A parsimonious model for calculating the greenhouse gas emissions of miscanthus cultivation using current commercial practice in the United Kingdom

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Abstract

Life cycle assessment (LCA) is a widely recognized tool for the assessment of the potential environmental impacts associated with the life cycle of a product or service. The environmental impact category most commonly quantified in LCAs is global warming potential, a measure of greenhouse gas (GHG) emissions. For agricultural products such as miscanthus, the creation of an inventory can be labour-intensive and is context-specific. This impairs the transfer of results to comparable but not necessarily similar situations. Farmers and small- and medium-sized enterprises cannot easily dedicate resources for this purpose (in particular when using marginal land) and often lack the expertise to do so. Simplified LCA models could offer a promising solution to this problem. They are simplified versions of more complex models that require only a few critical parameters to calculate representative results. This study develops such a model for the computation of GHG emissions associated with commercial miscanthus cultivation. The model focuses on rhizome-based propagation and the indirect harvesting method (cutting to swath, swathing, baling). A parametric life cycle inventory (LCI) was established and used to identify the most influential parameters by means of a global sensitivity analysis (GSA). A simplified model for calculating GHG emissions associated with miscanthus cultivation was developed by fixing input parameters with a low relevance at their median impact values. Six of 38 parameters were identified as relevant parameters: soil carbon sequestration, harvestable yield, duration of cultivation period, quantities of nitrogen and potassium fertilizer applied, and distance between field and customer. The simplified model allows practitioners an easy assessment of the GHG emissions associated with the production and supply of miscanthus. It thus provides a wider audience facilitated access to LCA knowledge and promotes its use as a management and reporting tool in bio-based industries.

KEYWORDS

global warming potential, greenhouse gas emissions, LCA, miscanthus, simplified LCA, sustainability
1 | INTRODUCTION

Miscanthus is considered a promising crop for the supply of biomass, in particular lignocellulose, to help meet the growing global demand. The plant uses resources, water and nutrients, efficiently and can grow in a wide range of environments, including marginal sites (Clifton-Brown et al., 2017; Lewandowski et al., 2016; van der Weijde et al., 2013). In recent years, industry's interest in miscanthus has grown due to its possible usage in a range of applications. It has been shown that miscanthus biomass can be used for the production of insulation material and chemicals, and can also serve as a bioenergy feedstock (Lask, Martínez Guajardo, et al., 2020; Lask, Rukavina, et al., 2020; Moll et al., 2020; Wagner et al., 2017). Each of these application pathways has been considered in environmental sustainability assessments, which commonly rely on the life cycle assessment (LCA) methodology (Kiesel et al., 2017; Lask et al., 2019; Wagner & Lewandowski, 2017; Wagner et al., 2019).

LCA is a widely recognized tool for the assessment of potential environmental impacts associated with the life cycle of a product or service. This is achieved by inventorying exchanges between the system under study and the environment (ISO, 2006a, 2006b). For agricultural products such as miscanthus, the creation of an inventory can be labour-intensive and is context-specific. This is due, firstly, to biophysical conditions that shape the cultivation system (e.g. with respect to yield and soil carbon sequestration) and secondly to a wide range of crop management approaches that may or may not be taken (e.g. with respect to the fertilizer amount applied). Each change in a parameter may affect the overall LCA result.

The environmental impact category most widely quantified in LCAs is global warming potential, which is a measure of greenhouse gas (GHG) emissions. Several studies, usually focusing on the physical flows related to the production system (attributional LCA; Finnveden et al., 2009), have assessed the GWP impacts associated with miscanthus production. In attributional assessments, estimates range between 58 and 156 g CO$_2$eq (kg dry matter)$^{-1}$, neglecting credits from direct land use change (dLUC; soil carbon sequestration). The lower-end value stems from the ecoinvent dataset from direct land use change (dLUC; soil carbon sequestration). The lower-end value stems from the ecoinvent dataset for miscanthus production in Germany (Nemecek, 2020). The values of these parameters (and also others) can vary substantially on account of site- and management-specific diversity. This impairs the transfer of results to comparable but not necessarily similar situations and makes performing LCAs complex and resource-consuming (Finnveden et al., 2009; Zamagni et al., 2012). Farmers and small- and medium-sized enterprises cannot easily dedicate resources to this task (in particular when using marginal land) and often lack the expertise to do so, and this hinders the wider application of LCA as a management and reporting tool in bio-based industries.

