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

JANINE SCHWEIER[1], SAÚL MOLINA-HERRERA[2], ANDREA GHIRARDO[3], RÜDIGER GROTE[2], EUGENIO DÍAZ-PINÉS[2], JÜRGEN KREUZWIESER[4], EDWIN HAAS[2], KLAUS BUTTERBACH-BAHL[2], HEINZ RENNENBERG[4], JÖRG-PETER SCHNITZLER[3] and GERO BECKER[5]

[1]*Chair of Forest Operations, Albert-Ludwigs-University Freiburg, Werthmannstraße 6, 79085 Freiburg, Germany,* [2]*Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research, Atmospheric Environmental Research, Kreuzeckbahnstraße 19, 82467 Garmisch-Partenkirchen, Germany,* [3]*Helmholtz Zentrum München, Research Unit Environmental Simulation, Institute of Biochemical Pathology, Ingolstädter Landstraße 1, 85764 Neuherberg, Germany,* [4]*Chair of Tree Physiology, Albert-Ludwigs-University Freiburg, Georges-Köhler-Allee 53/54, 79110 Freiburg, Germany,* [5]*Chair of Forest Utilisation, Albert-Ludwigs-University Freiburg, Werthmannstraße 6, 79085 Freiburg, Germany*

Abstract

For avoiding competition with food production, marginal land is economically and environmentally highly attractive for biomass production with short-rotation coppices (SRCs) 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 (7 × 3 and 3 × 7 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_3) leaching and soil nitrous oxide (N_2O) 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_2O emissions. Greenhouse gas (GHG) emissions associated with the heat production from poplar SRC on marginal land ranged between 8 and 46 kg CO_2-eq. GJ^{-1} (or 11–57 Mg CO_2-eq. ha^{-1}). However, if the produced wood chips substitute oil heating, up to 123 Mg CO_2-eq. ha^{-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.

Keywords: ammonium nitrate fertilization, ecosystem respiration, LandscapeDNDC, life cycle assessment, nitrate leaching, nitrous oxide, short-rotation coppices, technology and agronomy, wood chips, yield-scaled emissions

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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 (SRCs) 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 the total GHG emissions by up to 90% compared to coal combustion (Djomo *et al.*, 2010). In contrast to crops that

Correspondence: Janine Schweier, tel. +4976120397616, fax +497612033763, e-mail: janine.schweier@foresteng.uni-freiburg.de

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can be used for food and energy (e.g., corn), SRCs are dedicated bioenergy crops only. However, due to their low nutritional demands and maintenance requirements, they can be cultivated on marginal lands, thus reducing the impacts on land availability for food and feed production (Butterbach-Bahl & Kiese, 2013; Dillen *et al*., 2013). Hybrid poplars have exceptional vegetative regeneration abilities (Aylott *et al*., 2008) and 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-Pines *et al*., 2016).

The global environmental impact of hybrid poplar SRC cultivation is, however, not positive *per se*. Hybrid poplar SRCs are usually fertilized to increase biomass growth (Balasus *et al*., 2012), which can boost nitrogen (N) losses such as N_2O, a much more potent GHG than carbon dioxide (CO_2). Hence, the positive effect of C sequestration may be counterbalanced by N_2O 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, for example, NO_3 leaching losses, needs to have a long-term perspective. 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 N_2O 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, and harvesting (Heller *et al*., 2003; Gasol *et al*., 2009; Nassi o di Nasso *et al*., 2010; Rödl, 2010; Bacenetti *et al*., 2012; Fiala & Bacenetti, 2012; Gabrielle *et al*., 2013; Manzone *et al*., 2014; Murphy *et al*., 2014; Quartucci *et al*., 2015; Schweier *et al*., 2016), or on agronomic aspects such as plant growth or N_2O fluxes (Pecenka *et al*., 2013; Rösch *et al*., 2013; Zona *et al*., 2013a,b; Walter *et al*., 2015; Brilli *et al*., 2016; Sabbatini *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.

In this 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 the use of biomass for energy production (Cherubini & 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-Pines *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

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 were included, starting 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-year plantation lifetime, we analyzed 2 different cycle lengths (7 × 3 years = seven rotation cycles: 7 harvests each 3 years and 3 × 7 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 NH_4NO_3-N per hectare and rotation). Thus, in total, 14 production chains were assessed regarding their environmental impacts (Table 1).

