Comparative environmental and economic life cycle assessment of biogas production from perennial wild plant mixtures and maize (Zea mays L.) in southwest Germany

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Abstract
Maize silage is the main biogas co-substrate in Germany, but its use is often questioned due to negative environmental impacts. Perennial wild plant mixtures (WPM) are increasingly considered alternatives, as these extensive systems improve soil quality and enhance agrobiodiversity. Methane yields per hectare however do not match those of maize. This study examined whether the potential advantages of replacing maize with WPM for biogas production are counteracted by lower yields and associated effects. Life cycle assessment and life cycle cost assessment were used to compare the environmental and economic performance of electricity generation from WPM in two establishment procedures, ‘standard’ (WPM E1) and ‘under maize’ (WPM E2). These metrics were benchmarked against those of maize. The production of 1 kWh electricity was chosen as functional unit. The life cycle inventory of the agricultural phase was based on multi-annual field trials in southwest Germany. Both WPM E1 and E2 had lower marine eutrophication and global warming potentials than maize. The GWP favourability was however sensitive to the assumptions made with regard to the amount and fate of carbon sequestered in the soil. WPM E1 performed less favourable than WPM E2. This was mainly due to lower yields, which could, in turn, result in potential indirect land use impacts. These impacts may outweigh the carbon sequestration benefits of WPM cultivation. Maize performed best in terms of economic costs, freshwater eutrophication, terrestrial acidification, fine particulate matter and ozone formation. We conclude that the widespread deployment of WPM systems on productive agricultural land should only take place if permanent soil carbon sequestration can be ensured. In either case, WPM cultivation could be a valid alternative for bioenergy buffers and marginal land where competitive yields of common crops cannot be guaranteed, but which could accommodate low-input cultivation systems.

KEYWORDS
agrobiodiversity, alternative substrates, bioenergy, biogas, environmental performance, LCA, LCC, maize, perennial cropping system, wild plant mixtures
Electricity production based on biogas can contribute to greenhouse gas mitigation (Kiesel, Wagner, & Lewandowski, 2017; Scarlatt, Dallemand, & Fahl, 2018; Wagner et al., 2019). Germany has seen a large deployment of biogas production during the last two decades and has become the world’s largest producer with an installed electrical capacity of 4.8 GW in 2018. Energy crops, of which 69% are maize (Zea mays L.) silage, accounted for more than half of the substrates in 2016 (FNR, 2019). The wide cultivation of maize in Germany is often questioned due to potential negative impacts on the environment, including the risk of soil erosion and compaction, nitrate leaching and high pesticide use (Herrmann, 2013; Kiesel et al., 2017).

For this reason, an extensification of biogas production is increasingly being investigated and alternative biogas substrates sought (Herrmann, Idler, & Heiermann, 2016; von Cossel, Möhring, Kiesel, & Lewandowski, 2018). Perennial crops such as miscanthus and Silphium perfoliatum are considered particularly promising alternative biogas substrates (Kiesel & Lewandowski, 2017; Mayer et al., 2014; von Cossel, Wagner, et al., 2019). Wild plant mixtures (WPM) have also been suggested as a potential future biogas substrate production system (BSPS) and have recently become the subject of research interest (Carlsson, Mårtensson, Prade, Svensson, & Jensen, 2017; Vollrath et al., 2012; Vollrath, Werner, Degenbeck, & Marzini, 2016; von Cossel & Lewandowski, 2016; von Cossel, Steberl, et al., 2019). WPM are perennial polycultures, consisting of wild, flower-rich plant species of annual, biennial and perennial nature. The dynamic cultivation systems are characterized by changing compositions over the cultivation period: Annual plant species are predominant in the first cultivation year, biennial species in the second and perennial plants in the following years. The perennial nature provides almost constant soil coverage, preventing soil erosion and contributing to soil carbon sequestration and improved soil quality (Emmerling, 2014; Emmerling, Schmidt, Ruf, Francken-Welz, & Thielen, 2017). The seed mixtures include legume species such as lucerne (Medicago sativa L.), white and yellow melilot (Melilotus spp.), to ensure atmospheric nitrogen (N) fixation, thus reducing the amount of fertilizer needed (von Cossel & Lewandowski, 2016). The main reason for encouraging WPM cultivation as a BSPS is its potential contribution to the protection and preservation of agrobiodiversity. Their perennial nature can provide food and habitats for wild/field animal species. Insects, in particular pollinators, benefit from the species mix of the plant stands (von Cossel & Lewandowski, 2016). These systems could thus contribute to an extensification of the present maize-dominated biogas substrate production, while enhancing a range of ecosystem functions on a local scale (Carlsson et al., 2017; von Cossel, Steberl, et al., 2019).

