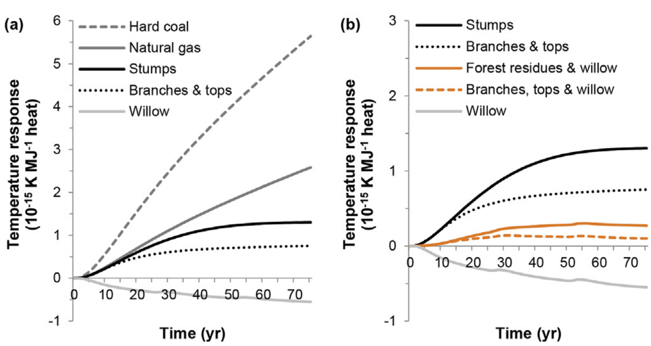

Fig. 10. Temperature response of: a) willow and forest residues (branches, tops and stumps) compared with that of the fossil fuel alternatives natural gas and hard coal and b) heat produced from a mix of forest residues (branches, tops and stumps) and willow harvested in Uppsala County. Note scale difference.

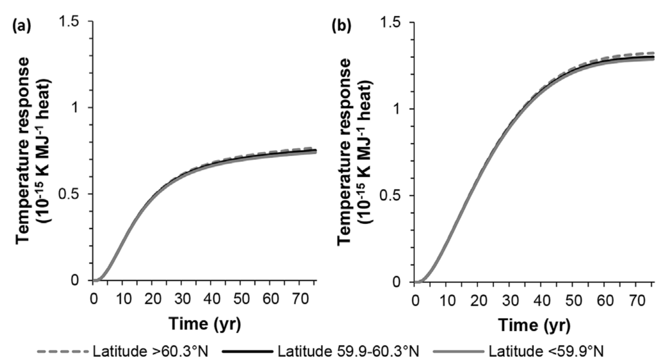

Fig. 11. Temperature response of heat produced from: a) branches and tops and b) stumps harvested from forest stands located at different latitudes in Uppsala County.

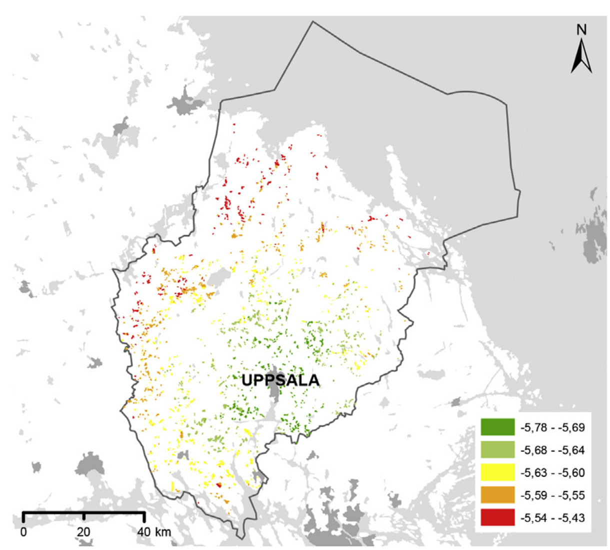

Fig. 12. Final temperature response (10^{-16} K MJ^{-1} heat) of willow energy for the different willow fields in Uppsala County (N = 2083).

residues started to level off over time, since the accumulated carbon fluxes stabilised around a new level (as can be seen in Fig. 8). The fossil fuel alternatives hard coal and natural gas resulted in continuously increasing temperature responses over time, indicating that the climate benefit of the bioenergy systems studied increased over time. A biomass mix consisting of both willow and wood chips resulted in a decreased climate impact, since the carbon sequestration effect in the willow system counteracted some of the GHG emissions in the conventional forest system (Fig. 10b).

The landscape analysis showed that the spatial variations in the study regions had a relatively small effect on the climate impact of forest residues. Prioritising forest stands located at more southerly latitudes lowered the temperature slightly (by around 3% lower at year 75), which was due to shorter transport distances and faster decomposition rates compared with the north of the study region (Fig. 11).

For the willow system, the variation between different fields was relatively small when considering the net land use effect (partly due to a constant yield level for all fields), but the initial soil organic carbon content and transport distance had some effect (Fig. 12).