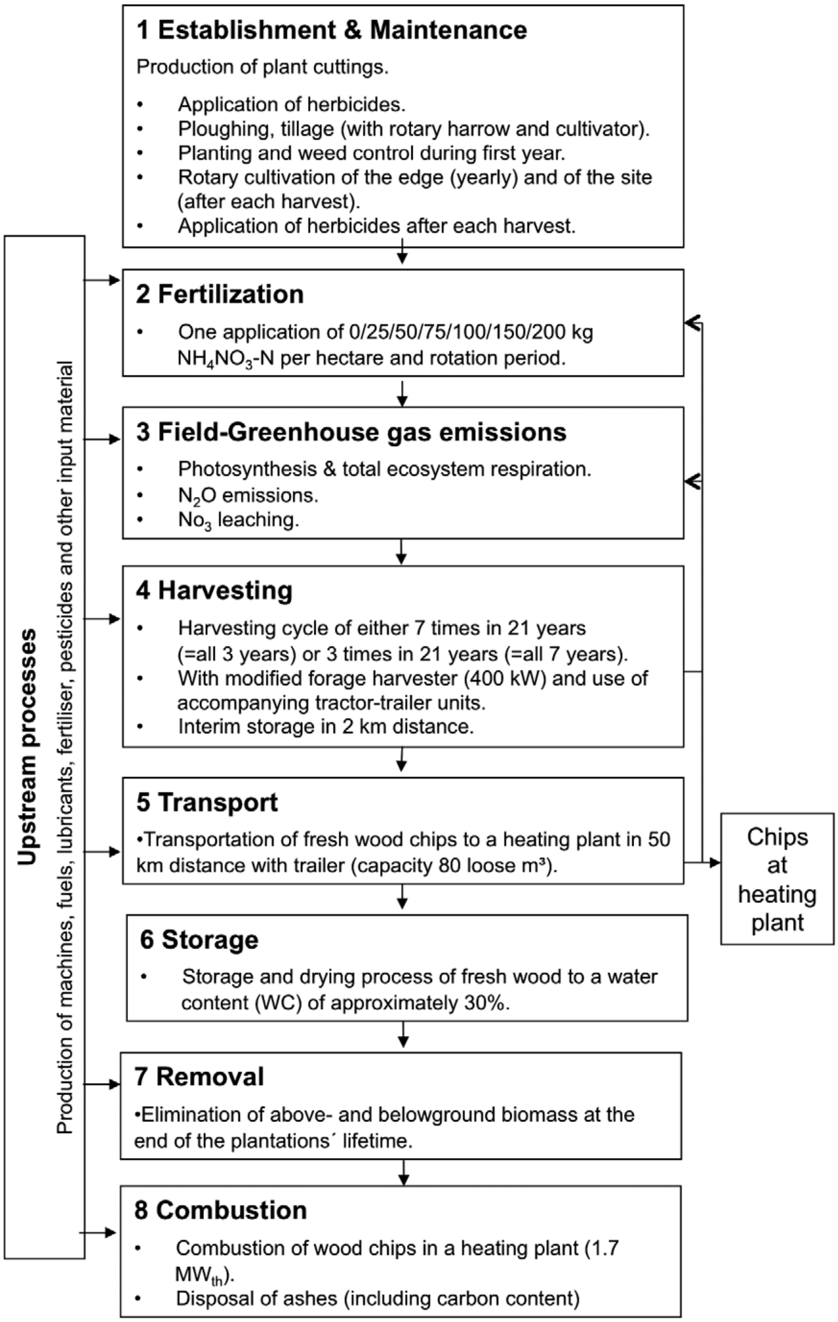

Fig. 1 System boundary of analyzed production chains of wood chips from hybrid poplar SRC. ammonium nitrate (NH_4NO_3), nitrous oxide (N_2O), nitrate (NO_3), megawatt (MW).

