Environmental impacts of bioenergy wood production from poplar short rotation coppice grown at a marginal agricultural site in Germany

Running head: LCA of bioenergy wood production from poplar SRC

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Abstract
For avoiding competition with food production, marginal land is economically and environmentally highly attractive for biomass production with short-rotation coppices (SRC) of fast-growing tree species such as poplars. Herein, we evaluated the environmental impacts of technological, agronomic and environmental aspects of bioenergy production from hybrid poplar SRC cultivation on marginal land in southern Germany. For this purpose different management regimes were considered within a 21-year lifetime (combining measurements and modeling approaches) by means of a holistic Life Cycle Assessment (LCA). We analyzed two coppicing rotation lengths (7x3 and 3x7 years) and seven
nitrogen fertilization rates and included all processes starting from site preparation, planting and coppicing, wood chipping and heat production up to final stump removal. The 7-year rotation cycles clearly resulted in higher biomass yields and reduced environmental impacts such as nitrate (NO\textsubscript{3}) leaching and soil nitrous oxide (N\textsubscript{2}O) emissions. Fertilization rates were positively related to enhanced biomass accumulation, but these benefits did not counterbalance the negative impacts on the environment due to increased nitrate leaching and N\textsubscript{2}O emissions. Greenhouse gas (GHG) emissions associated with the heat production from poplar SRC on marginal land ranged between 8-46 kg CO\textsubscript{2}-eq. GJ\textsuperscript{−1} (or 11-57 Mg CO\textsubscript{2}-eq. ha\textsuperscript{−1}). However, if the produced wood chips substitute oil heating, up to 123 Mg CO\textsubscript{2}-eq.ha\textsuperscript{−1} can be saved, if produced in a 7-year rotation without fertilization. Dissecting the entire bioenergy production chain, our study shows that environmental impacts occurred mainly during combustion and storage of wood chips, while technological aspects of establishment, harvesting and transportation played a negligible role.

Introduction

Anthropogenic greenhouse gas (GHG) emissions need to decrease substantially in order to limit the global temperature rise to 2°C compared to the pre-industrial period (UNFCCC, 2015) and to avoid that the global biosphere crosses irreversible tipping points (e.g., Ramanathan & Feng, 2008). In this context, the role of bioenergy production as a useful means to decrease GHG emissions from energy production is widely discussed. Currently, mankind already uses biomass with an annual gross calorific value of about 300 EJ (Haberl et al., 2007), but with the continuing rise in population and living standards the demand for bioenergy is expected to increase further.

A promising option to increase lignocellulosic biomass production for energy use is the use of short rotation coppices (SRC) of fast growing tree species. Such systems are considered as the most energy efficient carbon (C) conversion technology (Styles & Jones, 2007), which – if used for energetic purposes - can reduce total GHG emissions by up to 90 % compared to coal combustion (Djomo et al., 2011). In contrast to crops that can be used for food and energy (e.g., corn), SRC are dedicated bioenergy crops only. However, due to their low nutritional demands and maintenance requirements
Hybrid poplars have exceptional vegetative regeneration abilities (Aylott et al., 2008), high biomass production rates and can be cultivated and adapted to a wide range of geographical conditions - especially in temperate climate (Fortier et al., 2015). Established as SRC on marginal agricultural sites they further have the potential to increase soil C sequestration (Anderson-Teixeira et al., 2013), while reducing soil nitrate (Díaz-Pinés et al., 2016).

The global environmental impact of hybrid poplar SRC cultivation is, however, not positive per se. Hybrid poplar SRC are usually fertilized to increase biomass growth (Balasus et al., 2012), which can boost nitrogen (N) losses such as N₂O, a much more potent GHG than carbon dioxide (CO₂). Hence, the positive effect of C sequestration may be counterbalanced by N₂O emissions due to fertilization and also due to other processes during the plantations’ lifetime. For example, technological processes such as storage and transport may cause high GHG emissions (Schweier et al., 2016). Therefore, a comprehensive evaluation of SRC cultivation focusing on the GHG balance of such systems together with other environmental impacts, e.g., NO₃ leaching losses need to have a long-term perspective (Raney et al., 1994). Also, differences in management practices, in particular changing rotation cycle length, can have significant impacts on biomass yield and environmental effects such as soil C storage or soil N₂O emissions (e.g., Fang et al., 2007; Bacenetti et al., 2012).

Up to now, most analyzes addressing SRC cultivation and its environmental impacts have focused either on technological processes such as establishment, planting, harvesting etc. (Heller et al., 2003; Gasol. et al., 2009; Nasi o Di Nasso et al., 2010; Rödl, 2010; Fiala and Bacenetti, 2012; Bacenetti et al., 2012; Gabrielle et al., 2013; Manzone et al., 2014; Murphy et al., 2014; Schweier et al., 2016), or on agronomic aspects such as plant growth or N₂O fluxes (Pecenka et al., 2013; Rösch et al., 2013; Zona et al., 2013a, 2013b; Sabbatini et al., 2015; Walter et al., 2015; Brilli et al., 2016). However, studies simultaneously addressing technological, agronomic as well as environmental aspects of SRC production are scarce. Moreover, they usually do not include long-term GHG emission balances for the full lifetime of a SRC, including a number of rotation cycles and the final removal of the remaining biomass.

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In the present study, we conducted an integrated analysis of the environmental impact categories *Global Warming Potential* (GWP) and the *Eutrophication Potential* (EP) related to energy produced from wood chips from a hybrid poplar SRC established on marginal land in southern Germany. We focused our analysis on these two categories, which are the primary criteria in numerous papers that deal with the cultivation and use of biomass for energy production (Cherubini and Strømman, 2011), because they address different environmental spheres (air and soil) and are often found to show significant differences between management regimes (McBride *et al.*, 2011). Our study addressed all phases of the technological and agronomic production of poplar wood chips, based on experimental (Díaz-Pinés *et al.*, 2016) and literature data (Burger, 2010) as well as data collections concerning technological activities (c.f. Schweier *et al.*, 2016) and the use of a database (Ecoinvent, 2010) in combination with simulation estimates (for 21 years) performed with the process-based ecosystem model *LandscapeDNDC* (Haas *et al.*, 2013) and *Umberto*, a software which supports ISO compliant LCAs (IFU, 2011). We hypothesize that the energy production from hybrid poplar SRC on marginal land (from cradle-to-site) results in a C sink due to C uptake during plant growth, while the overall production of energy out of SRC (from cradle-to-grave) results in a C source, however, being significantly lower compared to the use of fossil fuels.

**Materials and methods**

**Life Cycle Assessment**

In order to assess the environmental impacts of SRC wood chip production, the methodological framework of Life Cycle Assessment (LCA) was applied and 14 production chains were modeled using the software *Umberto* v5.6 (IFU, Hamburg, Germany).

