Relevance of environmental impact categories for perennial biomass production

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Abstract
The decarbonization of the economy will require large quantities of biomass for energy and biomaterials. This biomass should be produced in sufficient quantities and in a sustainable way. Perennial crops in particular are often cited in this context as having low environmental impacts. One example of such crops is miscanthus, a tall perennial rhizomatous C4 grass with high yield potential. There are many studies which have assessed the global warming potential (GWP) of miscanthus cultivation. This is an important impact category which can be used to quantify the environmental benefit of perennial crops. However, the GWP only describes one impact of many. Therefore, the hypothesis of this study was that a holistic assessment also needs to include other impact categories. A life cycle assessment (LCA) with a normalization step was conducted for perennial crops to identify relevant impact categories. This assessed the environmental impact of both miscanthus and willow cultivation and the subsequent combustion for heat production in eighteen categories using a system expansion approach. This approach enables the inclusion of fossil reference system hot spots and thus the evaluation of the net benefits and impacts of perennial crops. The normalized results clearly show the benefits of the substitution of fossil fuels by miscanthus or willow biomass in several impact categories (e.g. for miscanthus: climate change −303.47 kg CO₂ eq./MWhth; terrestrial acidification: −0.22 kg SO₂ eq./MWhth). Negative impacts however occur, for example, in the impact categories marine ecotoxicity and human toxicity (e.g. for miscanthus: +1.20 kg 1.4-DB eq./MWhth, and +68.00 kg 1.4-DB eq./MWhth, respectively). The results of this study clearly demonstrate the necessity of including more impact categories than the GWP in order to be able to assess the net benefits and impacts of the cultivation and utilization of perennial plants holistically.

Keywords: combustion, environmental performance, global warming potential, life cycle assessment, miscanthus, normalization, perennial crop, willow

Introduction
In 2009, the European Commission set mandatory targets for the production and promotion of energy from renewable resources. The EU renewable energy directive stipulates that, by the year 2020, 20% of total EU energy consumption should come from renewable sources and at least 10% of petrol and diesel consumption for transport should be supplied through biofuels (European Commission, 2009). The European Commission expects the use of renewable energy to increase considerably over the next decades and its proportion of gross final energy consumption to reach values of up to 55% by the year 2050. In the energy roadmap 2050, the European Commission also emphasizes the need for large quantities of biomass for heat, electricity and transport to achieve the goal of the decarbonization of the economy (European Commission, 2011). There is a wide range of biomass resources available, which can be potentially exploited for bioenergy production. Of these, dedicated energy crops such as miscanthus have emerged as a promising future feedstock for biomass-based energy production. For this reason, miscanthus was chosen as the main representative perennial crop for this study. In addition to miscanthus, willow short rotation coppice was included in this study to examine whether there are any differences between woody perennials and perennial grasses.

Miscanthus is a tall perennial rhizomatous C4 grass, which can yield up to 25 Mg ha⁻¹ yr⁻¹ (dry matter) in Central Europe after a two-year establishment period and can be harvested annually over a twenty-year cultivation period (Lewandowski et al., 2000; Christian et al., 2008; Felten et al., 2013; Iqbal et al., 2015). It is a low-input crop with a high nitrogen, land-use and energy efficiency (Lewandowski & Schmidt, 2006) and has the potential to remove CO₂ from the atmosphere through
carbon sequestration (Clifton-Brown et al., 2007). In an editorial regarding the environmental benefits of miscanthus, Voigt (2015) recommends Miscanthus x giganteus ‘as the energy crop of choice’. In the context of sustainability requirements, it is important to assess the performance of each crop in economic, social and ecological terms. This study focuses on evaluating the ecological performance of the utilization of perennial energy crops. One option available for such an evaluation is life cycle assessment (LCA). Life cycle assessment is a method which is standardized by two ISO norms – 14040 and 14044 (ISO, 2006a, b). In the last ten years, several papers have been published which use LCA to assess the potential environmental impacts and benefits of miscanthus. The impact categories examined in these are presented in Table 1.

As shown in Table 1, most of the studies carried out to evaluate the environmental performance of miscanthus focus on one impact category – the global warming potential (GWP). In the EU, political support for bioenergy aims at reducing greenhouse gas (GHG) emissions from fossil fuels. Therefore, any LCA study on bioenergy includes an assessment of the GWP.