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 yr^{-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, that is, Max 4 (*Populus maximowiczii* A. Henry × *P. nigra* L.) and Monviso (*P.* × *generosa* A. Henry × *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 (including C and N contents, soil pH, bulk density, soil water-holding capacity, wilting point,

Table 1 Overview of the 14 analyzed production chains

Chain no.	Scenario name	Rotation cycle Year	Fertilization rate kg NH_4NO_3 ha^{-1} $rotation^{-1}$	Fertilization (in total) kg NH_4NO_3 ha^{-1}
1	3 yr/0 kgN	3-year: 7*3	0	0
2	3 yr/25 kgN	3-year: 7*3	25	175
3	3 yr/50 kgN	3-year: 7*3	50	350
4	3 yr/75 kgN	3-year: 7*3	75	525
5	3 yr/100 kgN	3-year: 7*3	100	700
6	3 yr/150 kgN	3-year: 7*3	150	1,050
7	3 yr/200 kgN	3-year: 7*3	200	1,400
8	7 yr/0 kgN	7-year: 3*7	0	0
9	7 yr/25 kgN	7-year: 3*7	25	75
10	7 yr/50 kgN	7-year: 3*7	50	150
11	7 yr/75 gN	7-year: 3*7	75	225
12	7 yr/100 kgN	7-year: 3*7	100	300
13	7 yr/150 kgN	7-year: 3*7	150	450
14	7 yr/200 kgN	7-year: 3*7	200	600

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 models' reliability has been shown in the previous studies evaluating C, N, and water balances (Holst *et al.*, 2010; Grote *et al.*, 2011a,b), 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-Pines *et al.*, 2016), and NO_3 leaching (Díaz-Pines *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} yr^{-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 the literature and various previous experiments (Behnke *et al.*, 2012; Schnitzler *et al.*, 2014; Díaz-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 SRCs all over Europe (Werner *et al.*, 2012).

To compute the total GHG balance, the results from *LandscapeDNDC*, such as net ecosystem C exchange (NEE), N_2O emissions, and NO_3 leaching, were combined with estimated indirect N_2O emissions due to soil nitrate leaching (calculated according to Denman *et al.*, 2007), and measured soil CH_4 fluxes (based on a 4-year measurement campaign at the studied site; c.f. Díaz-Pines *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 plowing, harrowing with a disk harrow, application of herbicides (5 l ha^{-1} Round up; Monsanto, St. Louis, MO, USA) with a boom sprayer, and mechanical weed control with a field cultivator. Planting of single rows (6350 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).

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 and after each harvest	0.7	Tractor	83	94.5	Glyphosate (1.8 kg ha^{-1}) Dicamba (0.1 kg ha^{-1}) Pendimethalin (8 kg ha^{-1})
	Ploughing	Establishment	1.8	Tractor	102	23.2	
	Harrowing	Establishment	1.1	Tractor	83	13.5	
	Planting	Establishment	2.2	Tractor	83	21.9	6350 Cuttings
	Mechanical weed control	Year 0, 1 and after each harvest	0.8	Tractor	83	51.6	
	Application of fertilizer	1× per rotation	0.7	Tractor	83	0–1400 (Table 1)	Nitrogen
	Harvesting	1x per rotation	1.09–1.14 (Table S4)	Forager	400	444–464 (Table 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^{-1}) Dicamba (0.1 kg ha^{-1}) Pendimethalin (4 kg ha^{-1})
	Ploughing	Establishment	1.8	Tractor	102	23.2	
	Harrowing	Establishment	1.1	Tractor	83	13.5	
	Planting	Establishment	2.2	Tractor	83	21.9	6350 Cuttings
	Mechanical weed control	Year 0, 1 and after each harvest	0.8	Tractor	83	103.2	
	Application of fertilizer	1× per rotation	0.7	Tractor	83	0–600 (Table 1)	Nitrogen
	Harvesting	1× per rotation	1.52–1.53 (Table S4)	Forager	400	265–268 (Table S4)	
	Removal	Year 21	9.0	Tractor	233	351.8	

*Inputs refer to the overall lifetime of the plantation.

Information regarding machines and inputs is given in Table 2. Data regarding operating machines can be found in Table 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 first year of each rotation (Tables 1 and 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_4NO_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, that is, soil N_2O and methane (CH_4) emissions as well as indirect N_2O emissions following NO_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 as 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 (Table 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-year lifetime (Table 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 m³, 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 (Table 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_2 emissions (Table 3) from freshly harvested wood chips, around 60 kg biomass from the first harvest in 2012 was enclosed into 4 environmentally controlled chambers (temperature of 20 °C, relative air humidity of 40%, light intensity of ~50 μmol photons m^{-2} s^{-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 3 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-Pines *et al*., 2016). The related C release is reported in Table 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 with this process (Strömgren *et al*., 2012). Data regarding machinery and fuel input of stump removal were taken from the literature (Burger, 2010) and can be found in Table 2. The use of biomass from stump removal for energy production was not considered, as this is not a common practice in Germany.
8. *Combustion*: We considered the combustion of wood chips in a heating plant. In 2015, data from one year were collected in 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 hardwood 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 CO_2 emissions caused by upstream processes, for example, 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