3.4. Impact of methodological choices

The impact of methodological choices was evaluated using two spatial scale perspectives (stand and landscape perspective), a distinction that is particularly important for long-rotation forest systems where the dynamics of biogenic carbon fluxes vary greatly between the two perspectives. From a stand perspective, the temperature response was initially high, due to biomass combustion, after which it decreased

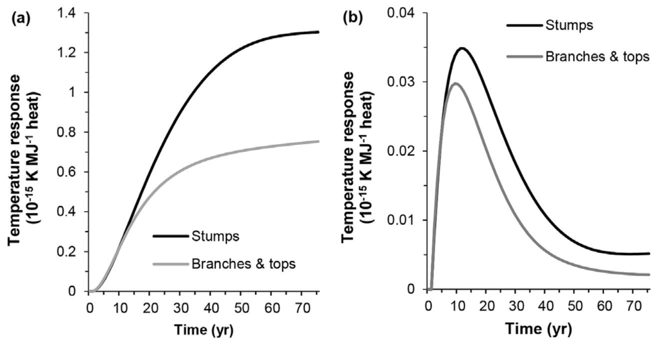

Fig. 13. Temperature response of forest residues calculated from: a) a landscape perspective and b) a stand perspective (based on an average stand in Uppsala County). Note scale difference.

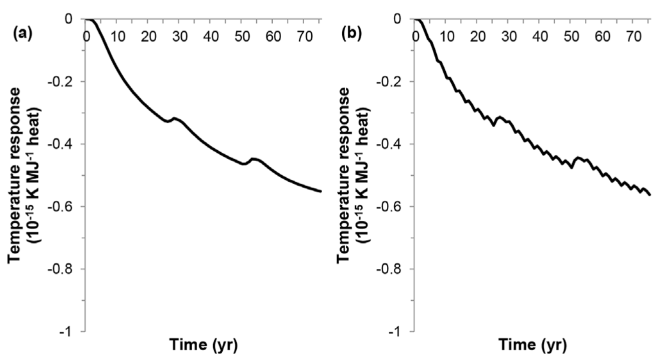

Fig. 14. Temperature response of willow calculated from: a) a landscape perspective and b) a stand perspective (based on average willow field in Uppsala County).

over time (Fig. 13b). From a landscape perspective, the temperature response increased over time as new forest stands were harvested, but the rate of change decreased and the temperature stabilised at a new level (Fig. 13a).

For the short-rotation willow system, the dynamics in a stand and landscape perspective were similar to the temperature response of the average willow stand (Fig. 14), which is due to the shorter harvest interval (as can be seen in Hammar, Hansson and Sundberg [17]). The importance of a landscape perspective for willow energy is thereby more to capture spatial variations, while for long-rotation forests it is to capture the time variation in the forest landscape.

The function of producing heat from different biomass fractions at a CHP plant was assessed in this study, meaning that emissions were allocated between the two outputs heat and power (as described in section 2.7.1 *Impact allocation*). A functional unit of MJ heat is relevant in a Swedish context, where a main driver for biomass CHP is to provide heat for district heating. However, a functional unit of MJ power may be more relevant in energy systems where heat is a less valued energy product and electricity is seen as the most important product from CHP. Studying the function of producing one MJ of power instead of heat affected the temperature response curves differently for the fuels, due to differences in conversion efficiency. The temperature response per MJ power for forest residues was even greater than for natural gas during the first two decades, but the final temperature response difference (*i.e.* climate benefit) after 75 years was larger (Fig. 15).

4. Discussion

This assessment of the effect of including spatial variations when performing LCA of bioenergy systems revealed that spatial variation affects the primary energy demand (mainly as a result of varying transport distances), which in turn affects the energy ratio (heat and

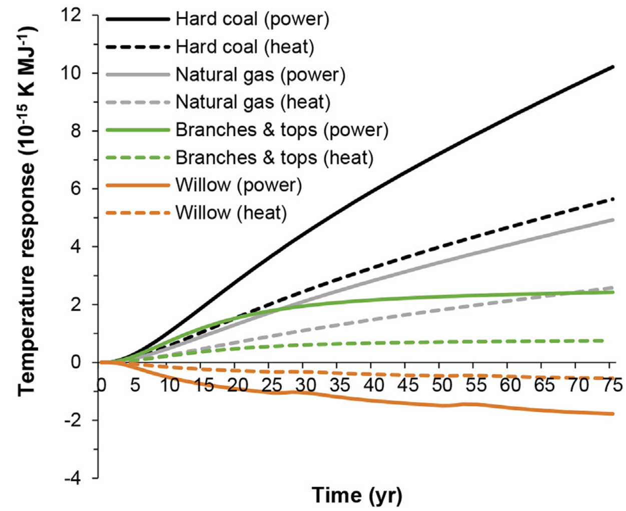

Fig. 15. Temperature response of hard coal, natural gas, forest residues (branches and tops) and willow calculated by the two functional units MJ heat and MJ power (and heat and power allocation factors).

power produced per unit of input energy) (Fig. 6). Spatial variations had some effect on the climate impact of willow energy (mainly due to varying transport distances and initial soil organic carbon content), but this effect was relatively low when considering the net land use effect, partly due to the assumption of equal productivity and N_2O fluxes for all sites. However, calculation of N_2O emissions is associated with large uncertainties and N_2O emissions for short-rotation coppice have been shown to vary greatly with both site and time [56]. Improved data on willow productivity and N_2O fluxes under site-specific growing conditions would improve the accuracy of the results.