**Scope definition**

All processes associated with the cultivation and growth of poplar SRC and the subsequent production of wood chips over a full rotation cycle started with the initial site preparation. This was followed by the cultivation and repeated harvesting, the chip production and delivery of the chips at gate of the...
heating plant. The entire chain also included the final removal of the stems and stumps from the plantation site (Fig. 1) after 21 years of cultivation. To assess the impact of harvesting rotation cycle lengths within the 21-years plantation lifetime we analyzed 2 different cycle length (7x3 years = seven rotation cycles: 7 harvests each 3 years and 3x7 years = 3 rotation cycles: 3 harvests each 7 years). In combination with this two management practices we also analyzed seven different N fertilization rates (0/25/50/75/100/150/200 kg NH₄NO₃-N per hectare and rotation). Thus, in total 14 production chains were assessed regarding their environmental impacts (Tab. 1).

**Site description**

Most of the data that were required as inputs for the LCA have been collected on an experimental site in southern Germany. The site has a soil quality index (SQI) of 37 representing typical conditions for marginal agricultural land in the region (slope 10%, mean annual air temperature 7.2 °C and mean annual rainfall 790 mm y⁻¹ (May-September: 466 mm)). Thereby the SQI is a numerical value that characterizes the quality and production potential of cropland for annual crops. The scale of possible values ranges from 7 to 100 (c.f. Aust et al., 2014). The 4.5 ha site was established in 2009 with two commercial hybrid poplar clones, *i.e.* Max 4 (*Populus maximowiczii* A. Henry x *P. nigra* L.) and Monviso (*P. x generosa* A. Henry x *P. nigra* L.). It is located in the mountainous Swabian Alps region in southwest Germany (48°6’N/9°14’E; 650 m a.s.l.). Data on soil properties (incl. C and N contents, soil pH, bulk density, soil water holding capacity, wilting point, stone content, hydraulic conductivity, soil type, clay - silt - and sand contents), biomass production, gross primary production or photosynthesis, soil GHG fluxes and nitrate leaching were obtained within four experimental years (Schnitzler et al., 2014; Díaz-Pines et al., 2016).

**Simulation model**

For providing comprehensive input data for *Umberto* regarding the biomass estimation during 21 years, the GHG exchange and nitrate leaching rates of poplar SRC cultivation and the plant growth we used the model *LandscapeDNDC* (Haas et al., 2013). *LandscapeDNDC* is an assembled modular modeling platform that integrates process-based models for describing C, N and water fluxes within
terrestrial ecosystems. It was initialized with data from the above-mentioned experimental site. The model’s reliability has been shown in previous studies evaluating C, N and water balances (Holst et al., 2010; Grote et al., 2011a, 2011b), plant growth for poplar plantations (Werner et al., 2012), GHG emissions under the influence of mean commodity crops and poplar plantations (Kim et al., 2014, 2015; Kraus et al., 2015; Molina-Herrera et al., 2015, 2016; Zhang et al., 2015, Díaz-Pinés et al., 2016), and NO₃ leaching (Díaz-Pinés et al., 2016; Dirnböck et al., 2016). For the present study, LandscapeDNDC was run with the physiological model “PSIM” (Physiological Simulation Model) (Grote et al., 2011a), the soil biogeochemical model “DNDC” (DeNitrification-Decomposition) (Li et al., 1992, 2000; Stange et al., 2000), the empirical microclimate model “ECM” (Grote et al., 2009) and the hydrology module originating from “DNDC” (Li et al., 1992). Several input data regarding soil, vegetation, climate and air chemistry were required to run LandscapeDNDC. As stated, most of the input data were collected on the experimental site. The meteorological input data were obtained from the nearest German Weather Service meteorological station Sigmaringen (Deutscher Wetterdienst DWD, Offenbach, Germany) for the period 2009-2014 and then repeated until 2030 for the analysis of the LCA in a long-term prospective. A constant atmospheric N deposition rate (15-20 kg N ha⁻¹ y⁻¹, estimated from regional values presented by Schaap et al., 2015) was applied along the 21 years for all cases. Physiological parameterization (e.g. RuBisCO (Ribulose-1,5-bisphosphate carboxylase/oxygenase) activity, water use efficiency, respiration) has been derived from literature and various previous experiments (Behnke et al., 2012; Schnitzler et al., 2014; Diaz-Pines et al., 2016). Additional parameters for clone-specific allometric relationships (e.g., maximum height: diameter ratio, crown width: diameter ratio) and final leaf area index, became adjusted to the detailed measurements at the sites made throughout the first rotation phase and the beginning of the second (5 years). The ability to cover a wide range of site and climatic conditions has been shown by the representation of various poplar SRC all over Europe (Werner et al., 2012).

In order to compute the total GHG balance, the results from LandscapeDNDC such as net ecosystem C exchange (NEE), N₂O emissions and NO₃ leaching, were combined with estimated indirect N₂O emissions due to soil nitrate leaching (calculated according to Denman et al., 2007), measured soil

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CH$_4$ fluxes (based on a 4-years measurement campaign at the studied site; c.f. Díaz-Pinés et al., 2016) were used as inputs in Umberto.

**System boundaries**

All 14 production chains (Fig. 1) comprise the following eight main process steps:

1. *Establishment and Maintenance*: We included the production of plant cuttings in a nursery, initial ploughing, harrowing with a disc harrow, application of herbicides (5 L ha$^{-1}$ Round up; Monsanto, USA) with a boom sprayer and mechanical weed control with a field cultivator. Planting of single rows (6,350 cuttings ha$^{-1}$) was carried out with a professional planting machine owned by Probstdorfer Saatzucht GmbH (Vienna, Austria) (Fig. S11). GHG emissions due to these activities were based on data collected on site (Schweier, 2013; Schweier et al., 2016). Information regarding machines and inputs are given in Tab. 2. Data regarding operating machines can be found in Tab. S3. Besides, it was assumed that after each harvesting cycle a mechanical weed control was carried out with a field cultivator and herbicides were applied (2.5 L ha$^{-1}$ Stomp SC; COMPO, Münster, Germany) with a boom sprayer. Respective emission data were taken from a database (Ecoinvent, 2010).

2. *Fertilization*: We considered one application of fertilizer in the 1$^{st}$ year of each rotation (Tab. 1, Tab. 2). Simulated fertilization rates were derived from past studies (Hellebrand et al., 2008; Kavdir et al., 2008; van den Driessche et al., 2008; Kern et al., 2010; Balasus et al., 2012) and reflect common procedures for poplar SRC. Respective emission data were taken from Ecoinvent database, too (Ecoinvent, 2010). It should be noted that while liquid NPK fertilizer was given to the experimental site as fertigation, simulations only assumed the application of NH$_4$NO$_3$ because the model is not sensitive to P and K nutrition, implicitly assuming that differences between sites regarding these elements have no significant impact on plant development.