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 CO_2-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 CO_2 sinks while positive signs indicate CO_2 sources

	Process step							
Chain	*EstMain*	*Fert*	*Field-GHG*	*Har*	*Trans*	*Stor*	*Rem*	*Comb*
1: 3 yr/0 kgN	+0.34	+0.00	−150.04	+0.55	+2.19	+28.02	+4.49	+139.20
2: 3 yr/25 kgN	+0.33	+1.37	−149.13	+0.54	+2.19	+28.02	+4.16	+139.20
3: 3 yr/50 kgN	+0.33	+2.65	−148.07	+0.54	+2.19	+28.02	+4.17	+139.20
4: 3 yr/75 kgN	+0.33	+3.89	−147.09	+0.54	+2.19	+28.02	+4.16	+139.20
5: 3 yr/100 kgN	+0.32	+5.09	−145.43	+0.53	+2.19	+28.02	+4.12	+139.20
6: 3 y/150 kgN	+0.31	+7.37	−141.43	+0.53	+2.19	+28.02	+4.02	+139.20
7: 3 y/200 kgN	+0.31	+9.76	−138.30	+0.53	+2.19	+28.02	+4.02	+139.20
8: 7 yr/0 kgN	+0.30	+0.00	−167.27	+0.36	+2.19	+28.02	+5.55	+139.20
9: 7 yr/25 kgN	+0.30	+0.56	−166.23	+0.35	+2.19	+28.02	+5.51	+139.20
10: 7 yr/50 kgN	+0.30	+1.06	−165.81	+0.35	+2.19	+28.02	+5.51	+139.20
11: 7 yr/75 gN	+0.30	+1.55	−165.40	+0.35	+2.19	+28.02	+5.51	+139.20
12: 7 yr/100 kgN	+0.30	+2.04	−164.95	+0.35	+2.19	+28.02	+5.50	+139.20
13: 7 yr/150 kgN	+0.29	+2.99	−164.28	+0.35	+2.19	+28.02	+5.47	+139.20
14: 7 yr/200 kgN	+0.29	+3.95	−163.36	+0.35	+2.19	+28.02	+5.47	+139.20

(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_2O 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 detail elsewhere (Martens & Martens, 2001; Gottlieb *et al.*, 2004). Before computing the PCA, data were logarithmically transformed (log2), centered, and scaled with $1 \times SD^{-1}$. The resulting significant principal components were cross-validated using 7 validation rounds and 200 maximum iterations. Additionally, two-way 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} yr^{-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: 3 yr/200 kgN and chain 14: 7 yr/200 kgN) (Fig. 2). Within the 3-year rotation cycles, the maximum production was reached in the second rotation of the plantations' lifetime, while in the 7-year rotation cycles, it was in the first 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_2O 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 first and second 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