The GWP of forest residues showed large variation depending on harvest year (Fig. 9), while the effect of spatial variations was relatively small (Fig. 11). Forest stands harvested in the end of the study period resulted in larger biogenic CO_2 emissions than forest stands harvested in the beginning, since a shorter period of decomposition was included for the late harvests. The time horizon chosen for the analysis is thus very important for the outcome of climate impact assessments. A landscape perspective is relevant when including forest stands of different ages, to account for the time variation. Furthermore, the two spatial scale perspectives describe two different functions, where yearly biomass outtake (*i.e.* a theoretical or real landscape perspective) is more relevant from an energy system perspective than a single biomass outtake (stand perspective), since the energy demand in the region needs to be fulfilled continuously. The landscape analysis showed that selecting forest stands at higher latitudes resulted in a slightly higher climate impact (due to slower decomposition and longer transport distances), which agrees with conclusions in previous studies [8,9].

Combining willow chips with forest residues lowered the temperature response compared with only combusting forest biomass (Fig. 10b). The raw material that is prioritised thus has an effect on the climate. However, compared with natural gas and hard coal, there was a climate change mitigation potential for all biomass fractions studied.

Several methodological aspects influence the result of an LCA study. Besides spatial scale, the choice of climate metric is an important factor, especially for biomass-based systems, where fluxes of biogenic carbon can vary greatly in time. Performing a time-dependent LCA, *i.e.* considering yearly fluxes of GHG and applying a time-dependent climate metric, is helpful for better understanding the effect of biogenic carbon. Using the temperature response metric (AGTP) displays both the short-term and long-term effect and, even though performing a spatial and time-dependent LCA adds complexity to the analysis, it also improves the reliability of the results. In the present study, choice of functional unit and allocation method was also shown to affect the results, but the conclusions about the long-term temperature effect compared with the fossil fuel alternatives remained the same (Fig. 15).

As this study showed, biogenic carbon fluxes have a large impact on the temperature response of bioenergy systems. This means that it is important to include these fluxes in LCAs of bioenergy systems, even though modelling land use or management change effects incorporates uncertainties. To reduce these uncertainties, better empirical data on SOC development from land use is one important aspect [57]. There is also a risk that harvesting additional biomass from forests will affect future forest productivity negatively, since nutrients are removed [58]. However, previous studies have shown ambiguous results and this effect is therefore difficult to include. Studies of stump harvesting have even shown positive effects for the establishment of new seedlings, since competing vegetation is removed [59,60].

The result from this type of assessment could be used as basis for decision making, e.g. by regional stakeholders to decide which biomass feedstock that should be prioritised in order to reach the highest climate change mitigation potential, as well as for determining the full potential of regionally produced bioenergy. The landscape analysis showed that the biomass potential in the studied region (under the assumption that only fallow land forest residues were used for energy production) was only enough to cover about 56% of the current heat production in the region (1.8 TW h per year from CHP and heating plants; [61], where the population density is 44.1 per km^2 [62]). Future demand for biomass will most likely increase in this and other sectors (*e.g.* production of transport fuel and biomaterials). Therefore biomass imports, both from other Swedish regions and from other countries, together with the use of other renewable energy sources and energy efficiency measures, will be necessary to reach future climate and energy targets.

5. Conclusions

The main conclusions from this study were:

- Prioritising willow energy resulted in lower climate impacts than energy from forest residues, since growing willow on previous fallow land involved a land use change that increased carbon stocks while harvesting forest residues resulted in decreased forest carbon stocks over the landscape.
- Harvesting branches and tops was more energy efficient than willow energy.
- The spatial variations in the studied landscape had an effect on both energy efficiency and climate impact. The effect on climate impact was however relatively small, and thus it is more important for climate change mitigation to harvest biomass from a large area to replace fossil fuels than to select certain fields or forest stands for bioenergy production.
- The landscape analysis also showed that the yearly biomass potential (branches, tops, stumps and willow grown on fallow land) was not sufficient to fulfil the regional energy demand.
- Methodological choices on spatial scale, time perspective and allocation method have an impact on the results and it is therefore crucial that such methodological choices are based on the aim of the LCA study.

Acknowledgements

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