Simplified LCA models could offer a promising solution to this problem. They are reduced versions of more complex LCA models that require only a few critical parameters to calculate representative results (Beemsterboer et al., 2020). They incorporate knowledge from LCA experts and allow non-experts easy and fast computation of LCA results. The present study develops a simplified model for the calculation of GHG emissions associated with commercial miscanthus cultivation in Europe. For this purpose, a parametric life cycle inventory (LCI) model is developed based on the experience of practitioners. It is used to identify those parameters that account for the major sources of variation in the GHG emissions and then to set up the simplified model.

2 | MATERIALS AND METHODS

2.1 | Goal and scope

This study aims to develop a simplified parametric model for the computation of GHG emissions related to commercial miscanthus cultivation. The model follows the LCA framework as standardized in ISO (2006a, 2006b) and therefore accounts for all impacts associated with crop production and subsequent transport of biomass by truck (Figure 1). It is intended to be applicable to situations in which miscanthus is grown on arable land (marginal or non-marginal) in Europe for commercial purposes. It focuses on rhizome-based propagation and the indirect harvesting method (cutting to swath,

![FIGURE 1 Product system, for which a simplified model for the computation of GHG emissions is developed](image)
swathing, baling). The identification of critical parameters influencing the GHG emissions of miscanthus production is a prerequisite for the development of the simplified model and is thus considered a sub-goal of the study.

The calculations are based on a unit of 1 kg dry matter (DM; moisture content <15%) of miscanthus harvested in spring, baled and transported by truck. In line with the study’s goal, the only impact category considered was climate change. Characterization factors were derived from the impact method IPCC, 2013 (100 years; IPCC, 2013). Data for the foreground processes were determined in close collaboration with practitioners experienced in commercial miscanthus cultivation (J. Kam, personal communication, October 2020). The few remaining gaps were filled using information from the literature. Background data were derived from ecoinvent 3.7 cut-off (Wernet et al., 2016).

### 2.2 Basic calculations, global sensitivity analysis and simplified models

All calculations were performed using the LCA software Brightway2 (Mutel, 2017) and the library lca-algebraic (https://github.com/oie-mines-paristech/lca_algebraic). Lca-algebraic is a library that provides a layer above Brightway2 and implements a functional definition of models. It permits quick LCA computation, fast Monte Carlo simulations and advanced statistical analyses. This also includes global sensitivity analyses (GSAs), which are required to set up simple parametric models. In the present study, the following steps were conducted to define a simple model for computing life cycle GHG emissions of miscanthus production. First, a parametric LCI was defined. It contained information on the probability distributions of the parameters included. Second, the probabilistic distribution of the GHG emissions associated with miscanthus cultivation was calculated, using the assumed input variables. For this, a Monte Carlo simulation with 10,000 runs was conducted. Each run considered a characteristic set of values for the individual parameters. Third, a variance-based GSA was performed and Sobol indices derived for each of the parameters included. These indicate the parameters’ influence on the total variation in the resulting GHG emissions. Finally, a simple parametric model was established using the information on the Sobol indices and by fixing input parameters with low relevance at their median impact values. The corresponding script is available from the main author’s GitHub page (https://github.com/janlask/simplifiedmiscanthusLCA).

Each of the steps is described individually in the sections below. The development of the parametric inventory is explained in the sub-section ‘Life Cycle Inventory and Parametrization’. The probabilistic distribution of the GHG emissions and Sobol indices is presented graphically in the results section followed by the simplified model developed.

### 2.3 Life cycle inventory and parametrization

In line with the scope of the study, the inventory included all processes required for miscanthus production: land preparation (liming, ploughing and harrowing), establishment of the crop (rhizome planting incl. production of planting material, rolling and weed management), fertilization, harvest-related activities (cutting to swath, swathing, baling, bale loading and transport by truck) and recultivation (preparation of land for subsequent use). For each of the agricultural operations, standard ecoinvent datasets were taken, with the diesel consumption adapted according to information from practitioners. All required agricultural inputs (fertilizers, herbicides, etc.) and associated field emissions were accounted for. This includes emissions from lime application (CO2), nitrogen fertilization (direct and indirect N2O emissions) and decay of non-harvested biomass (leaves and stubble) (N2O). As the simplified model is intended to be representative of average European cultivation conditions, market datasets were selected for background processes, where possible. This means that, for example, for fertilizers, a substrate mix representative of the European market for inorganic fertilizers was taken. The influence of this assumption was tested by specifying the fertilizer type (calcium ammonium nitrate and potassium chloride) in a sensitivity analysis (specified fertilizer model).