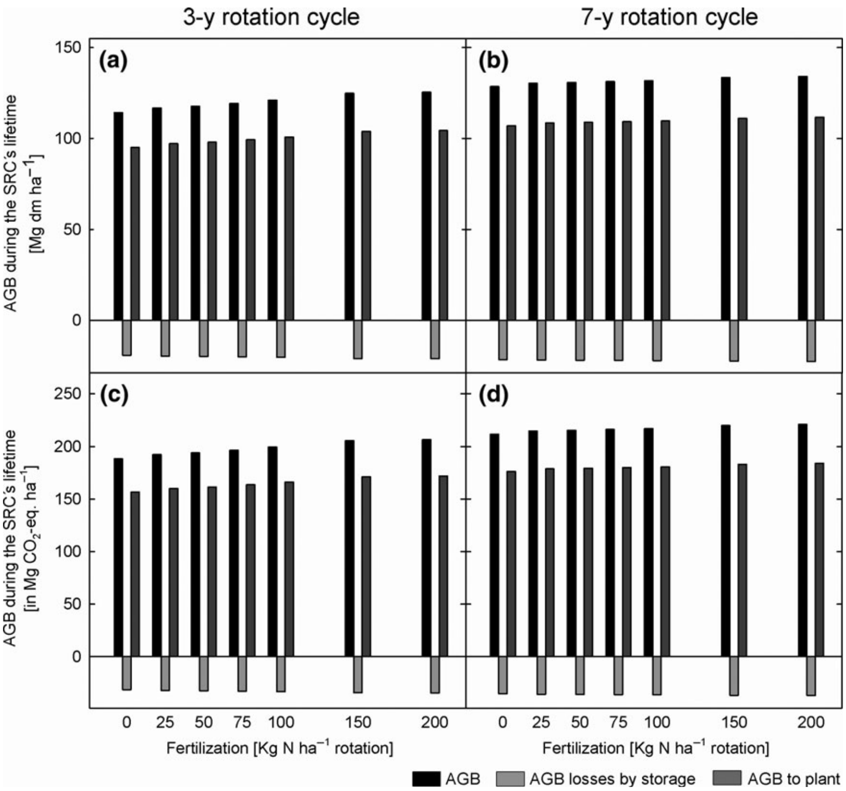

Fig. 2 Production of *aboveground biomass* (*AGB*) during the SRC's lifetime and losses during storage [in (a) and (b) Mg_{dm} ha^{-1} and (c) and (d) Mg CO_2-eq. ha^{-1}]. An overview of the 14 analyzed production chains can be found in Table 1.

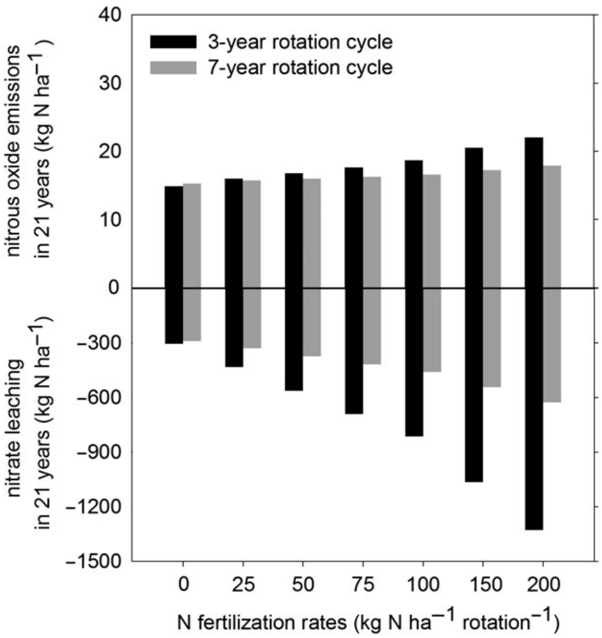

Fig. 3 Results of Life Cycle Inventory – soil N_2O emissions and NO_3 leaching per hectare during the plantations' lifetime, for all 14 production chains. An overview of the 14 analyzed production chains can be found in Table 1.

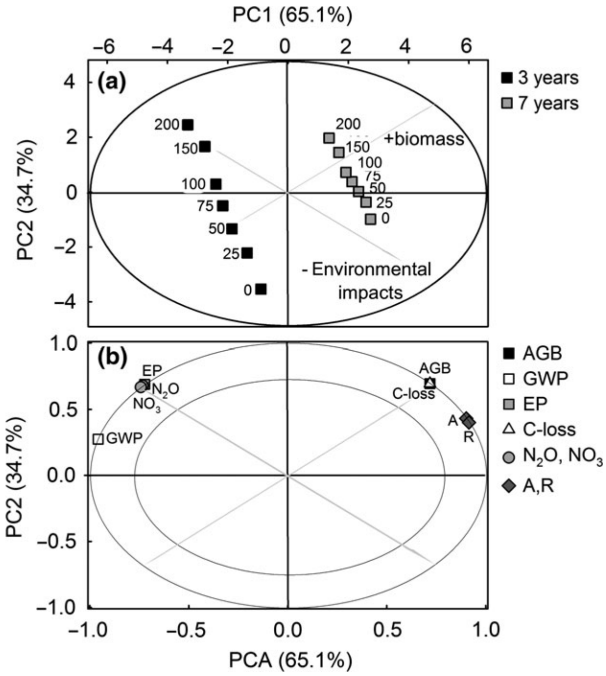

Fig. 4 Results of principal component analysis. Score (a) and correlation loading (b) plots of principal component analysis (PCA) of 7 different N fertilizer treatments (0, 25, 50, 75, 100, 150, 200 kg NH_4NO_3-N per hectare) and two alternative harvesting rotation cycles (no. harvest × years) of (7 × 3, in black) and (3 × 7, in gray). PCA was computed using *aboveground biomass* (*AGB*), *GWP, EP*, C loss during storage, net photosynthesis (A), ecosystem respiration (R), N_2O emissions, and NO_3 leaching data per unit ground area (hectare). In plot A, the Hotelling's T^2 ellipse denotes a significance level of $\alpha = 0.05$. In plot B, the loading values 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, NO_2, NO_3, respectively. Model fitness (referring to the first 2 principal components): cross-validated fraction of the total predicted variation (Q^2) = 98.9%; explained total data variation R^2 = 99.7%.