3. *Field GHG*: We simulated the GHG emissions of this site with the LandscapeDNDC (as described in simulation model) and considered besides NEE (gross primary production minus autotrophic and heterotrophic respiration) also other components of the field-GHG balance, i.e.
soil N\textsubscript{2}O and methane (CH\textsubscript{4}) emissions as well as indirect N\textsubscript{2}O emissions following NO\textsubscript{3} leaching.

4. **Harvesting**: We assumed harvesting cycles of either 7 times in 21 years (= each 3-years) or 3 times in 21 years (= each 7-years). Harvesting was carried out with a modified forage harvester (400 kW) (Fig. S12), cutting and chipping all stems and branches in one operation. The use of this machine in all rotation cycles was justified since the biomass simulation has shown that the stem diameters at ground level are unlikely to exceed the machines´ capacity even after seven years of growth (Tab. S7). For all harvests, the accompanying tractor-trailer units were considered to transport the wood chips to an interim storage site at 2 km distance. Related data were collected from the first coppice after a 3-year cycle only, but detailed productivity figures of the machine were collected in an earlier study (Schweier & Becker, 2012). Thus, specific time and fuel consumptions were calculated for each harvesting operation within the 21-years lifetime (Tab. S4) depending on the amount of biomass per harvest.

5. **Transportation**: We included loading of fresh low-density wood chips (water content (WC) 55% (w/w)) at the interim storage site into trucks with a capacity of 80 loose m\textsuperscript{3}, the full loaded transport to a heating plant in 50 km distance, as well as the empty return of the trucks. GHG emissions due to transportation were taken from the database Ecoinvent (2010). Ton kilometers were calculated per each harvest (Tab. S4).

6. **Storage**: We considered the drying process during storage of fresh wood chips to lower the water content (WC) down to ~30% (w/w), which is required before burning the biomass in small and medium-sized heating plants. To quantify C losses in terms of CO\textsubscript{2} emissions (Tab. 3) from freshly harvested wood chips, around 60 kg biomass from the first harvest in 2012 were enclosed into 4 environmentally controlled chambers (temperature of 20\textdegree C, relative air humidity of 40%, light intensity of ~50 \textmu mol photons m\textsuperscript{-2} s\textsuperscript{-1}) at the phytotron facility at the Helmholtz Zentrum München (e.g., Vanzo et al., 2015) and online measurements of trace gases (GHG and VOCs (volatile organic compounds)) were performed immediately after harvest and continuously for 6 weeks using infrared spectroscopy and online proton transfer reaction mass
spectrometry (Ghirardo et al., 2010, 2014; Vanzo et al., 2015). GHG and VOC fluxes were calculated as previously described (Ghirardo et al., 2011) and given per dried biomass.

7. **Removal:** We considered the removal of remaining above- and belowground biomass on site within three months after the last harvest at the end of the plantations’ lifetime in year 21, thereby assuming that the disturbance effects have ceased during this time period (by Díaz-Pinés et al., 2016). The related C release is reported in Tab. S8. LandscapeDNDC did not consider any changes in soil properties caused by the extraction (e.g., changes in bulk density, redistribution of C-contents, hydrological properties) or any priming associated to this process (Strömgren et al., 2012). Data regarding machinery- and fuel input of stump removal were taken from literature (Burger, 2010) and can be found in Tab. 2. The use of biomass from stump removal for energy production was not considered, since this is not a common practice in Germany.

8. **Combustion:** We considered the combustion of wood chips in the heating plant. In 2015 data were collected from a modern medium-sized biomass heating plant (1.7 MWh a⁻¹, 90% efficiency, built in 2012) located in the Black Forest, Germany. The data included all technological processes and used inputs from takeover of wood chips until removal of ashes. As chips were dried before, it was assumed that the energy density of the chips is 11.84 GJ per ton wood chips at a WC of 31.8% (Hartmann, 2009). Resulting amounts of energy per hectare are shown in Table S6. The system boundary is when the product heat (GJ) is leaving the plant (water at 100°C in winter, 75°C in summer). Collected data refer to a mixed input of hard- and softwood. However, to calculate the amount of required wood chips per year we assumed that the heating plant was fed with poplar wood chips from SRC only.

**Others:** Following the LCA approach we considered also CO₂ emissions caused by upstream processes, e.g., due to the production and use of machineries or fuels. Inputs were calculated according to Nemecek & Kägi (2007) and related emission data were gathered from the commercial database Ecoinvent (Ecoinvent, 2010).
**Functional Units**

Emissions refer to the cultivated surface in hectares. In addition, we calculated all GHG emissions referring to dry matter in megagram (Mg$_{dm}$) of produced wood chips and to gigajoule (GJ) because an energy unit is needed to compare the results to various other combustion studies.

**Statistical analysis**

The relationships between aboveground biomass (AGB), GWP, EP, photosynthesis, total ecosystem respiration, N$_2$O emissions and NO$_3$ leaching were explored by Principal Component Analysis (PCA) (SIMCA-P v13, Umetrics, Umeå, Sweden). PCA was here employed for data mining and data description, where the resulting graphic plot (Fig. 4) summarized the largest variability in the data set and could be interpreted more easily than a matrix of data (Ghirardo et al., 2005). The principles of PCA and its objectives can be found in details elsewhere (Martens and Martens, 2001; Gottlieb et al., 2004). Before computing the PCA, data were logarithmically transformed (log2), centered and scaled with 1 x SD$^{-1}$. The resulting significant principal components were cross-validated using 7 validation rounds and 200 maximum iterations. Additionally, two-ways ANOVA was carried out with a significance level of $\alpha = 0.05$ for all tests.

**Results**

**Life cycle inventory**

Aboveground biomass (AGB) under the 14 production chains ranged from 5.44 to 6.39 Mg$_{dm}$ y$^{-1}$ ha$^{-1}$ (Fig. 2). Plant productivity with a 7-year-rotation cycle was on average 10.4 % higher than with a 3-year rotation cycle ($P=0.016$). Highest biomass productivities were reached in the production chains with highest fertilization rates (chain 7: 3y/200kgN and chain 14: 7y/200kgN) (Fig. 2). Within the 3-year rotation cycles the maximum production was reached in the 2$^{nd}$ rotation of the plantations’ lifetime while in the 7-year rotation cycles it was in the 1$^{st}$ rotation (Fig. S10). The application of fertilizer after each harvest had no significant influence on the total AGB of the poplar SRC, however, it lead to increased soil N$_2$O emissions and stimulated nitrate leaching, especially in the 3-year rotation cycles (Fig. 3).
Life cycle impact assessment

Effect of rotation cycle length

Our study shows that the GWP of the different production chains depended mostly on the length of the rotation cycles, and successively on fertilization regimes, as indicated by the 1\textsuperscript{st} and 2\textsuperscript{nd} principal components of the PCA, respectively (Fig. 4). The dependency of the GWP on rotation cycle length was found highly significant ($P<0.001$). Cases with 7-year rotation cycles resulted in a lower, thus better, GWP (on average: 15.6 Mg CO$_2$-eq. ha$^{-1}$) than the 3-year cycles (on average: 39.4 Mg CO$_2$-eq. ha$^{-1}$) (Fig. Error! Reference source not found.). The lowest GWP was reached for the 7-year rotation cycle without fertilization (chain 8 (7y/0kgN): 10.6 Mg CO$_2$-eq. ha$^{-1}$, Fig. 5) whereas the highest GWP corresponded to chain 7 (3y/200kgN) with 56.5 Mg CO$_2$-eq. ha$^{-1}$ (Fig. 5).