Present-day commercial miscanthus production relies on rhizome-based, vegetative propagation, which is costly and impedes faster uptake of the crop by industry and farmers. Seed-based plugs from new miscanthus hybrids could overcome these hurdles and are on the verge of market introduction (Clifton-Brown et al., 2017). For this reason, the default model using rhizome-based cultivation was complemented by a sensitivity analysis assessing plug-based miscanthus production. Inventory data for the rhizome production were taken from the ecoinvent database (Wernet et al., 2016), while inventory data for the seed plug production were compiled based on insights from commercial seed plug production (J. Kam, personal communication, October 2020; inventory provided in Table S2).

Following the initial creation of the inventory, influential parameters were collated for all process steps (see Figure S1) and incorporated into the model. In collaboration with experts from research and practice, each parameter was characterized using one of the following options: linear, triangular or normal distribution, or fixed values. The distributions were further defined by providing descriptive information (default/mean, min/max and standard deviation) representative of commercial-scale cultivation. The outcome is summarized in Table 1, where the parameters are classified in four groups: diesel consumption, biomass-related, management-related and transport...
| Phase                  | Parameter                        | Description                                               | Unit                        | Default | Min   | Max   | Std   | Distribution | Main reference                    |
|-----------------------|----------------------------------|-----------------------------------------------------------|-----------------------------|---------|-------|-------|-------|--------------|-----------------------------------|
| Biomass               | yield harv                       | Average annual harvestable DM yield after establishment   | kg DM ha^{-1} year^{-1}     | 14,000  | 9500  | 23,500|       | Trianglec   | McCalmont et al. (2017); Witzel and Finger (2016) |
|                       | mass rhizomes                    | Mass of rhizomes                                          | kg piece^{-1}               | 0.0750  | 0.0500| 0.1000|       | Trianglec   | d                                  |
|                       | carbon seq                       | Carbon sequestered                                        | kg C ha^{-1} year^{-1}      | 0       | (0)   | (2200)|       | Fixeda      | McCalmont et al. (2017)            |
|                       | dmshare_stubbles                 | Proportion of DM peak yield remaining on field after harvest | %                           | 0.04    | 0.02  | 0.06  |       | Trianglec   | d                                  |
|                       | dmshare_leaves                   | Proportion of DM peak yield lost as leaves                | %                           | 0.24    | 0.20  | 0.29  |       | Trianglec   |                                    |
|                       | RS                               | Ratio of below- and above-ground biomass                 |                             | 0.80    | 0.70  | 1.50  |       | Trianglec   | IPCC (2006)                         |
|                       | N_stubbles                       | Nitrogen content of stubbles                              | kg N (kg DM)^{-1}           | 0.0020  | 0.0015| 0.0025|       | Trianglec   | d                                  |
|                       | N_leaves                         | Nitrogen content of leaves lost                           | kg N (kg DM)^{-1}           | 0.0070  | 0.0060| 0.0080|       | Trianglec   |                                    |
|                       | N_bgr                            | Nitrogen content of below-ground biomass                 | kg N (kg DM)^{-1}           | 0.0100  | 0.0060| 0.0140|       | Trianglec   |                                    |
|                       | mass rhizomes                    | Mass of rhizomes                                          | kg piece^{-1}               | 0.0750  | 0.0600| 0.1000|       | Trianglec   |                                    |
| Diesel consumption    | diesel ploughing                 | Diesel consumption for ploughing                          | kg ha^{-1}                  | 16.62   | 12.61 | 20.97 |       | Trianglec   | d                                  |
| in agricultural       | diesel harrowing                 | Diesel consumption for harrowing                          | kg ha^{-1}                  | 14.78   | 10.75 | 19.76 |       | Trianglec   |                                    |
| operations            | diesel_rhizome planting          | Diesel consumption for rhizome planting                  | kg ha^{-1}                  | 13.57   | 11.13 | 16.56 |       | Trianglec   |                                    |
|                       | diesel rolling                   | Diesel consumption for rolling                            | kg ha^{-1}                  | 2.15    | 1.75  | 2.66  |       | Trianglec   |                                    |
|                       | diesel appplantprot              | Diesel consumption for application of plant protection agents | kg ha^{-1}                  | 2.11    | 1.50  | 2.66  |       | Trianglec   |                                    |
|                       | diesel fertilisation             | Diesel consumption for broadcasting of fertilizer        | kg ha^{-1}                  | 0.20    | 0.15  | 0.25  |       | Trianglec   |                                    |
|                       | diesel combine                   | Diesel consumption for combine harvester                | kg ha^{-1}                  | 9.03    | 7.56  | 10.5  |       | Trianglec   |                                    |
|                       | diesel swathing                  | Diesel consumption for swathing                           | kg ha^{-1}                  | 2.94    | 2.46  | 3.42  |       | Trianglec   |                                    |
|                       | diesel baling                    | Diesel consumption for baling                             | kg bale^{-1}                | 0.84    | 0.60  | 1.10  |       | Trianglec   |                                    |
|                       | diesel baleload                  | Diesel consumption for bale loading                       | kg bale^{-1}                | 0.42    | 0.35  | 0.49  |       | Trianglec   |                                    |
|                       | diesel recultivation             | Diesel consumption for recultivation                     | kg ha^{-1}                  | 16.62   | 12.61 | 20.97 |       | Trianglec   |                                    |