Agriculture contributes significantly to GWP. The agricultural sector is responsible for about 10–12% of total anthropogenic emissions of greenhouse gases globally (Smith et al., 2007). However, agriculture also has an influence on other impact categories, such as eutrophication potential (EP) and acidification potential (AP) (EEA, 2005; Rice & Herman, 2012). In the European Union, the agricultural sector is responsible for 93.3% of ammonia emissions (Eurostat, 2015), which are a main driver of AP. In addition, the use of mineral and organic fertilizers on agricultural land leads to a gross nitrogen surplus of 51 kg nitrogen ha⁻¹ yr⁻¹ and a gross phosphorus surplus of 2 kg P ha⁻¹ yr⁻¹ (Eurostat, 2012, 2013). These nutrients can enter groundwater, for example, through nitrate leaching and lead to marine eutrophication. High concentrations of nutrients in water can pose health risks for humans (Di & Cameron, 2002). Nitrate leaching is only one example of the manifold emissions released by the entire agricultural value chain and the subsequent biomass utilization. From this, it can be concluded that, when trying to assess the environmental performance of perennial crops, the estimation of GWP alone is too simplistic. An analysis of the studies on the environmental performance of perennial crops listed in Table 1 confirms this conclusion. Jeswani et al. (2015) found that, when considering the GWP of second-generation biofuels, the production of the feedstock for the ethanol plant – the cultivation of the biomass – is the most important hot spot. However, the influence of the feedstock on other impact categories is relatively small. For the impact categories abiotic resource depletion (ADP, elements), AP, EP and freshwater aquatic ecotoxicity potential (FAETP), the main driver is the subsequent conversion of the biomass. Considering GWP alone grossly underestimates the

| Authors          | Method                  | GWP | EP | AP | ADP | POCP | ODP | TET | FET | MET | HT |
|------------------|-------------------------|-----|----|----|-----|------|-----|-----|-----|-----|----|
| Jeswani et al. (2015) | CML                     | x   | x  | x  | x   | x    | x   | x   | x   | x   | x  |
| Monti et al. (2009)   | CML                     | x   | x  | x  | x   | x    | x   | x   | x   | x   | x  |
| Godard et al. (2013)  | CML; USES-LCA 2.0; CED  | x   | x  | x  | x   | x    | x   | x   | x   |    |    |
| Styles et al. (2015)  | CML                     | x   | x  | x  | x   |      |     |     |     |     |    |
| Nguyen & Hermansen (2015) | EDIP 97; IPCC; Impact 2002+ | x   | x  | x  | x   |     | x   | x   | x   | x   | x  |
| Murphy et al. (2013)  | CML                     | x   | x  | x  |     |     |     |     |     |     |    |
| Brandão et al. (2011) | CML                     | x   | x  | x  |     |     |     |     |     |     |    |
| Tonini et al. (2012)  | EDIP 2003               | x   | x  |     |     |     |     |     |     |     |    |
| Sanscartier et al. (2014) | IPCC                   |     | x  |     |     |     |     |     |     |     |    |
| Styles & Jones (2008) | IPCC                   | x   |     |     |     |     |     |     |     |     |    |
| Felten et al. (2013)  | IPCC                   | x   |     |     |     |     |     |     |     |     |    |
| Dwivedi et al. (2015) | n.a.                   | x   |     |     |     |     |     |     |     |     |    |
| Brandão et al. (2010) | IPCC                   | x   |     |     |     |     |     |     |     |     |    |
| Scown et al. (2012)   | n.a.                   | x   |     |     |     |     |     |     |     |     |    |
| Roy et al. (2015)     | n.a.                   | x   |     |     |     |     |     |     |     |     |    |
| Wang et al. (2012)    | n.a.                   | x   |     |     |     |     |     |     |     |     |    |
| Iqbal et al. (2015)   | IPCC                   | x   |     |     |     |     |     |     |     |     |    |
| Parajuli et al. (2015) | Stepwise 2006         | x   |     |     |     |     |     |     |     |     |    |
| Smeets et al. (2009)  | IPCC                   | x   |     |     |     |     |     |     |     |     |    |

GWP, global warming potential; EP, eutrophication potential; AP, acidification potential; ADP, abiotic depletion potential; POCP, photochemical ozone creation potential; ODP, ozone depletion potential; TET, terrestrial ecotoxicity; FET, freshwater ecotoxicity; MET, marine water ecotoxicity; HT, human toxicity.
influence of the conversion stage on the environmental performance of the second-generation biofuels. Godard et al. analysed the environmental performance of heat produced from different feedstocks (flax shives, miscanthus, cereal straw, linseed straw and triticale as whole plant). Using economic allocation, heat produced from miscanthus has the lowest GWP, but scores worse in all the other impact categories in comparison with flax shives as feedstock. If an allocation based on mass is used, heat produced from miscanthus has the best environmental performance in all selected impact categories (Godard et al., 2013). If GWP alone is analysed, it is not only impossible with economic allocation to select the feedstock with the best environmental performance, but it is also impossible to thoroughly analyse the impact of different allocation procedures. The comparison of different perennial crops revealed that marine water eutrophication is the most affected impact category after normalization. It is 20–30 times higher than the other categories. Switchgrass, for example, achieved very low values in this important impact category. For this reason, it is a very suitable crop for sites near rivers or coastlines (Monti et al., 2009). In order to select the biomass crop best adapted to specific conditions, it is essential to have a complete picture of the environmental performance of each crop. Various studies on short rotation coppice (poplar and willow), which analysed the environmental performance of the cultivation and utilization in several impact categories, confirm the hypothesis that a number of categories need to be assessed. González-García et al. (2012a) showed that, for poplar plantations, in addition to GWP, the impact categories ADP, AP, EP, FE and ME were the most significant after a normalization step. Further results showed that the selection of the most environmentally friendly energy conversion pathway for willow chips largely depends on which impact categories analysed (González-García et al., 2012b). The same applies to the management practice of willow plantations (González-García et al., 2012c).