CO_2-eq. ha^{-1}) (Fig. 5). The lowest *GWP* was reached for the 7-year rotation cycle without fertilization (chain 8 (7 yr/0 kgN): 10.6 Mg CO_2-eq. ha^{-1}, Fig. 5), whereas the highest *GWP* corresponded to the 3-year rotation cycle with highest fertilization treatment (chain 7 (3 yr/200 kgN) 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 (7 yr/0 kgN): 195.6 kg PO_4-eq. ha^{-1}, Fig. 5). The *EP* ranged from 0.15 PO_4-eq. GJ^{-1} (chain 8: 7 yr/0 kgN) to 0.56 kg PO_4-eq. GJ^{-1} (chain 7: 3 yr/200 kg) (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: 3 yr/0 kgN & chain 8: 7 yr/0 kgN) and the highest (chain 7: 3 yr/200 kgN & chain 14:7 yr/200 kgN) fertilization treatments ($P = 0.007$).

Environmental impacts with respect to produced amount of aboveground biomass. When considering the amount of produced biomass, the increases in yield-scaled emissions, that is, 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), that is, 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* (Table 3). Most influencing was *Field-GHG* – as C sink. Therefore, we conducted a contribution analysis

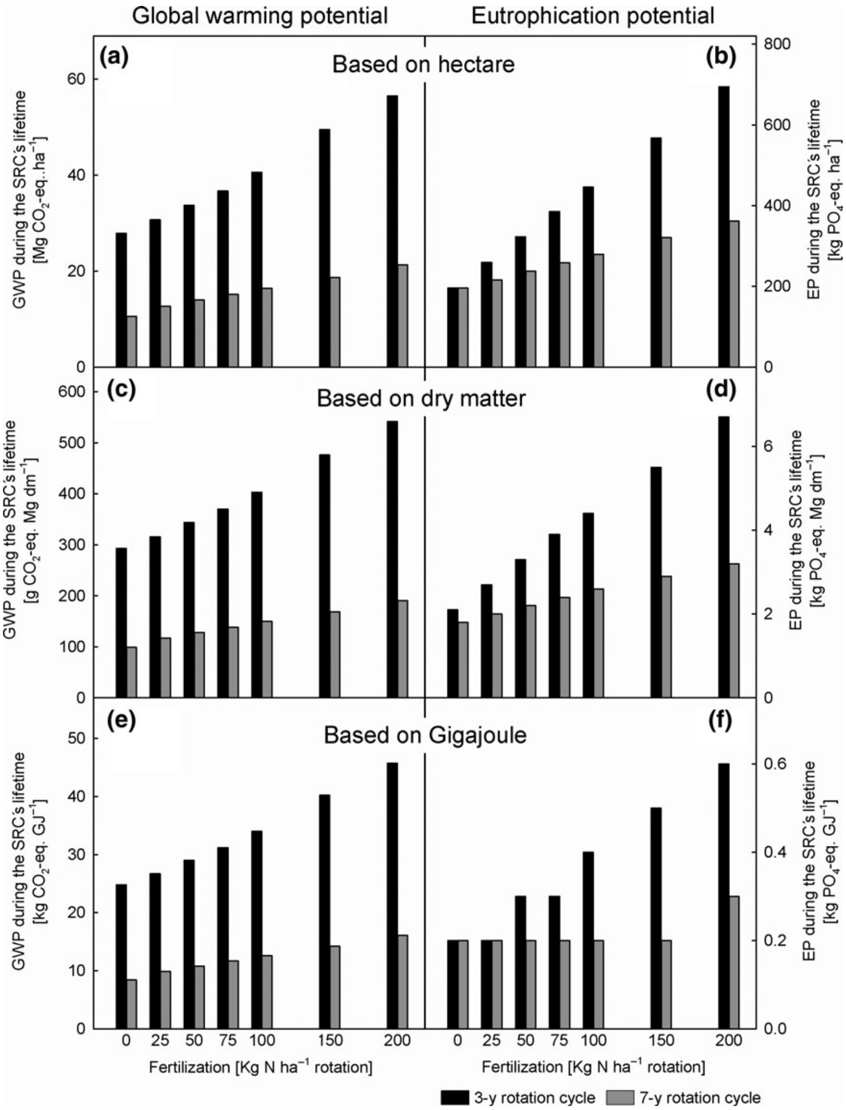

Fig. 5 *Global Warming Potential* and *Eutrophication Potential* for the production of poplar wood chips from SRC in 21 years, shown for all 14 production chains in different functional units. An overview of the 14 analyzed production chains can be found in Table 1.