(Continues)
| Phase     | Parameter      | Description                              | Unit             | Default | Min | Max | Std | Distribution | Main reference |
|----------|---------------|------------------------------------------|------------------|---------|-----|-----|-----|--------------|----------------|
| Management | *cult per* | Duration of cultivation period | years | 20 |     |     |     | Normal<sup>b</sup> |                |
|          | *num rhizomes* | Number of rhizomes for planting | pieces ha<sup>−1</sup> | 15000 |     |     |     | Fixed<sup>a</sup> |                |
|          | *bale m* | Bale weight | kg bale<sup>−1</sup> | 615 |     |     |     | Fixed<sup>a</sup> |                |
|          | *freq N fertilisation* | Nitrogen fertilization per cultivation period | | 0 | 0 | 0.5 |     | Triangle<sup>c</sup> | and McCalmont et al. (2017) |
|          | *freq K fertilisation* | Potassium fertilization per cultivation period | | 1 | 0.75 | 1 |     | Triangle<sup>c</sup> |                |
|          | *freq P fertilisation* | Phosphorus fertilization per cultivation period | | 0.25 | 0.25 | 0.5 |     | Triangle<sup>c</sup> |                |
|          | *N fert* | Total nitrogen fertilizer applied | kg N (cult. period)<sup>−1</sup> | 0 | 0 | 600 |     | Triangle<sup>c</sup> |                |
|          | *K fert* | Total potassium fertilizer applied | kg K<sub>2</sub>O (cult. period)<sup>−1</sup> | 2380 | 1700 | 3500 |     | Triangle<sup>c</sup> |                |
|          | *P fert* | Total phosphorus fertilizer applied | kg P<sub>2</sub>O<sub>5</sub> (cult. period)<sup>−1</sup> | 280 | 200 | 350 |     | Triangle<sup>c</sup> |                |
|          | *lime app* | Liming | Yes (1) – No (0) | 1 |     |     |     | Fixed<sup>a</sup> |                |
|          | *lime fert* | Lime applied | kg (cult. period)<sup>−1</sup> | 2160 | 1500 | 2500 |     | Triangle<sup>c</sup> |                |
|          | *herb_app* | Number of herbicide applications | | 3 | 1.5 | 5 |     | Triangle<sup>c</sup> |                |
|          | *amount Glyphosate* | Avg. amount of glyphosate applied per herbicide application | kg active substance (average application)<sup>−1</sup> | 0.3240 | 0.2916 | 0.3564 |     | Triangle<sup>c</sup> |                |
|          | *amount pendimethalin* | Avg. amount of pendimethalin applied per herbicide application | | 0.2610 | 0.2349 | 0.2871 |     | Triangle<sup>c</sup> |                |
|          | *amount phenoxy* | Avg. amount of phenoxy-compound applied per herbicide application | | 0.3300 | 0.2970 | 0.3630 |     | Triangle<sup>c</sup> |                |
|          | *amount pesticide_unspec* | Avg. amount of unspecified pesticide applied per herbicide application | | 0.0110 | 0.0099 | 0.0121 |     | Triangle<sup>c</sup> |                |
| Phase                  | Parameter            | Description                                                   | Unit | Default | Min | Max | Std | Distribution | Main reference |
|-----------------------|----------------------|---------------------------------------------------------------|------|---------|-----|-----|-----|--------------|----------------|
| Transport distances   | distance rhizomesplugs| Distance between rhizome/seed plug nursery and farm           | km   | 800     | 20  | 2000|     | Trianglec    | d              |
|                       | distance rhizomesplugsfield | Distance between farm and field                              |      | 2       | 0.5 | 10  |     | Trianglec    |                |
|                       | distance cust         | Distance between field and customer or collection point      |      | 60      |     | 18  |     | Normalb      |                |
|                       | distance generic input | Distance for input materials, if not further specified      |      | 150     |     |     |     | Fixeda       | Authors’ estimate |
| Emission factors      | EF_1                 | Direct N₂O from application of nitrogen fertilizer           |      | 0.0100  |     |     |     | Fixeda       | IPCC (2019)    |
|                       | Frac_GASF            | Fraction of N lost through volatilization (NH₃ and NOₓ)      |      | 0.1100  |     |     |     | Fixeda       |                |
|                       | EF_4                 | Indirect N₂O from N volatilized and redeposited              |      | 0.0100  |     |     |     | Fixeda       |                |
|                       | Frac_LEACH           | Fraction of N lost through leaching (NO₃⁻)                   |      | 0.2400  |     |     |     | Fixeda       |                |
|                       | EF_5                 | Indirect N₂O from nitrate leached                            |      | 0.0110  |     |     |     | Fixeda       |                |
|                       | EF_limestone         | CO₂ from liming                                              |      | 0.1200  |     |     |     | Fixeda       |                |