In this study, an LCA was conducted according to the ISO standards 14040 and 14044 to analyse the environmental performance of miscanthus cultivation and utilization in eighteen different impact categories in comparison with a fossil reference (ISO, 2006a,b). This was done employing the widely used ecoinvent database (version 3.1) and openLCA, an open source LCA software. One objective was to identify those impact categories that need to be included in a holistic assessment of environmental impacts and benefits of the production and utilization of perennial crops, such as miscanthus. To compare the importance of the different impact categories analysed, a normalization step was carried out. According to ISO, normalization is defined as ‘calculation of the magnitude of category indicator results relative to reference information’ (ISO, 2006a). Normalization factors were taken from the ReCiPe methodology. The result for each impact category is divided by the respective emissions caused by an average European citizen in the year 2000. This results in values without units, which show the calculated emissions as a proportion of the emissions of an average European citizen. Through this additional calculation, it is possible to compare the importance of different impact categories (Goedkoop et al., 2008). A hot spot analysis was also conducted. It reveals which processes are responsible for the largest share of emissions in each impact category.

Through the normalization and the hot spot analysis, it is possible to determine not only the relevant impact categories in the cultivation and utilization of perennial crops, but also which processes or emission sources are most important for each category.

This study aimed to provide guidelines for future research on the environmental performance of perennial crops, with regard to both the choice of relevant impact categories and the focus on data for the most important processes and emission sources.

Material and methods

Scope and boundaries

The scope of this study is a cradle-to-grave analysis of the environmental performance of the cultivation of miscanthus (Miscanthus x giganteus) and willow (Salix viminalis) short rotation coppice (variety ‘Tora’) and subsequent combustion in a biomass-fuelled boiler. In order to compare this performance with a fossil reference (heat produced through combustion of light fuel oil), a system expansion approach was applied. This approach enables the inclusion of fossil reference system hot spots. The outcome of this analysis shows the net benefits and impacts through the substitution of fossil fuel by the energetic utilization of miscanthus and willow chips. One megawatt hour of heat (MWhth) was chosen as the functional unit. These systems are described in Fig. 1. The system boundaries include the production of the mineral fertilizers and the pesticides used, the production of the propagation material (miscanthus rhizomes and willow cuttings) and the land management (soil preparation, planting, mulching, fertilizing, spraying of pesticides, harvesting, recultivation) over a twenty-year cultivation period. The miscanthus was mulched in the first year and harvested from the second year onwards; the willow plantation was harvested from the fourth year on and then in three-year cycles. Both crops were harvested with a self-propelled forage harvester. The biomass is then transported to a biomass heater where it is combusted to produce heat. The coarse ash is rich in potassium and phosphorus and is used as fertilizer. The fly ash is disposed of in landfill.
Life cycle inventory

The data for the cultivation process used in this LCA study was obtained from a multiannual field trial at Ihinger Hof, a research station of the University of Hohenheim. The Ihinger Hof is located in southwest Germany (48.75°N and 8.92°E). The soil belongs to the soil class Haplic Luvisol. The mean annual temperature for the measurement period was 9.2 °C, and the average annual rainfall was 707.5 mm. The experimental design of the trial is described in Iqbal et al. (2015). Data on cultivation practices, fertilizer and pesticide inputs as well as the yields was available for a 10-year period from 2002 to 2012. For both perennial crops, three different fertilizer regimes were applied: N1 with 0 kg of nitrogen, N2 with 40 kg nitrogen and N3 with 80 kg nitrogen per year and hectare in the form of calcium ammonium nitrate. Potassium and phosphate fertilizer levels were the same in all three application regimes. For miscanthus, herbicides only were applied (described in Iqbal et al., 2015). For willow, one insecticide (Karate Zeon, Syngenta, active ingredient 100 g l⁻¹ lambda-cyhalothrin) was applied in 2004 at a rate of 0.075 l ha⁻¹. Three herbicides (3 l ha⁻¹ Durano, Monsanto, active ingredient 360 g l⁻¹ glyphosate; 5 l ha⁻¹ U-46 M-Fluid, Nufarm, active ingredient 500 g l⁻¹ MCPA; and 2 l ha⁻¹ Starane 180, Syngenta, active ingredient 180 g l⁻¹ fluroxypyr) were applied in 2006. In the following years, no pesticides were applied. The principle data for the cultivation of miscanthus and willow used in this analysis is summarized in Table 2. As yield data was only available for the first ten years, it was predicted for the rest of the 20-year cultivation period. For willow, the average of the three measured harvests (years 4, 7 and 10) was taken to estimate the yield for years 11 to 20. For miscanthus, the average of year four to ten was taken for this prediction. The yields of the first three years were excluded in the estimation because the crop was still in its establishment period and has lower yield than after full establishment. However, the yield data inputted into the LCA is the average yield over the whole cultivation period including the establishment phase. Background data for the environmental impacts associated with the production of the input substrates and the cultivation processes (soil preparation, harvesting) was taken from the ecoinvent database version 3.1 (Weidema et al., 2013).