The $EP$ was influenced by the length of the rotation cycles ($P=0.0066$, Fig. 4). The lowest $EP$ was reached with a 7-year rotation cycle and no fertilization treatment (chain 8 (7y/0kgN): 195.6 kg PO$_4$-eq. ha$^{-1}$, Fig. 5). The $EP$ ranged from 0.15 PO$_4$-eq. GJ$^{-1}$ (chain 8: 7y/0kgN) to 0.56 kg PO$_4$-eq. GJ$^{-1}$ (chain 7: 3y/200kg) (Fig. 5).

Effect of fertilization

The GWP was positively correlated with the fertilization rates within each rotation cycle length, meaning that the GWP increased with increasing fertilization rate. The $EP$ showed the same behavior and tended to increase with increasing amount of fertilizer. There was a significant difference between the impacts in the lowest (chain 1: 3y/0kgN & chain 8: 7y/0kgN) and the highest (chain 7: 3y/200kgN & chain 14:7y/200kgN) fertilization treatments ($P=0.007$).

Environmental impacts with respect to produced amount of aboveground biomass

When considering the amount of produced biomass, the increases of yield-scaled emissions, i.e. the ratios between AGB production and GWP, were much larger between the 3-year and the 7-year rotation cycles than those obtained by enhancing the fertilization rates from 0 to 200 kg N ha$^{-1}$ rotation$^{-1}$ (Fig. S13). The use of the 7-year rotation cycles decreased yield-scaled emissions by a factor of 2.2 ± 0.1 compared to the 3-year rotation cycles. Furthermore, fertilization increased
significantly yield-scaled emissions (Fig. S13), i.e. GHG emissions associated with fertilization increased faster as biomass production.

**Environmental impacts per process step**

Each process step of the production chain contributed differently to the GWP (Tab. 3). Most influencing was Field-GHG – as C sink. Therefore, we conducted a contribution analysis and highlighted the CO₂-fluxes within Field-GHG for the most favourable production chain no. 8 (Fig. S1): net ecosystem exchange was estimated to be -167.4 kg CO₂-eq. GJ⁻¹, which is derived from simulated ecosystem respiration of +399 kg CO₂-eq. GJ⁻¹ and N₂O emissions of +8 kg CO₂-eq. GJ⁻¹ (Fig. S1) on the one hand, and photosynthesis of -574 kg CO₂-eq. GJ⁻¹ as well as CH₄ deposition of -0.4 kg CO₂-eq. GJ⁻¹ on the other. Thus, in contrast to all other process steps, Field-GHG is acting as C sink (Fig. S1, Tab. 3). Tab. S2 presents more detailed emission data of all production chains for the process step Field-GHG.

On the other hand, Combustion is the major contributor for increasing the GWP (P<0.001) (Tab. 3) by causing 75-79 % of the total C emissions. Another significant impact on GWP is caused by the process step Storage, as it is associated with significant C losses (+28 kg CO₂-eq. GJ⁻¹, Tab. 3). Emissions in Removal contributed with 6-33 % to the GWP (+4.0-5.6 kg CO₂-eq. GJ⁻¹, Tab. 3). It has to be noted that 87-95 % of this C release occurred after the elimination of plant roots from the soil (Tab. S8).

Among the technological processes, Transport caused the highest impact (+2.2 kg CO₂-eq. GJ⁻¹, Tab. 3). This aspect, however, strongly depended on the transport distance: the longer the way the stronger the impact. Each additional kilometer (km) of transport with a lorry (20-28 t payload) emits +0.02 kg CO₂-eq. per GJ and km. Finally, the contribution of Fertilization to the GWP was very variable and depended on the management practice (Tab. 3). The more fertilizer was applied, the higher was the impact on GWP ha⁻¹ - mainly due to upstream processes, in particular the production of fertilizer. Other processes (Establishment & Maintenance, Harvesting) were of negligible magnitude (Tab. 3).
Due to the use of fuels, machineries and fertilizer, all process steps contributed to EP (Table S5). In particular, Field-GHG, Removal and Fertilization were the components causing 73-92 % of the potential impacts (Tab. S5): Field-GHG and Removal due to nitrate leaching and Fertilization mainly due to upstream processes (i.e. fertilizer production). Combustion caused 7-25 % of the burdens, mainly due to the disposal of rost ash in land farming (33 t y\(^{-1}\)). All other process steps (Establishment & Maintenance, Harvesting, Transport, Storage) were negligible (Tab. S5).

**Carbon sources**

The LCA showed that all process steps up- and downstream of Field-GHG released CO\(_2\) to the atmosphere (Fig. 6). By stepwise subtracting the impact of each process from the GWP savings gained in Field-GHG, the contribution of each process can be calculated, thereby allowing to assess the importance of each process to the overall GWP of poplar SRC Field-GHG reduction. We exemplified this calculation for four selected production chains (chain 1: 3y/0kgN, chain 7: 3y/200kgN, chain 8: 7y/0kgN and chain 14: 7y/200kgN; Fig. 6). In all cases heat production from poplar SRC finally resulted in a moderate C release varying between 8 and 46 kg CO\(_2\)-eq. GJ\(^{-1}\) (which equals to 11-57 Mg CO\(_2\)-eq. ha\(^{-1}\)).

**Discussion**

**Applied tools, data and assumptions**

The combination of the LCA-Umberto with the process-based ecosystem model LandscapeDNDC demonstrated the analytical power of combining the two methodologies for embracing environmental and technological impacts of SRC production systems. Particular the feature of Umberto to include “own” data as well as data from the database Ecoinvent could be conveniently used for the integration of model outputs from LandscapeDNDC.