*Fixed: default value taken.

bNormal: default is taken as mean.

cTriangle: default represents highest probability.

dExpert estimate.
distances. Some of these parameters are selected for more detailed explanation below, on account of their sheer number (diesel consumption) or relevance for the study’s results (see Section 4).

Parameters for diesel consumption in the agricultural operations are provided in Table 1 and were defined considering mean values and ranges provided by practitioners (J. Kam, personal communication, October 2020). These parameters were used to adjust standard ecoinvent datasets of agricultural operations in terms of the diesel input and associated emissions.

Biomass-related parameters include, among others, the estimated miscanthus dry matter yield (fully established crop) and potential carbon sequestration. Given the possible cultivation on marginal as well as on non-marginal land, a wide yield range (min = 9500 kg DM ha⁻¹, max = 23,000 kg DM ha⁻¹) with a mean of 14,000 kg DM ha⁻¹ was considered. The mean value was calculated as the average of published data on yields in Europe (McCalmon et al., 2017; Witzel & Finger, 2016), while minimum and maximum values were based on expert estimates. A triangular distribution was selected, as mean yields are more likely and yields below the minimum value do not seem viable from a commercial perspective. It was assumed that the plantations reach 50% of their full yield potential in the second year and 100% from the third year onwards. During its cultivation, miscanthus can substantially increase the amount of carbon in the soil through the turnover of leaves, harvest residues and below-ground biomass (rhizomes and roots). In addition, the absence of tillage operations during the cultivation period can retard the mineralization of carbon (Chimento et al., 2016; McCalmont et al., 2017). The extent of these effects and their accounting in LCA greatly depends on site-specific characteristics as well as on methodological choices of LCA practitioners (Goglio et al., 2015). As seen in preliminary analyses performed in the context of the present study, the parameter carbon sequestration can easily dominate the variation in GHG emissions associated with miscanthus cultivation. This is due to the broad range of values that could be taken, ranging from 0 to 2.2 t C ha⁻¹ year⁻¹ (McCalmont et al., 2017). The inclusion of this parameter impeded further assessments. For this reason, carbon sequestration was not included as a variable in the GSA. However, as it is a critical parameter, it was subsequently incorporated into an extended simplified model (see Section 4.3).

Management-related parameters include those variables that can be actively influenced by farmers, for example, the application of fertilizers and duration of the cultivation period. LCA studies commonly assume cultivation periods of 20 years for miscanthus. The effect of extended cultivation periods is rarely assessed, although the maximum lifetime of miscanthus plantations can be up to 25 years (Lewandowski et al., 2003). In practice, however, farmers occasionally decide to terminate the miscanthus cultivation earlier. For these reasons, we described the duration of the cultivation period (cult_per) using a normal distribution, given a mean of 20 years and a standard deviation of 3 years. Two parameters were defined for the application of each fertilizer. This includes one parameter detailing the application frequency (freq_Nfertilisation, freq_Pfertilisation and freq_Kfertilisation) and one for the total fertilizer amount applied per hectare during the cultivation period (N_fert, P_fert and K_fert). Academic cultivation trials commonly consider moderate nitrogen fertilization (e.g. 60 kg N ha⁻¹ year⁻¹, see for instance Kiesel et al., 2017). This is despite the fact that contradicting effects of nitrogen application on miscanthus biomass yield have been reported and in commercial practice, no nitrogen is commonly applied (J. Kam, personal communication, October 2020 and McCalmont et al., 2017). In line with the study's objective of representing commercial miscanthus cultivation, a triangular distribution with a maximum probability at 0 kg nitrogen per hectare was defined. By default, lime application was assumed. The quantities of fertilizers and lime applied were estimated using first-hand experience from commercial miscanthus cultivation (J. Kam, personal communication, October 2020).