Direct N₂O and NO emissions from mineral fertilizers were estimated according to Bouwman et al. (2002). Indirect N₂O emissions from mineral fertilizers and N₂O emissions from harvest residues were calculated according to IPCC (2006). Ammonia emissions were estimated using emission factors from the Joint EMEP/CORINAIR Atmospheric Emission Inventory Guidebook (EMEP/CORINAIR, 2001). Nitrate leaching to groundwater was calculated according to the SOCB – NO₃ model described in Faist Emmenegger et al. (2009). Phosphate and phosphorus emissions to surface water

![System description and boundaries for miscanthus and willow biomass production and subsequent utilization in a biomass heater.](image-url)
and groundwater as well as heavy metal emissions to agricultural soils were calculated according to Nemecek & Kägi (2007). The nitrogen, phosphorus and heavy metal emissions are summarized for the respective crops and fertilizer levels in Table S1.

As no data for the transport of the input substrates (fertilizer, pesticides and propagation material) to the farmer and the biomass to the biomass heater were available, a transport distance of 150 km for the input material and 50 km for the biomass, both by truck, was assumed. The average field-to-farm distance was assumed to be 2 km. The emission stage for the truck used was EUR5. The process data for the transportation of the input material and the biomass was taken from the ecoinvent database (Weidema et al., 2013).

The biomass heater used in this LCA study is a furnace of 300-kW capacity for heat production. The background data for the emissions associated with the combustion of the different biomasses is taken from the ecoinvent database. The data set is based on a Froling Turbomat 320-kW woodchip boiler. The thermal efficiency is assumed to be 75%. As stipulated in the process description of the ecoinvent database, this thermal efficiency is lower than in the technical specification, because it represents the average annual operation, including start and stop phases (Weidema et al., 2013). As there is not enough specific information available regarding the emissions from the combustion of miscanthus, a straw combustion process was used as a worst-case assumption. Where miscanthus-specific emissions factors were available, the straw combustion process was adapted accordingly. This was the case for carbon monoxide, sulphur dioxide, hydrogen chloride, nitrogen oxides and particulates. The emission factors are based on Dahl & Obernberger (2004). A scenario analysis with an improved emission setting was performed to analyse the impact of this assumption.

Miscanthus has a water content of around 15% at the time of harvest, so a further drying process was not necessary. This corresponds to a calorific value of 4.3 kWh kg\(^{-1}\) fresh biomass. The wood chips have a water content of 50% at the time of harvest. The chips are then stored on the farm where natural drying is employed. This process results in a water content of around 20%, which corresponds to a calorific value of 3.86 kWh kg\(^{-1}\) fresh biomass.

For all willow fertilization levels and the N2 and N3 miscanthus variants, the use of the coarse ash as fertilizer allows the crops to be cultivated without additional input of mineral phosphate or potassium fertilizers. Therefore, the boundaries applied in this study only include nitrogen fertilizer. For the N1 miscanthus variant, an additional input of 4 kg P\(_2\)O\(_5\) and 14 kg K\(_2\)O was necessary. Information on ash content, amount of fly and coarse ash and the nutrient as well as the heavy metal content of the coarse ash can be found in Table S2. The fly ash is disposed to landfill.

### Choice of impact categories

This LCA study used the life cycle impact assessment method ReCiPe, which consists of eighteen different impact categories (Goedkoop et al., 2008). All mid-point indicators described in the ReCiPe methodology were included. The following impact categories were considered: climate change (CC), which corresponds to global warming potential (GWP); ozone depletion (OD); terrestrial acidification (TA); freshwater eutrophication (FE); marine eutrophication (ME); human toxicity (HT); photochemical oxidant formation (POF); particulate matter formation (PMF); terrestrial ecotoxicity (TET); freshwater ecotoxicity (FET); marine ecotoxicity (MET); ionizing radiation (IR); agricultural land occupation (ALO); urban land occupation (ULO); natural land transformation (NLT); mineral resource depletion (MRD); fossil fuel depletion (FD); and water depletion (WD). Characterization and normalization factors were taken from Goedkoop et al. (2008). A normalization factor for the impact category water depletion is not available in the ReCiPe methodology. For this reason, only absolute values are given for this impact category.