The quality of our comprehensive LCA depends very much on the reliability of the ecosystem simulations, which in the present study were evaluated with a large body of experimental data obtained from own field and laboratory experiments. It is therefore, to a certain degree, specific for hybrid poplar SRC on marginal land under environmental conditions typical for southwest Germany.
However, our experimental investigations focused on the first 4-year period and included only one transition between rotation cycles. The extrapolation to multiple rotation cycles thus includes uncertainties regarding long-term soil development and the impact of climatic events that may have not been observed within these four years. Particularly the effort for removing the tree stumps in the end as well as the impact on soil emissions due to disturbance of the soil structure is prone to possible under- or overestimations. It should be noted that plant growth was well reproduced by the model during the first 2 years of the second rotation (Fig. S10). Likewise, the observed soil N\textsubscript{2}O emissions, which are very difficult to be tracked by model predictions, were covered by LandscapeDNDC very well with a coefficient of determination of $r^2 = 0.41$ (Fig. S14). Other uncertain assumptions include the regeneration capacity of poplar plants after harvest and the combustion method. For example the increase in productivity from the 1\textsuperscript{st} to the 2\textsuperscript{nd} rotation cycle might have originated either from an initial lower investment of the plants into roots and soil micro-organisms, faster re-sprouting from already established root systems, or from unknown factors depending on site-specific conditions (Hofmann-Schielle \textit{et al.}, 1999; Verlinden \textit{et al.}, 2015). On the other hand, it is not fully clear if the growth capacity of hybrid poplars can be sustained during up to 7 rotation cycles. At an Italian site, growth of poplars persisted over 12 years and 3 cutting cycles (Nassi o Di Nasso \textit{et al.}, 2010) while specific hybrid poplars performed poorly after the 4\textsuperscript{th} rotation on marginal soils in Belgium (Dillen \textit{et al.}, 2013). However, the chosen time period of 21 years seems reasonable. The re-sprouting ability of poplars is indeed declining with age, but reports indicate that the mortality rate is small after 16 years (at least for some clones) (Dillen \textit{et al.}, 2013), and reports of long-term studies indicate that growth vigor can even increase after 15 years of repeated harvesting. Although, poplar SRCs are more profitable when harvested several times without replanting and thus praxis oriented. Additionally, similar studies (e.g, Deckmyn \textit{et al.}, 2004) have chosen comparable time periods (25 years) for growing poplar coppice in a 3-year rotation system, which is in line with the present investigation.
**Potential impacts on GWP and EP**

The *Global Warming Potentials* (GWP) and *Eutrophication Potentials* (EP) associated with the heat production from poplar SRC on marginal land ranged between 8-46 kg CO$_2$-eq. GJ$^{-1}$ and 0.15-0.56 kg PO$_4$-eq. GJ$^{-1}$, respectively. This span is very large and can be explained by the 14 simulated management scenarios covering fertilization rates varying between 0 and 1.4 t NH$_4$NO$_3$ ha$^{-1}$ in 21 years. These values are considerably higher than results of previous studies (Rödl, 2010; Bacenetti et al., 2012; Fiala and Bacenetti, 2012; González-García et al., 2012ab; Gabrielle et al., 2013; Miguel et al., 2015). As noticed, studies simultaneously addressing technological, agronomic as well as environmental aspects of SRC production haven’t been performed so far. Also, some studies use literature data only (e.g., Rugani et al., 2015). I.e., González-García et al. (2012a) and Bacenetti et al. (2016) focused only on technological processes when analyzing environmental impacts of woody biofuel production, both in the Po Valley, Italy. In the case of Bacenetti et al. (2016) the estimated GWP was 24.7-49.6 kg CO$_2$-eq. Mg dm$^{-1}$ compared to 98.9-541.4 kg CO$_2$-eq. Mg dm$^{-1}$ in our study. Keeping in mind that main C sources as storage for up to several weeks, combustion and long distance transport processes were not considered by Bacenetti et al. (2016) the higher GWP herein can be explained. Also, inputs varied between the studies, for example González-García et al. (2012a) assumed a diesel consumption of 92 l ha$^{-1}$ for soil cultivation while it was up to 423 l ha$^{-1}$ in our case (Burger, 2010).

The same is true for EP: The resulting EP for two management regimes for willow SRC in Sweden (González-García et al., 2012b) was much lower (5.9-159.5 kg PO$_4$-eq. ha$^{-1}$) than our results (195.6-694.4 kg PO$_4$-eq. ha$^{-1}$). In our case, 92-95 % of the emissions occurred in the process step “Field-GHG” due to NO$_3$ leaching, and another 1-4 % resulted from the removal of ashes in the combustion. The latter process was not considered by González-García et al. (2012). González-García and colleagues included the leaching of nutrients, using modeled data following the literature recommendations. From their analysis they concluded that NO$_3$ leaching is an important component and that environmental assessments would profit from field measurement and modelling data (e.g., Díaz-Pines et al., 2016). The study by Murphy et al. (2013) evaluated the environmental impacts
associated with cultivation, fertilization (max. 800 N ha\(^{-1}\)), harvest and transport of willow biomass on Field-GHG. They considered the transport process (50 km), however, not the impact of the combustion process. The omission of the combustion process resulted therefore in lower GWP values (5.8-11.7 kg CO\(_2\)-eq. GJ\(^{-1}\)) compared to our study (8.4-45.7 kg CO\(_2\)-eq. GJ\(^{-1}\)).

In conclusion, the somehow higher GWP and EP values found herein result mainly by our holistic approach that aimed to address technological, agronomic as well as environmental aspects and thus, by having different system boundaries compared to other studies and by higher level of details concerning the data input.

**Effect of rotation cycle length**

The combination of LCA and PCA clearly showed that the main factor controlling the biomass production and the environmental impact was the rotation cycle length. The biomass production from SRC was higher in 7-year rotation cycles compared to the 3-year cycles, conversely to the impacts on GWP, which decrease by increasing the rotation cycle length. Also in other studies longer rotation cycles were related to higher biomass yields (Guidi et al., 2009; Nassi o Di Nasso et al., 2010; Bacenetti et al., 2012, Rugani et al., 2015) which corroborate our modeling study. It has to be noted, however, that the initial planting density was equal in all studies although shorter rotation cycles might be associated with higher densities than the longer cycles. The growth potential would probably be reached faster, but the outcome of the simulations also depends on other factors (e.g., N availability). Thus, different plant densities were not considered (c.f. Nassi O Di Nasso et al., 2010), as it would lead to decreasing comparativeness and increasing uncertainties (e.g., representation of competition, speed of crown expansion).

The benefit of longer rotation cycles mainly originates from the fact that leaf area index tends to be smaller in the first year of re-growth than in the later stages and that these years are less frequent in the 7-year rotation cycles (DeBell et al., 1996; Fang et al., 1999). Such a development has been reproduced with LandscapeDNDC also at the experimental site (unpublished data). Coppicing poplars in longer periods is visibly positive not only because of the higher biomass accumulation. Further
benefits concern the N cycle: in a 7-year rotation period, N cycling within the system is enhanced due to a larger (average) litter fall and intensified N uptake (due to in average larger requirements) decreasing the N loss. In addition, less N inputs are required due to only 3 fertilization events (instead of 7). Furthermore, fewer harvests lead to less organizational effort for the farmer and thus, SRC is easier to be adopted. A more extensive management also leads to lower environmental impacts (Fig. 5, S13) due to lower fuel consumption in field and transport operations (Tab. S2, Tab. S3) and due to a reduced requirement for N input. From our results, we recommend to establish hybrid poplar SRC with longer rotation cycles in order to minimize environmental impacts and to maximize biomass production.