The group transport distances comprises parameters describing all truck transport distances involved. Analyses performed in preparation of the current study indicated transport distance of the harvested biomass as the only parameter that substantially contributes to the variation of results in the model. The parameter (dist_cust) was defined according to commercially relevant information (J. Kam, personal communication, October 2020).

Parameters describing emission factors were fixed at IPCC default values, as is standard LCA practice (IPCC, 2019). For the specified fertilizer model, more specific emission factors were taken using calcium ammonium nitrate as nitrogen source.

# RESULTS

## Probabilistic distribution of the life cycle GHG emissions and Sobol indices

The probabilistic distribution of the GHG emissions associated with the rhizome-based production of 1 kg miscanthus DM is presented in Figure 2. For each of the 10,000 runs, the parameter values varied within the range indicated in Table 1 (carbon_seq fixed to 0). The distribution is characterized by a mean (µ) of 87.1 and a median of 85.0 g CO₂eq (kg DM)⁻¹, and a 5th and 95th percentile of 66.2 and 115.0 g CO₂eq (kg DM)⁻¹ respectively.
As mentioned above, Sobol indices indicate how strongly an individual parameter influences the variation of the overall result. Indices were calculated for all (non-fixed) parameters. Figure 3 presents the contribution to variation of each of these parameter. The most important ones (in descending order) are yield\_harv, cult\_per, N\_fert, K\_fert and dist\_cust, which together account for more than 96% of the total variation. From these results, it becomes clear that the biomass yield is the most influential parameter in the model, followed by the duration of cultivation period and the amount of nitrogen and potassium fertilizer applied. In addition, the distance between field and final customer or storage site should not be neglected. As described in Section 2.3, it was observed in preliminary analyses that the parameter carbon\_seq dominated the overall variability due to its substantial variation (see also Figure S2). To enable the analysis of other parameters, it was excluded from the GSA.

### 3.2 Simplified model

Based on the results of the GSAs and the Sobol indices, a simplified model was created by fixing less influential parameters at their median impact value. The resulting equation is given below:

\[
\frac{\text{GHG emissions}}{\text{kg CO}_2\text{eq} (\text{kg DM})^{-1}} = \frac{3.09K_{\text{fert}} + 10.4N_{\text{fert}} + 83.3\text{cult\_per} + 2310}{\text{yield\_harv (cult\_per - 1.5)}} + \frac{0.0713}{(\text{cult\_per - 1.5})} + 0.000162\text{dist\_cust} + 0.0224, \tag{1}
\]

where K\_fert is the total potassium fertilizer applied [kg K\text{2O} (cult. period)\text{−1}]; N\_fert is the total nitrogen fertilizer applied [kg N (cult. period)\text{−1}]; cult\_per is the duration of cultivation period [years]; yield\_harv is the harvestable DM yield when established [kg DM ha\text{−1}]; dist\_cust is the distance between field and customer or collection point [km].

### 3.3 Extending the simplified model to account for carbon sequestration

In the previous calculations, the parameter carbon\_seq was fixed and thus not considered in the GSA due to its substantial impact on the results. Nevertheless, carbon accumulation through miscanthus cultivation is an important and relevant parameter. For this reason, a term was added to the simplified model, which enables the integration of the carbon amount sequestered over the cultivation period (carbon\_seq * \(\frac{44}{12}\) * cult\_per). This results in an adjusted simplified model:

\[
\frac{\text{GHG emissions}}{\text{kg CO}_2\text{eq} (\text{kg DM})^{-1}} = \frac{3.09K_{\text{fert}} + 10.4N_{\text{fert}} + 83.3\text{cult\_per} + 2310}{\text{yield\_harv (cult\_per - 1.5)}} + \frac{0.0713}{(\text{cult\_per - 1.5})} + 0.000162\text{dist\_cust} + 0.0224 + (\text{carbon\_seq} * \frac{44}{12} * \text{cult\_per}), \tag{2}
\]

where K\_fert is the total potassium fertilizer applied [kg K\text{2O} (cult. period)\text{−1}]; N\_fert is the total nitrogen fertilizer applied [kg N (cult. period)\text{−1}]; cult\_per is the duration of cultivation period [years].
[yards]; yield\textsubscript{harv} is the harvestable DM yield when established [kg DM ha\textsuperscript{-1}]; dist\textsubscript{cust} is the distance between field and customer or collection point [km]; carbon\textsubscript{seq} is the carbon sequestered due to miscanthus cultivation [kg C ha\textsuperscript{-1} year\textsuperscript{-1}].