### Results

#### Life cycle impact assessment (LCIA)

Table 3 presents the environmental impact in the different impact categories per MWh\(_{th}\) of the miscanthus and willow cultivation and subsequent combustion of the biomass. The results are shown for the N2 fertilization level. With these data, it is possible to compare the environmental performance of cultivation and combustion for the two perennial crops in different impact categories. However, due to the different reference units, it is not possible to compare the significance of the different impact categories themselves. For that, a normalization step is necessary.
Comparison of the environmental performance of the cultivation and combustion of miscanthus and willow

Figure 2 presents a comparison between the environmental performance of the cultivation and utilization of miscanthus and willow. For each crop, the LCIA results of the fertilizer level N2 (40 kg nitrogen) are shown. In fifteen of the eighteen impact categories analysed, there are no differences in the rankings of the impact categories between the two perennial crops. The exceptions are human toxicity, terrestrial ecotoxicity and particulate matter formation. In the case of human toxicity potential, the values for willow are significantly lower than for miscanthus. This is in part due to the higher uptake of heavy metals by willow than by miscanthus. These are partially removed from the system through the disposal of the fly ash (which is rich in heavy metals) to landfill. Another reason is the fact that the combustion process of miscanthus produces higher emissions. These are also the main cause of the significantly higher terrestrial ecotoxicity. Differences in the emissions from the combustion of the biomasses are also responsible for the lower particulate matter formation with miscanthus than with willow. Heat produced

Table 3  LCIA of the combustion of miscanthus and willow (fertilization level N2) per MWhth.

| Impact category                  | Miscanthus | Willow | Reference unit   |
|---------------------------------|------------|--------|-----------------|
| Fossil fuel depletion           | 7.3780     | 7.2425 | kg oil eq.      |
| Agricultural land occupation    | 135.7814   | 168.6545 | m^2a           |
| Photochemical oxidant formation | 0.5002     | 0.7597 | kg NMVOC       |
| Particulate matter formation    | 0.2008     | 0.6375 | kg PM_{10} eq. |
| Marine ecotoxicity              | 1.7175     | 1.4394 | kg 1,4-DB eq.  |
| Natural land transformation     | 0.0072     | 0.0074 | m^2             |
| Ozone depletion                 | 2.91E-06   | 0.0829 | kg CFC-11 eq.  |
| Terrestrial ecotoxicity         | 0.1781     | 0.0030 | kg 1,4-DB eq.  |
| Freshwater eutrophication       | 0.0220     | 0.0258 | kg P eq.        |
| Freshwater ecotoxicity          | 0.7532     | 1.5774 | kg 1,4-DB eq.  |
| Marine resource depletion       | 2.2788     | 2.8192 | kg Fe eq.       |
| Urban land occupation           | 0.5211     | 0.5168 | m^2a            |
| Human toxicity                  | 84.3484    | 6.8041 | kg 1,4-DB eq.  |
| Water depletion                 | 97.6863    | 103.8735 | m^3          |
| Marine eutrophication           | 0.1626     | 0.2581 | kg N eq.        |
| Ionising radiation              | 4.3592     | 4.5147 | kg U235 eq.     |
| Climate Change                  | 37.4125    | 40.1806 | kg CO_{2} eq. |
| Terrestrial acidification       | 0.5058     | 0.5015 | kg SO_{2} eq.  |

Fig. 2  Assessment of the environmental performance of the cultivation and utilization of miscanthus and willow.

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by the combustion of willow chips also has a higher marine eutrophication caused by slightly higher nitrate leaching rates during cultivation. Nitrate is a main source of the marine eutrophication potential. A further difference in the environmental performance of the utilization of the two crops is the freshwater ecotoxicity. Here, the differences in emissions from the combustion process are the main driver.

Life cycle emissions of miscanthus cultivation and combustion using a different combustion scenario

The LCIA results reveal that most of the main differences seen in the comparison of the cultivation and utilization of the two biomasses stem from the combustion process rather than the cultivation phase. The results for the comparison between miscanthus and willow cultivation and combustion using a second combustion scenario for the miscanthus biomass are presented in Fig. 3. A scenario analysis was performed with a boiler with emission characteristics comparable to wood combustion. Under this setting, the differences between willow and miscanthus are much less pronounced.