**Effect of fertilization treatments**

Although less important compared to the rotation cycle length, the present study indicates that the studied fertilization regimes affect the SRC biomass production while negatively impacting the environment. Fertilizers are commonly applied in SRC to improve plant biomass growth (Rewald et al., 2016). However, generally the effect of fertilization of hybrid poplars is largely variable reaching from extremely relevant (Luo & Polle, 2009) to minor importance or not detectable at all (e.g., Scholz & Ellerbrock, 2002; Balasus et al., 2012). In the present study, biomass yields responded to the fertilizer N rates very modest, indicating that other parameters were limiting. The biomass growth in the LandscapeDNDC simulations is limited by three factors: (i) Photosynthesis, (ii) soil water and (iii) nutrient availability, while the two latter are coupled. As the response to different N fertilization rates is weak we assume that our system was not nitrogen limited and therefore additional N inputs will not pronounce plant growth. This assumption is supported by leaf (around 2.5% N), bark (around 0.5% N) and wood (0.12-0.16% N) total N contents (data not shown), indicating no clear fertilization effects. Only leaves of cv. Monviso showed a small increase in leaf total N contents from 2.31+/−0.42% (controls) to 2.83+/−0.52% (fertilized trees). Additional nitrogen sources are dry deposition, the high soil nutrient pools from the land use management change and the mobilization from litter decomposition.
Also, the fertilization effects on growth depend next to the initial N availability on the time course of N depletion indicating that the fertilization effect is often only visible in later rotation cycles (Hofmann-Schielle et al., 1999; Jug et al., 1999). Short rotations profit particularly if initial N is low, while otherwise much of the fertilization gets lost (Balasus et al., 2012) and the effect of additional N input is only visible in later rotation cycles when the soil is already more depleted. Another important reason why the response to N was weak is because we applied the fertilization once per rotation cycle. A yearly application was not considered because farmers aim to minimize labour input and costs by cultivating extensive SRC. The supply of fertilizer had a strong influence on environmental impacts. In particular, the Eutrophication Potential (EP) increased with increasing application of fertilizer resulting from stimulated nitrate leaching. This has been reflected by the LCA, and is well in accordance with other field investigations (e.g., Balasus et al., 2012). In the present study, EP ranged from 0.15 to 0.56 kg PO₄eq. GJ⁻¹ (chain 8: 7y/0kgN & chain 7: 3y/200kgN, respectively). An input of 50 kg N ha⁻¹ rotation⁻¹ led to an increase in EP by a factor of 1.2-1.6 and an input of 100 kg N ha⁻¹ rotation⁻¹ increased EP by a factor 1.4-2.3. Also, N₂O emission increased significantly with fertilization, adding another environmental trade-off to the relative small gain in biomass production. The difference between C sequestration and release was highest when the rotation cycle was longer (7-year) and fertilization was omitted (chain 8: 7y/0kgN). According to our results, fertilization cannot be recommended during the first rotation period of hybrid poplar cultivation and should be considered only in small amounts in later cycles of the plantation’s lifetimes.

**Environmental impacts per process step**

The two most relevant process steps along the production chains are plant growth as such (Field-GHG, acting as C sink) and combustion procedures (Combustion, acting as C source), the latter because fixed C is released. In this respect, it should be noted that the process step Combustion can considerably contribute to the EP due to the disposal of rost ash in land farming. Since its main component is calcium it has an eutrophication effect, which, however, could be mitigated when used as limestone.
When excluding Field-GHG and Combustion, it turned out that the Storage of wood chips is the main emission source causing 62-78 % of the total burden. Nevertheless, considering storage with accompanied drying of wood chips is necessary because small- to medium-sized heating plants usually require wood chips with low water content to increase heat efficiency. Unfortunately, this process also implies a substantial loss of C to the atmosphere (approx. 17 %) and, consequently, a loss in terms of energy efficiency. The measured C loss rate is well in line with previous findings (e.g., Lenz et al., 2015 (17-22 %) or Manzone & Balsari, 2016 (10 %)). If the wood chips would not be dried, considerably less energy would be produced, compensating the gain in C to feed the power plants. However, the optimum balance between losses and gains is an ongoing discussion. Possible options to decrease losses include outdoor drying (Lenz et al., 2015), different chip sizes or pile heights (Jirjis, 2005; Scholz et al., 2005; Pari et al., 2015) and the application of technological assistant systems such as ventilation.

Among the technological processes, the transport operation caused the highest environmental impacts. Of course this result strongly depends on the transport distance (here 50 km). However, it is well known that a regional use of wood chips can be favored and that either a reduction of WC (Schweier et al., 2016) or a densification process (Adams et al., 2015) before the transport operation would highly reduce environmental impacts.

Effect of substitution

To conclude, LCA results show that in all cases heat production from hybrid poplar SRC finally resulted in a moderate C release (8-46 kg CO₂-eq. GJ⁻¹). However, the use of poplar wood chips for bioenergy production is still much more favorable compared to heat production from fossil fuels (Fig. 6, Djomo et al., 2013; Hansen et al., 2013). The impacts of the most frequently used fossil energy on GWP (Fig. 6a right bars) vary between and 70-85 kg CO₂-eq. GJ⁻¹heat (natural gas), 90-120 kg CO₂-eq. GJ⁻¹heat (oil) and 110-150 kg CO₂-eq. GJ⁻¹heat (coal) (Cherubini et al., 2009; Ecoinvent, 2010). Generation of heat from the most favorable production chain 8 (7y/0kgN) (GWP of 8.4 kg CO₂-eq. GJ⁻¹heat) substituting the same amount produced by fossil oil (GWP of 90-120 kg CO₂-eq.GJ⁻¹heat), Fig.
6a) will result in a CO$_2$-saving potential of ~97 kg (82-112) CO$_2$-eq. GJ$^{-1}$ heat (which equals 123 Mg CO$_2$-eq. ha$^{-1}$).

In addition, it should be noted that environmental impacts from poplar SRC cultivation could be easily offset to assure a carbon-neutral system, e.g., by incorporating 4-8 t C rotation cycle$^{-1}$. Another option may be the use of belowground biomass for energy production. So far we assumed that it was taken out at the end of the plantations’ lifetime, but simply remained in the field. The additional biomass (5.3-6.3 Mg$_{an}$ ha$^{-1}$) could be either used for heat production in the plant or upgraded to biochar and then put on the site, the last one favoring the increase of soil organic C stocks.