and highlighted the CO_2 fluxes within *Field-GHG* for the most favorable production chain no. 8 (Fig. S1): Net ecosystem exchange was estimated to be −167.4 kg CO_2-eq. GJ^{-1}, which is derived from simulated ecosystem respiration of +399 kg CO_2-eq. GJ^{-1} and N_2O emissions of +8 kg CO_2-eq. GJ^{-1} (Fig. S1) on the one hand, and photosynthesis of −574 kg CO_2-eq. GJ^{-1} as well as CH_4 deposition of −0.4 kg CO_2-eq. GJ^{-1} on the other. Thus, in contrast to all other process steps, *Field-GHG* is acting as C sink (Fig. S1, Table 3). Table 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* ($P < 0.001$) (Table 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 CO_2-eq. GJ^{-1}, Table 3). Emissions in *Removal* contributed with 6–33% to the *GWP* (+4.0–5.6 kg CO_2-eq. GJ^{-1}, Table 3). It has to be noted that 87–95% of this C release occurred after the elimination of plant roots from the soil (Table S8).

Among the technological processes, *Transport* caused the highest impact (+2.2 kg CO_2-eq. GJ^{-1}, Table 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 CO_2-eq. per GJ and km. Finally, the contribution of *Fertilization* to the *GWP* was very variable and depended on the management practice (Table 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 and Maintenance, and Harvesting*) were of negligible magnitude (Table 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 (Table 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 yr^{-1}). All other process steps (*Establishment and Maintenance, Harvesting, Transport, and Storage)* were negligible (Table S5).

Carbon sources. The LCA showed that all process steps upstream 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

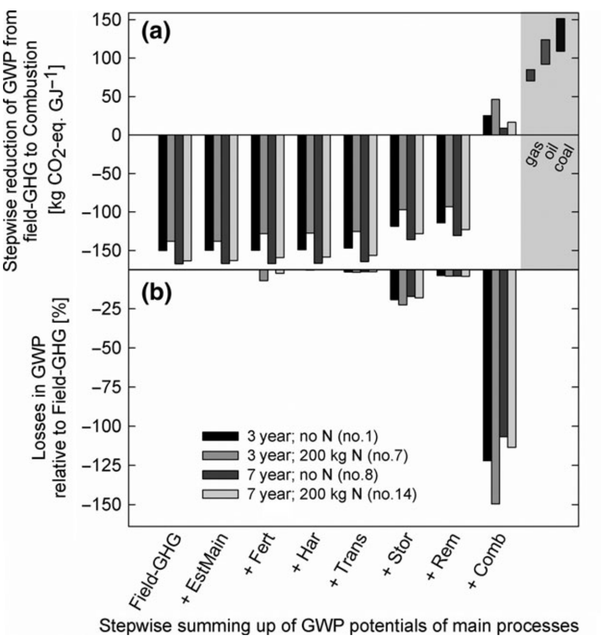

Fig. 6 Stepwise reduction of the beneficial *Global Warming Potential (GWP)* of the process biological production by other processes. (a) Summing up of the *GWP* starting with the process *Field-GHG.* On the right-hand side, the ranges of *GWP* from fossil sources (Cherubini *et al*., 2009; Ecoinvent, 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.