Life cycle emissions of miscanthus cultivation and combustion using a system expansion approach

In Fig. 4, the results of the LCIA of the miscanthus cultivation and utilization are shown for the three different fertilization regimes using a system expansion approach. The values include the emissions avoided through the substitution of heat produced from a conventional furnace using light fuel oil by heat produced from a biomass heater. In this approach, negative values represent burdens avoided by the substitution of fossil by renewable fuels, while positive values represent an additional impact due to the use of the biomass heater. The substitution of fossil fuels by miscanthus biomass leads to burdens avoided especially in the impact categories fossil fuel depletion, climate change and terrestrial acidification. However, it causes additional impacts in the categories marine ecotoxicity, human toxicity, agricultural land occupation, freshwater eutrophication and terrestrial ecotoxicity. It should be noted that these results are strongly depending on the fossil reference used. In the case of the substitution of heat produced from hard coal instead of light fuel oil, the use of miscanthus biomass would lead to an avoided burden in the impact category human toxicity instead of an additional impact (data not shown).

In most impact categories analysed, there are only small differences between the three fertilization levels. These are mainly caused by differences in yield and the amount of fertilizer used. Marine eutrophication, for which nitrate leaching is an important driver, increases significantly from N1 to N3 due to the higher nitrate leaching through the additional input of nitrogen fertilizer.

Life cycle emissions of willow cultivation and combustion using a system expansion approach

The substitution of heat produced from the combustion of light heating fuel by heat produced from willow chips leads to burdens avoided especially in the impact categories fossil fuel depletion, climate change and
human toxicity (see Fig. 5). However, it also causes additional impacts in the categories marine ecotoxicity, freshwater ecotoxicity, agricultural land occupation, freshwater eutrophication and particulate matter formation.

The differences between the results of the three fertilization levels (e.g. in marine eutrophication) can be explained in the same way as for miscanthus. The results for the impact category urban land occupation are mapped in Fig. 5; however, the normalized values are too small to be visible (−9.6 E-05).

**Comparison of the environmental performance of the cultivation and combustion of miscanthus and willow using a system expansion approach**

Figure 6 shows a comparison of heat produced from miscanthus and willow biomass at fertilization level N2 using a system expansion approach. Because the fossil reference is identical for both crops, the reasons for the differences in environmental performance between heat produced from miscanthus and willow are the same as for the normalized values without system expansion.
While the results for both crops are very similar in impact categories such as climate change, fossil fuel depletion and ionizing radiation, there are substantial differences in other impact categories, especially freshwater ecotoxicity and human toxicity.

Results for natural land transformation (data not shown) using a system expansion approach are lower than \( C_0 \) (in normalized values) and are therefore much lower than the results of all other impact categories.

Hot spot analysis

The hot spot analysis reveals which processes are responsible for the largest share of emissions in each impact category. The grouping ‘cultivation’ summarizes all cultivation steps up to and including harvest, the production and transport of input substrates (e.g. mineral fertilizers), and the transport of the coarse ash from the biomass heater back to the field. The transport of the input substrates and ash each accounts for <1% of the total emission of the respective impact category. For this reason, they are not represented individually in the hot spot analysis (Figs 7–9). The grouping ‘biomass transport’ represents the environmental impacts of the transport of the biomass from the field to the biomass heater. The grouping ‘combustion’ indicates the proportion of total emissions associated with the combustion process. Overall, the results of the hot spot analysis show no large differences between the utilization of miscanthus and willow for most of the impact categories.

In each of the impact categories shown in Fig. 7, the combustion of the biomass has a share of over 90% of total emissions. The negative values seen for the cultivation of willow can be explained by the higher uptake of heavy metals. The emissions associated with biomass transport have a substantial impact especially on the impact categories natural land transformation, urban land occupation, fossil fuel depletion and mineral resource depletion (see Fig. 8). The combustion process has an impact of over 50% on almost all impact categories shown in Fig. 8, in particular terrestrial acidification and photochemical oxidant formation. The differences in impact of the cultivation stage of miscanthus and willow on the photochemical oxidant formation are much smaller in absolute than in percentage terms.

The cultivation stage has a substantial impact on the categories shown in Fig. 9. In the case marine eutrophication, nitrate leaching is the main cause. Nitrous oxide emissions from the use of mineral nitrogen fertilizer are also an important driver of climate change. The impact of cultivation on freshwater eutrophication is mainly due to phosphor emissions to ground water and surface water. Its impact on ozone depletion stems from mineral fertilizer production and agricultural management. The cultivation stage is also responsible for over 99% of agricultural land occupation.

Discussion

Normalization and system expansion

The normalization of the results is a useful way of assessing the importance of different impact categories. It shows the impact of perennial crop production and utilization in each category and thus helps in the selection of the relevant ones for an assessment of their
environmental performance. However, a system expansion approach is necessary to reveal the net benefits and impacts of biomass utilization. Impact categories with a low ranking before a system expansion approach was applied, for example climate change and terrestrial acidification, show substantial benefits in avoided burdens after system expansion. In impact categories such as marine ecotoxicity and freshwater ecotoxicity, which have relatively high normalized values, the substitution of fossil fuels leads to additional impacts on the environment. If the normalized values alone are analysed, without a comparison to a fossil reference, the benefits of the utilization of perennial crops are substantially undervalued.