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Supporting information legends

S1. Main biological components of the Global Warming Potential of the process step Field-GHG for production chain no. 8 [in kg CO₂-eq. GJ⁻¹].

S2. Emissions occurring within the process step Field-GHG [in Mg CO₂-eq. ha⁻¹].

S3. Machinery inputs of agricultural and operating machines [in kg ha⁻¹].

S4. Machinery inputs of harvesting and transport operations.

S5. Eutrophication Potential for the production of poplar wood chips from SRC in 21 years, shown per process step and for all 14 production chains [in kg PO₄-eq. GJ⁻¹].

S6. Produced amount of energy [in Gigajoule per hectare].

S7. Stem diameter at ground level, for all 14 production chains [in cm].

S8. Carbon release occurring in the process step Removal, shown for all 14 production chains [in kg CO₂-eq. GJ⁻¹].

S9. Dimensional growth of poplar SRC at Sigmaringen, Germany.

S10. Produced amount of aboveground biomass [in Mg dm ha⁻¹] during 21-years life time of SRC, depending on the fertilizer scenario [in kg N ha⁻¹].

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S11. SRC planting machine owned by Probstdorfer Saatzucht GmbH (Vienna, Austria), used for planting poplar SRC in Sigmaringen, Germany.

S12. Case New Holland forage harvester FR 9060 (Heilbronn, Germany).

S13. Ratios between aboveground biomass (AGB) and Global Warming Potential (GWP), for all 14 production chains [in Mg dry per t CO2-eq.].

S14. Comparison between measured and simulated mean N2O emissions at the experimental site (Sigmaringen, Germany).

**Figure captions**

**Figure 1.** System boundary of analyzed production chains of wood chips from hybrid poplar SRC. Abbreviations: Ammonium nitrate (NH4NO3), nitrous oxide (N2O), nitrate (NO3), Megawatt (MW).

**Figure 2.** Production of aboveground biomass (AGB) during the SRC’s lifetime and losses during storage [in (a) and (c) Mg dry ha⁻¹ and (b) and (d) Mg CO2-eq. ha⁻¹]. An overview of the 14 analyzed production chains can be found in Table 1.

**Figure 3.** Results of Life Cycle Inventory – Soil N2O emissions and NO3 leaching per hectare during the plantations’ lifetime, for all 14 production chains. An overview of the 14 analyzed production chains can be found in Table 1.

**Figure 4.** Results of Principal Component Analysis.

Score (a) and correlation loading (b) plots of Principal Component Analysis (PCA) of 7 different N fertilizer treatments (0, 25, 50, 75, 100, 150, 200 kg NH4NO3-N per hectare) and two alternative harvesting rotation cycles (no. harvest x years) of (7 x 3, in black) and (3 x 7, in gray). PCA was computed using aboveground biomass (AGB), GWP, EP, C-loss during storage, net photosynthesis (A), ecosystem respiration (R), N2O- emissions and NO3 leaching data per unit ground area (hectare).

In plot A, the Hotelling’s T² ellipse denote a significance level of α=0.05. In plot B, the loading values

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are normalized to 1 and the ellipses denote the 100% (outer) and 75% (inner) explained variance. Two gray arrows were added to the plots indicating the dimension related to (i) AGB and (ii) EP, NO₂, NO₃, respectively. Model fitness (referring to the first 2 principal components): cross-validated fraction of the total predicted variation (Q²) = 98.9%; explained total data variation R² = 99.7%.

**Figure 5.** Global Warming Potential and Eutrophication Potential for the production of poplar wood chips from SRC in 21 years, shown for all 14 production chains in different functional units. An overview of the 14 analyzed production chains can be found in Table 1. Stepwise reduction of the beneficial Global Warming Potential (GWP) of the process biological production by other processes. (a) Summing up of the GWP starting with the process Field-GHG. On the right side the ranges of GWP from fossil sources (Cherubini et al., 2009; Ecoinvent, 2010) are shown. (b) Relative contribution of each process to the decline in GWP saving potentials starting from Field-GHG. An overview of the here presented production chains can be found in Table 1.

**Figure 6.** Stepwise reduction of the beneficial Global Warming Potential (GWP) of the process biological production by other processes. (a) Summing up of the GWP starting with the process Field-GHG. On the right side the ranges of GWP from fossil sources (Cherubini et al., 2009; Ecoinvent, 2010) are shown. (b) Relative contribution of each process to the decline in GWP saving potentials starting from Field-GHG. An overview of the here presented production chains can be found in Table 1.
Table 1. Overview of the 14 analyzed production chains.

| Chain no. | Scenario name | Rotation cycle   | Fertilization rate | Fertilization (in total) |
|-----------|---------------|------------------|--------------------|--------------------------|
| 1         | 3y/0kgN       | 3-year: 7*3      | 0                  | 0                        |
| 2         | 3y/25kgN      | 3-year: 7*3      | 25                 | 175                      |
| 3         | 3y/50kgN      | 3-year: 7*3      | 50                 | 350                      |
| 4         | 3y/75kgN      | 3-year: 7*3      | 75                 | 525                      |
| 5         | 3y/100kgN     | 3-year: 7*3      | 100                | 700                      |
| 6         | 3y/150kgN     | 3-year: 7*3      | 150                | 1,050                    |
| 7         | 3y/200kgN     | 3-year: 7*3      | 200                | 1,400                    |
| 8         | 7y/0kgN       | 7-year: 3*7      | 0                  | 0                        |
| 9         | 7y/25kgN      | 7-year: 3*7      | 25                 | 75                       |
| 10        | 7y/50kgN      | 7-year: 3*7      | 50                 | 150                      |
| 11        | 7y/75kgN      | 7-year: 3*7      | 75                 | 225                      |
| 12        | 7y/100kgN     | 7-year: 3*7      | 100                | 300                      |
| 13        | 7y/150kgN     | 7-year: 3*7      | 150                | 450                      |
| 14        | 7y/200kgN     | 7-year: 3*7      | 200                | 600                      |
### Table 2. Field operations and associated machinery data.