4 DISCUSSION

In this study, a simplified model for calculating the GHG emissions associated with miscanthus cultivation and supply was developed. It facilitates quick assessments by LCA practitioners and miscanthus farmers. As a prerequisite, those inventory parameters were identified that explain the major share of variation in the results of GHG emission calculations.

The most important is the amount of carbon sequestered during the cultivation period (carbon\textsubscript{seq}). This can vary widely and greatly depends not only on site-specific conditions (McCalmont et al., 2017) but also on the methodological approach selected for carbon accounting (Goglio et al., 2015) and the (assumed) permanence of the carbon sequestered (Lask, Martínez Guajardo, et al., 2020; Lask, Rukavina, et al., 2020). Due to the high variability in the possible values that this parameter can take, it is left to the user which value to select. Parameter values could be selected from the range provided in Table 1 (based on McCalmont et al., 2017) or using allometric models, as suggested in Ledo et al. (2018). In any case, the permanence of the carbon storage has to be critically reflected upon. For precautionary users of the model, it is recommended to consider only a temporary carbon storage during the cultivation period. This can be done using the approach suggested in the ILCD handbook (ILCD, 2010) and avoids overestimation of the benefits from carbon storage.

If carbon sequestration is not taken into account, five remaining parameters explain more than 96% of the variation in the results. The most influential of this group is dry matter yield, which is in line with previous publications (Meyer et al., 2017; Sanscartier et al., 2014). Actual yields vary substantially due to genotypic as well as climatic and soil variations. This applies in particular to cultivation on marginal land which is strongly advocated for miscanthus. If yield decreases are expected to occur over the cultivation period, the parameter yield\textsubscript{harv} has to be set in a way that reflects the average yield over the cultivation period after the establishment period.

The second most influential parameter was identified as the duration of the cultivation period. The relevance of this parameter in LCA studies on miscanthus cultivation and other perennial crops has been emphasized before (Hastings et al., 2017; Hastings, Clifton-Brown, Wattenbach, Mitchell, Stampfl, et al., 2009; Hastings Clifton-Brown, Wattenbach, Mitchell, & Smith, 2009; Ledo et al., 2020; McCalmont et al., 2017). With an increase in duration of the cultivation period, the emissions associated with the provision of planting material and establishment can be distributed over a higher biomass output. Consequently, the GHG intensity per kilogram miscanthus dry matter decreases. This aspect is relevant for miscanthus crop management in practice. While the annual decline is substantial during the first 11 years, the effect diminishes in the following years and levels out from year 15 onwards (Figure S3). Thus, we conclude that miscanthus, once established, should be cultivated for at least 10, ideally 15 years. LCA studies on miscanthus-based value chains usually use the default of 20 years. Given previous and present results, we highlight the importance of reflecting on the sensitivity of miscanthus LCA results in regard of this parameter.

Unsurprisingly, the amounts of potassium and mainly nitrogen fertilizer applied influence the GHG emissions associated with miscanthus cultivation substantially. Nitrogen fertilization, in particular, has previously been identified as an important parameter (Sanscartier et al., 2014). However, the present study also reveals a substantial influence of the potassium fertilizer applied. This is mainly due to the market datasets representing the average European market fertilizer mix that were selected to give the simplified model wider validity. NPK fertilizer accounts for a high share of the market mix for inorganic potassium fertilizer (Symeonidis, 2020), which results in substantially higher impacts than when using specific fertilizers. Taking potassium chloride, a common potassium fertilizer in the European context, results in a two-third reduction of GHG emissions per kilogram K\textsubscript{2}O supplied. A shift in fertilizer providers from market processes to, for example, calcium ammonium nitrate and potassium chloride, would affect the model outcome accordingly, reducing the overall impacts (see Figure S4).

In the simplified model, the four parameters mentioned above were complemented by one describing the distance between field and customer. This is particularly relevant for marginal sites, as these can also be marginal in an economic sense due to their remote location and/or poor accessibility. Together, these five identified parameters, complemented with the one on carbon sequestration, explain the major share of the variation in the results for GHG emissions associated with miscanthus cultivation.