Choice of relevant impact categories

The hypothesis of this study was that a holistic assessment of the environmental performance needs to include other impact categories than just global warming potential (climate change). As presented in Fig. 6, the cultivation and utilization of the two analysed crops show no significant differences in the impact category climate change. In order to choose a biomass or utilization pathway on the basis of its environmental performance, it is also necessary to compare other impact categories. As shown in this study, the substitution of fossil fuel by miscanthus or willow chips leads to net...
benefits in the impact category climate change. However, this substitution also leads to additional impacts on the environment in other categories. If climate change alone is assessed, other substantial environmental burdens are ignored. This again emphasizes the need to include more impact categories.

In order to assess the environmental performance of the cultivation and utilization holistically, the impact categories that show substantial benefits and those that show strong negative impacts on the environment need to be included. While there are only small differences between the two crops in the impact categories with net benefits (fossil fuel depletion, climate change, terrestrial acidification), there are substantial differences in the categories with the strongest impact (e.g. human toxicity, freshwater ecotoxicity). This is mainly due to differences in the heavy metal uptake (both in the amount and in the kind of heavy metal) of the crops and differences in emissions associated with the combustion process. This emphasizes the difficulties in preselecting impact categories and the need to analyse several impact categories when assessing the environmental performance of perennial crop-based value chains.

The assessment of the environmental impact of the cultivation and utilization of perennial crops carries a risk of double-counting emissions. For example, particulate matter formation has a strong impact on human toxicity and there is an overlap between mineral resource depletion and fossil fuel depletion. Nevertheless, as shown in Fig. 6, the normalized results for human toxicity and particulate formation can differ substantially. For this reason, both impact categories should be included, despite the double counting. However, the correlation between them should be clearly stated and integrated in the evaluation of their respective relevance.

The normalized results, however, are not necessarily the sole indicator in the assessment of impact categories’ relevance. The normalization does not, for example, include social preferences or specific perspectives of the company commissioning the study. Another important point not included in the normalization is the pre-load of the specific environment. For example, at a site where the initial acidification is low and the buffer capacity of the soils is high, terrestrial acidification might not be the most urgent issue. The selection of impact categories is thus always dependent on the specific conditions and the questions to be answered by the study. Nevertheless, normalization of the life cycle impact assessment results is a crucial step in the assessment and comparison of the magnitude of different impact categories for biomass production and utilization.

Uncertainties in assessing the environmental performance of the cultivation and utilization perennial crops

1. Yield. One important influence on the environmental performance of perennial crops is the yield. With increasing yields, the environmental impact per tonne biomass is decreasing if the input of fertilizers and pesticides remains the same. There are only few field data for miscanthus yield performance over a ten-year or longer period. Those reports on long-term yields which are available indicate an entire range of developments: from stable yields over long periods;
through year-to-year variations; to yield decreases after an early peak (Gauder et al., 2012; Iqbal et al., 2015). More long-term field trials at different locations are necessary to get a reliable data basis. In the present study, the uncertainty caused by the yield was reduced through the availability of yield data for both crops under very similar conditions from field trials over a 10-year period.

An important aspect in environmental impact assessment of perennial energy crops is the accounting for yield variations over plantation time and the length of the productive period. Low yields in the first years and the fact that woody perennials only are harvested every third year are also an important reason why the whole cultivation period of perennial crops should be considered instead of only one year. The first harvest of miscanthus is in the second year and for willow only feasible from the fourth year onwards. Therefore, the environmental impact of the establishment period is broken down on the subsequent years. If the cultivation period is shorter, the total impact of the establishment on the environmental performance of the harvested biomass is increasing.

Besides that, there are uncertainties regarding the influence of nitrogen fertilizer in the yield development of miscanthus. In the field trial, which provided the underlying data for this study, there were significant differences in the yield of miscanthus between the three nitrogen fertilizer levels (Iqbal et al., 2015). Similar results were found in field trials with miscanthus in the US Midwest, where the yield increased significantly with nitrogen fertilization (Arundale et al., 2014). In contrast, multiannual trials in England showed no significant yield differences under different nitrogen fertilization levels (Christian et al., 2008). If it would be possible to maintain high yields while decreasing the inputs of mineral fertilizers, it would improve the environmental performance significantly. On a location with good soils with a high nitrogen content and a high nitrogen deposition rate, it is reasonable to assume that no nitrogen fertilizer is applied. On the other hand, on poor sites the nitrogen fertilizer use should be included. Therefore, a recommended approach for LCA in perennial energy crops is to calculate with fertilization levels that are equivalent to the withdrawal of nutrients by the biomass.