| Rotation length | Operation                  | Timeline                              | Operating rate (h ha\(^{-1}\)) | Machine type | Power (kw) | Diesel consumption (kg ha\(^{-1}\))* | Implement *                      |
|-----------------|----------------------------|---------------------------------------|---------------------------------|--------------|-----------|--------------------------------------|----------------------------------|
| 3-years         | Application of herbicides  | Year 0,1 & after each harvest         | 0.7                             | Tractor      | 83        | 94.5                                 | Glyphosate (1.8 kg/ha)           |
|                 |                            |                                       |                                 |              |           |                                      | Dicamba (0.1 kg/ha)              |
|                 |                            |                                       |                                 |              |           |                                      | Pendimethalin (8 kg/ha)          |
|                 | Ploughing                  | Establishment                         | 1.8                             | Tractor      | 102       | 23.2                                 |                                  |
|                 | Harrowing                  | Establishment                         | 1.1                             | Tractor      | 83        | 13.5                                 |                                  |
|                 | Planting                   | Establishment                         | 2.2                             | Tractor      | 83        | 21.9                                 | 6,350 Cuttings                   |
|                 | Mechanical weed control    | Year 0,1 & after each harvest         | 0.8                             | Tractor      | 83        | 51.6                                 |                                  |
|                 | Application of fertilizer  | 1x per rotation                       | 0.7                             | Tractor      | 83        | 0-1,400 (Tab.1)                      | Nitrogen                         |
|                 | Harvesting                 | 1x per rotation                       | 1.09-1.14 (Tab. S4)             | Forager      | 400       | 444-464 (Tab. S4)                    |                                  |
|                 | Removal                    | Year 21                               | 9.0                             | Tractor      | 233       | 351.8                                |                                  |

| 7-years         | Application of herbicides  | Year 0,1 & after each harvest         | 0.7                             | Tractor      | 83        | 52.5                                 | Glyphosate (1.8 kg/ha)           |
|                 |                            |                                       |                                 |              |           |                                      | Dicamba (0.1 kg/ha)              |
|                 | Ploughing                  | Establishment                         | 1.8                             | Tractor      | 102       | 23.2                                 | Pendimethalin (4 kg/ha)          |
| Activity                          | Frequency                           | Equipment  | 2020   | 2030   | Notes                           |
|----------------------------------|-------------------------------------|------------|--------|--------|---------------------------------|
| Harrowing                        | Establishment                       | Yes        | 1.1    | 83     | 13.5                            |
| Planting                         | Establishment                       | Yes        | 2.2    | 83     | 21.9                            |
| Mechanical weed control          | Year 0, 1 & after each harvest      | Yes        | 0.8    | 83     | 103.2                           |
| Application of fertilizer        | 1x per rotation                     | Yes        | 0.7    | 83     | 0-600 (Tab.1)                  |
| Harvesting                       | 1x per rotation                     | Forager    | 1.52-1.53 (Tab. S4) | 400 | 265-268 (Tab. S4)           |
| Removal                          | Year 21                             | Yes        | 9.0    | 233    | 351.8                           |

* Inputs refer to the overall lifetime of the plantation.
Table 3. *Global Warming Potential* for the production of poplar wood chips from SRC in 21 years, shown per process step and for all 14 production chains [in kg CO₂-eq. GJ⁻¹]. An overview of the 14 analyzed production chains can be found in Table 1. Results are reported per process step (EstMain= Establishment and Maintenance; Fert= Fertilization; Field-GHG= Field-Greenhouse gases; Har= Harvesting; Tra= Transport; Rem= Removal; Comb= Combustion). Negative signs indicate CO₂ sinks while positive signs indicate CO₂ sources.

| Chain   | EstMain | Fert  | Field-GHG | Har   | Trans | Stor  | Rem   | Comb  |
|---------|---------|-------|-----------|-------|-------|-------|-------|-------|
| 1: 3y/0kgN | +0.34  | +0.00 | -150.04   | +0.55 | +2.19 | +28.02| +4.49 | +139.20 |
| 2: 3y/25kgN | +0.33  | +1.37 | -149.13   | +0.54 | +2.19 | +28.02| +4.16 | +139.20 |
| 3: 3y/50kgN | +0.33  | +2.65 | -148.07   | +0.54 | +2.19 | +28.02| +4.17 | +139.20 |
| 4: 3y/75kgN | +0.33  | +3.89 | -147.09   | +0.54 | +2.19 | +28.02| +4.16 | +139.20 |
| 5: 3y/100kgN | +0.32  | +5.09 | -145.43   | +0.53 | +2.19 | +28.02| +4.12 | +139.20 |
| 6: 3y/150kgN | +0.31  | +7.37 | -141.43   | +0.53 | +2.19 | +28.02| +4.02 | +139.20 |
| 7: 3y/200kgN | +0.31  | +9.76 | -138.30   | +0.53 | +2.19 | +28.02| +4.02 | +139.20 |
| 8: 7y/0kgN  | +0.30  | +0.00 | -167.27   | +0.36 | +2.19 | +28.02| +5.55 | +139.20 |
| 9: 7y/25kgN | +0.30  | +0.56 | -166.23   | +0.35 | +2.19 | +28.02| +5.51 | +139.20 |
| 10: 7y/50kgN| +0.30  | +1.06 | -165.81   | +0.35 | +2.19 | +28.02| +5.51 | +139.20 |
| 11: 7y/75gN | +0.30  | +1.55 | -165.40   | +0.35 | +2.19 | +28.02| +5.51 | +139.20 |
| 12: 7y/100kgN| +0.30  | +2.04 | -164.95   | +0.35 | +2.19 | +28.02| +5.50 | +139.20 |
| 13: 7y/150kgN| +0.29  | +2.99 | -164.28   | +0.35 | +2.19 | +28.02| +5.47 | +139.20 |
| 14: 7y/200kgN| +0.29  | +3.95 | -163.36   | +0.35 | +2.19 | +28.02| +5.47 | +139.20 |
1 Establishment & Maintenance
Production of plant cuttings.
- Application of herbicides.
- Ploughing, tillage (with rotary harrow and cultivator).
- Planting and weed control during first year.
- Rotary cultivation of the edge (yearly) and of the site (after each harvest).
- Application of herbicides after each harvest.

2 Fertilization
- One application of 0/25/50/75/100/150/200 kg NH₄NO₃-N per hectare and rotation period.

3 Field-Greenhouse gas emissions
- Photosynthesis & total ecosystem respiration.
- N₂O emissions.
- NO₃ leaching.

4 Harvesting
- Harvesting cycle of either 7 times in 21 years (=all 3 years) or 3 times in 21 years (=all 7 years).
- With modified forage harvester (400 kW) and use of accompanying tractor-trailer units.
- Interim storage in 2 km distance.

5 Transport
- Transportation of fresh wood chips to a heating plant in 50 km distance with trailer (capacity 80 loose m³).

6 Storage
- Storage and drying process of fresh wood to a water content (WC) of approximately 30%.

7 Removal
- Elimination of above- and belowground biomass at the end of the plantations’ lifetime.

8 Combustion
- Combustion of wood chips in a heating plant (1.7 MWₑₜₙ).
- Disposal of ashes (including carbon content)
Stepwise reduction of GWP from field-GHG to Combustion [kg CO₂-eq. GJ⁻¹]

Stepwise summing up of GWP potentials of main processes

(b)

Losses in GWP relative to Field-GHG [%]

- 3y; no N (no.1)
- 3y; 200 kg N (no.7)
- 7y; no N (no.8)
- 7y; 200 kg N (no.14)

Field GHG, EstMain, Fert, Har, Trans, Stor, Rem, Comb