selected production chains (chain 1: 3 yr/0 kgN, chain 7: 3 yr/200 kgN, chain 8: 7 yr/0 kgN, and chain 14: 7 yr/200 kgN; 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. In 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 the 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_2O 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 first- to the second-rotation cycle might have originated either from an initial lower investment of the plants into roots and soil microorganisms, and faster resprouting from already established root systems, or from unknown factors depending on the site-specific conditions (Hofmann-Schielle *et al*., 1999; Verlinden *et al*., 2015). On the other hand, it is not fully clear whether 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 *et al.*, 2010), while specific hybrid poplars performed poorly after the fourth rotation on marginal soils in Belgium (Dillen *et al.*, 2013). However, the chosen time period of 21 years seems reasonable. The resprouting 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 *et al.*, 2013), and reports of long-term studies indicate that growth vigor can even increase after 15 years of repeated harvesting. However, poplar SRCs are more profitable when harvested several times without replanting and thus praxis oriented. Additionally, similar studies (e.g., Deckmyn *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* (*GWPs*) and *Eutrophication Potentials* (*EPs*) 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_4NO_3 ha^{-1} in 21 years. These values are considerably higher than the results of previous studies (Rödl, 2010; Bacenetti *et al.*, 2012; Fiala & Bacenetti, 2012; González-García *et al.*, 2012a,b; Gabrielle *et al.*, 2013; Miguel *et al.*, 2015). As noticed, studies simultaneously addressing technological, agronomic as well as environmental aspects of SRC production have not been performed so far. Also, some studies use literature data only (e.g., Rugani *et al.*, 2015). For example, González-García *et al.* (2012a) and Bacenetti *et al.* (2016) focused only on technological processes when analyzing environmental impacts of woody biofuel production 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), and 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 process step *Combustion*. The latter was not considered by González-García *et al.* (2012a). 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 the field measurement and modeling data (e.g., Díaz-Pines *et al.*, 2016). The study by Murphy *et al.* (2014) evaluated the environmental impacts associated with cultivation, fertilization (max. 800 kg 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 regrowth 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 (R. Grote & K. Block, unpublished data). Coppicing poplars in longer periods are 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) due to lower fuel consumption in field and transport operations (Tables S2 and S3) and due to a reduced requirement for N input. From our results, we recommend to establish hybrid poplar SRC with longer rotation cycles to minimize the environmental impacts and to maximize the 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 the 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 the labor input and costs by cultivating extensive SRC. The supply of fertilizer had a strong influence on environmental impacts. In particular, the *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 PO_4-eq. GJ^{-1} (chain 8: 7 yr/0 kgN & chain 7: 3 yr/200 kgN, 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, N_2O 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 years) and fertilization was omitted (chain 8: 7 yr/0 kgN). 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. As 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* from the LCA, 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 the 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 CO_2-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, Hansen *et al.*, 2013). The impacts of the most frequently used fossil energy on *GWP* (Fig. 6a right bars) vary between 70–85 kg CO_2-eq. GJ^{-1}_{heat} (natural gas), 90–120 kg CO_2-eq. GJ^{-1}_{heat} (oil), and 110–150 kg CO_2-eq. GJ^{-1}_{heat} (coal) (Cherubini *et al.*, 2009; Ecoinvent, 2010). Generation of heat from the most favorable production chain 8 (7y/0kgN) (*GWP* of 8.4 kg CO_2-eq. GJ^{-1}_{heat}) substituting the same amount produced by fossil oil (*GWP* of 90–120 kg CO_2-eq.GJ^{-1}_{heat}, 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, for example, 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_{dm} 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 in soil organic C stocks.

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Supporting Information

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

Figure S1. Main biological components of the Global Warming Potential of the process step *Field-GHG* for production chain no. 8 [in kg CO_2-eq. GJ^{-1}].
Table S2. Emissions occurring within the process step *Field-GHG* [in Mg CO_2-eq. ha^{-1}].
Table S3. Machinery inputs of agricultural and operating machines [in kg ha^{-1}].
Table S4. Machinery inputs of harvesting and transport operations.
Table 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 PO_4-eq. GJ^{-1}].
Table S6. Produced amount of energy [in Gigajoule per hectare].
Table S7. Stem diameter at ground level, for all 14 production chains [in cm].
Table S8. Carbon release occurring in the process step *Removal*, shown for all 14 production chains [in kg CO_2-eq. GJ^{-1}].
Figure S9. Dimensional growth of poplar SRC at Sigmaringen, Germany.
Figure 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}].
Figure S11. SRC planting machine owned by Probstdorfer Saatzucht GmbH (Vienna, Austria), used for planting poplar SRC in Sigmaringen, Germany.
Figure S12. Case New Holland forage harvester FR 9060 (Heilbronn, Germany).
Figure S13. Ratios between *aboveground biomass* (*AGB*) and *Global Warming Potential* (*GWP*), for all 14 production chains [in Mg_{dm} per t CO_2-eq.].
Figure S14. Comparison between measured and simulated mean N_2O emissions at the experimental site (Sigmaringen, Germany).