2. Emission factors and calculation models. The hot spot analysis in this study revealed that the emissions associated with the use of mineral fertilizer – especially nitrogen fertilizers – have a huge impact on the environmental performance of the cultivation stage. The nitrate emissions, for example, are a main driver for the marine eutrophication potential. However, recent studies show that the nitrate leaching under perennial plants is much lower than under annual crops (Lesur et al., 2014; Pugesgaard et al., 2015). These results suggest that the data for nitrate leaching used in this study – which were calculated with a common agricultural model for nitrate leaching – are probably higher than actually experienced in perennial energy crop production. This emphasizes the need for emission models, which are adapted to the distinctive features of perennial crops.

3. CO2 sequestration. In the last years, there were several papers published which highlighted the potential of miscanthus to sequester carbon in the soil (Kahle et al., 2001; Clifton-Brown et al., 2007; Brandão et al., 2011; Felten & Emmerling, 2012). However, there are still huge uncertainties regarding the amount of CO2 which will be sequestered, and the time frame of the sequestration (Harris et al., 2015). Due to these uncertainties, the sequestration of carbon in the soil through the cultivation of perennial plants was not included in this study. Other LCA studies, which included the sequestration, showed that the cultivation of miscanthus could, under certain conditions, act as a real carbon sink (Brandão et al., 2011; Godard et al., 2013). Even if the carbon is only sequestered for the cultivation process and released again after the recultivation of the site, there still is a positive environmental impact in perennial crop production, which should be accounted for through the GWP based on a 20-year horizon (20-year GWP).

4. Missing impact categories. Miscanthus cultivation has a positive impact on the biodiversity with more weed vegetation and open-ground bird species (Semere & Slater, 2007a) and on the abundance of invertebrate populations (Semere & Slater, 2007b). The prolonged fallow period of perennial crops improves the soil quality, and the soil cover over winter reduces the erosion. However, it is not possible yet to include these positive effects of perennial crops in a LCA study. Therefore, approaches should be further developed for including these equally important environmental impacts into a holistic impact assessment. There are already some approaches to include these impacts. Oberholzer et al. (2012), for example, developed a method to include the impact of agricultural practice on soil quality in LCA. However, to date, this has only occasionally been used in LCA studies due to its complexity and huge data requirements. There are also approaches to integrate biodiversity aspects in LCA. Finnan et al. (2012) included a biodiversity indicator for miscanthus in their assessment of the environmental impacts of bioenergy plans. However, there
are still several shortcomings in the biodiversity indicators presently available for LCA (Souza et al., 2015). Therefore, further research is necessary to allow a realistic assessment of the impact of agriculture or land use in general on biodiversity.

5. Indirect land-use change. While there are many positive effects of perennial biomass crops on the environment, the expansion of their cultivation area still bears a risk. If their cultivation is not restricted to marginal or unused land, an increase in their production area can lead to food production displacement. These food crops then need to be produced elsewhere. This indirect land-use change can lead to substantial negative impacts on the environment.

6. Utilization. As shown in the hot spot analysis, the emissions associated with the combustion process have a substantial impact on the different categories. While the data basis for the combustion of willow chips is adequate, there is insufficient information available on emissions from the combustion of miscanthus. In this study, a straw combustion process was taken as a worst-case assumption. In practice, the combustion of miscanthus would produce less emissions than shown here and have a lower impact on the environment. A reason for that is the higher chloride and sulphur content of straw in comparison with miscanthus biomass. These elements lead to harmful emissions in the combustion process (Splithoff & Hein, 1998; Iqbal & Lewandowski, 2014)

A holistic environmental impact assessment of perennial biomass crops requires additional impact categories other than climate change (GWP). The GWP is a basic impact category due to the importance of climate change and the fact that the reduction in GHG emissions is one of the positive environmental contributions of perennial crop production. Based on the results of this study, an assessment of the environmental performance of the cultivation and combustion of perennial crops should also include the impact categories fossil fuel depletion, terrestrial acidification, freshwater eutrophication and human toxicity. However, the results of the study also show that the relevance of impact categories can differ depending on the crop and the utilization pathway. In order to resolve this issue, the choice of the relevant impact categories should be an iterative process. The first step is to analyse the relevance of the different impacts categories for the respective study goals and boundaries using initial data, a normalization step and a system expansion approach. After the determination of the relevant impact categories, the quality of the data important for these categories can be improved and the goal and scope adapted if necessary.

The choice of impact categories, emission models and data basis should also consider the special features of perennial crops in order to be able to assess the environmental benefits of their production. These include, for example, reduction in nitrate leaching, soil carbon sequestration and maintenance of biodiversity. Therefore, it is recommended that impacts on soil quality and biodiversity are included in future environmental impact studies and methodologies for integrating them into LCA are developed. In addition, nitrogen emission models currently available need to be adapted to actual data of perennial crop performance.

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