Other parameters were less relevant and not included as variables in the simplified model. The impact associated with these was included using the median GHG emissions derived from the range of the input variables given in Table 1. This applies, for instance, to the diesel consumptions of the agricultural procedures. For the ranges assumed, these parameters did not have a substantial influence on the variation in impact results for the system as a whole.

On the whole, the suggested simplified model can be used to estimate the GHG emissions associated with miscanthus cultivation. For a comparison with previously published assessments, the simplified model was run with the parameters given in two publications. Table 2 shows the results as given in the publication along with the ones derived using the simplified model. The comparison reveals that the
suggested simplified model provides a satisfactory estimation of the GHG emissions associated with miscanthus cultivation (Table 2). However, it seems that the generic model results in a conservative estimation when compared with the results from the reference studies. Comparing the results with the ecoinvent dataset (Nemecek, 2020), a more substantial deviation can be observed. The simplified model results in higher impacts, which can be attributed to substantially lower N2O flows in the ecoinvent dataset. This probably results from an omission of nitrogen losses via the degradation of leaves before harvest. For the other comparisons given in Table 2, the simplified model can deliver meaningful estimates for the assessment of impact variations through yield fluctuations and differences in management practices.

It should be emphasized that the simplified model can only be considered a representation of the current commercial miscanthus cultivation and changes in management need to be continuously monitored and incorporated into the model. An example of a change already taking place that could require adaptions to the model is related to the planting material. Seed-based plugs are at the threshold of achieving market readiness and their provision clearly differs from rhizome propagation. Possible discrepancies between GHG emissions arising from miscanthus establishment based on rhizomes and seed-based plugs were analysed in a sensitivity analysis. The screening indicated that impacts are almost twice as high for plugs as for rhizomes mainly due to the heat and light required to raise the plugs in the greenhouse. However, when taken over the entire cultivation period and total DM yield, differences between the two cultivation systems are relatively small, as the production of the planting material has only a minor impact (see Figures S4 and S5).

The major outcome of this study is the establishment of a simplified parametric model—an effort, which so far is only rarely undertaken in LCA practice and research. It allows practitioners simple calculation of GHG emissions associated with the production and supply of miscanthus, including marginal sites. Using this model would enable LCA know-how to be more easily shared among a wider audience. A simplified model with only a few variables would give non-LCA experts a better idea of central parameters to be used as leverage points in the optimization of their systems. In addition, simplified parametric models hold substantial opportunities for LCA research as they enable automated and faster computation of potential environmental impacts.

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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available in the supplementary material of this article and at the online repository: https://github.com/janlask/simplifiedmiscanthusLCA.

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| Reference | Study | Sanscartier et al. (2014) | Nemecek (2020) | Lask et al. (2019) |
|-----------|-------|--------------------------|----------------|-------------------|
|           | Scenario | A | B | C | D | E | — | GER | UK |
| Life span [years] | 20 | 20 | 15 | 15 | 15 | 20 | 20 | 20 |
| Yield [kg DM ha⁻¹] | 11100 | 10000 | 10000 | 8400 | 9500 | 17000 | 15316 | 9745 |
| N [kg N (cult. per)⁻¹] | 1200 | 1600 | 1200 | 900 | 1200 | 850 | 1200 | 1200 |
| P [kg P₂O₅ (cult. per)⁻¹] | 240 | 220 | 165 | 135 | 150 | 850 | 600 | 600 |
| K [kg K₂O (cult. per)⁻¹] | 2100 | 1900 | 1425 | 1185 | 1350 | 2023 | 2400 | 2400 |
| Transport distance [km] | 95 | 95 | 95 | 185 | 95 | 2 | 48 | 83 |
| g CO₂eq (kg DM)⁻¹ acc. to … | 129.20 | 149.33 | 167.79 | 167.79 | 182.89 | 58.00 | 109.49 | 153.99 |
| Reference (without dLUC) | 153.38 | 184.82 | 194.50 | 203.87 | 200.66 | 87.20 | 118.28 | 172.11 |
| Simplified model | 130.31 | 160.99 | 169.65 | 179.15 | 175.71 | 72.76 | 99.34 | 142.51 |
| Simplified model (spec. fert.) | 129.20 | 149.33 | 167.79 | 167.79 | 182.89 | 58.00 | 109.49 | 153.99 |
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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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