In addition to environmental advantages, it has occasionally been claimed that WPM cultivation also has economic benefits. For example, it has been suggested that perennial cropping systems can provide biomass more economically than annual systems, as less management is required (Lewandowski, 2016; Lewandowski et al., 2016). However, WPM tend to have lower yields than comparable maize systems, due to both lower biomass and specific methane yields (Friedrichs, 2013; Vollrath et al., 2016; von Cossel & Lewandowski, 2016; von Cossel, Steberl, et al., 2019). For this reason, approaches that combine the cultivation of maize and WPM are currently being investigated. The idea is to establish biennial and perennial WPM species under maize, in order to make use of the high maize yield in the first year and combine this with the beneficial characteristics of WPM in the following years. It has been demonstrated that this combination does not significantly reduce maize performance and can improve the long-term performance of WPM cultivation for biogas production (von Cossel, Steberl, et al., 2019). Despite these efforts, hectare yields do not match the output levels of conventional biogas crops over the cultivation period.

A more holistic assessment of WPM systems (WPM pure and WPM established under maize) for the extensification of biogas substrate production require a comparison with the conventional maize system. This study examines whether the advantages of an extensified biogas cropping system mentioned above are counteracted by lower yields, higher land requirements and the associated direct (e.g. soil carbon sequestration) and also potentially indirect effects. This question is relevant for both the environmental and economic dimension and has so far not been investigated. The study aims to quantify the environmental impacts and economic costs of electricity generated in a biogas plant based on three different feedstocks: maize only, WPM only and a combination of both. For this purpose, a comparative life cycle assessment (LCA) and a life cycle costing (LCC) are conducted. The results of the LCA are used for a comparison with a fossil reference to assess the greenhouse gas mitigation potential of the biogas systems analysed. This is an important motivation factor for investments in biogas technologies. If extensified BSPS, such as WPM, are intended for large-scale deployment, their contribution to achieving this goal needs to be ensured.

The first section introduces the methodological approach, including a description of the system to be analysed as well as fundamental assumptions. The second section presents the results of the sustainability assessment. In the final section, conclusions are drawn from these results, taking potential limitations and trade-offs into consideration.
2 | MATERIALS AND METHODS

2.1 | Goal and scope

This study conducted a comprehensive comparative environmental and economic assessment of the production of electricity from biogas. The BSPS analysed were mono-cropped maize (Maize) as reference crop, and two alternative systems with perennial features. Both alternatives were based on WPM but differed in the establishment approach: a standard WPM establishment procedure (WPM E1) and the establishment of WPM under maize, which served as a nurse crop (WPM E2; as described in von Cossel, Steberl, et al., 2019). All life cycle stages, namely the agricultural production of the systems mentioned, anaerobic digestion, and heat and electricity generation, were considered in the assessment. The alternative systems were compared based on a functional unit of 1 kWh electricity produced on a farm in southwest Germany, ready to be fed into the national grid. Marginal processes were used for modelling in line with Weidema, Pizzol, Schmidt, and Thoma (2018), who argue that this approach is fundamental for comparative assessments. As the arable land in southwest Germany is limited, an increase in biogas substrate production is likely to replace existing production systems. Since the global demand for agricultural products is still increasing, the replaced production is likely to be relocated elsewhere. Such implications need to be acknowledged in sustainability assessments of bioenergy cropping systems (Agostini, Giuntoli, Marelli, & Amaducci, 2019). The potential impacts of these considerations were investigated in a sensitivity analysis.

2.2 | Methods

This study is in accordance with the International Organisation for Standardization (ISO) framework (ISO 14040; ISO 2006). Data for the life cycle inventory of the BSPS (agricultural procedures and inputs, biomass yields and properties) were taken from a field trial performed at the University of Hohenheim between 2014 and 2018. Although the use of primary data limits the global significance of the results, it enables a more reliable comparison of the two biogas feedstocks under the given conditions. Biogas batch tests were performed to determine the potential methane yields, as described in von Cossel, Steberl, et al. (2019). For the anaerobic digestion and the heat and power generation, literature data were used. Background data and data on the fossil reference were taken from the ecoinvent database v3.5 consequential (Wernet et al., 2016). Modelling and impact calculations were performed using openLCA 1.8.0. The impact assessment methodology ReCiPe 2016 v1.1 was chosen due to its European focus and its up-to-date nature (Huijbregts et al., 2017). The following impact categories were selected because of their relevance in agricultural systems and biogas production: global warming potential (GWP), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial acidification (TA), fine particulate matter formation (PM) and ozone formation (OF). The economic assessment followed the Code of Practice for environmental Life-Cycle Costing (Swarr et al., 2011) and was primarily based on data from the KTBL database (KTBL, 2019). The economic assessment included all costs that occur over the cultivation period of the substrates and takes a discount rate of 6% into account. For the biogas plant, all investment, operation and capital costs were considered, assuming a lifetime of 20 years.

2.3 | System boundaries

Figure 1 shows the schematic representation of the assessed system. The temporal boundaries ranged from the establishment of the biogas substrates, through final harvest and clearing of the fields to a state where a new crop could be planted. A total cultivation period of 5 years was investigated due to data availability. The maximum cultivation period of WPM can exceed 5 years (von Cossel, Steberl, et al., 2019). All agricultural inputs, such as herbicides and seeds, and management procedures were included. It was assumed that the annually harvested biomass was transported by tractor to a nearby biogas plant, where it is ensiled and fermented in an anaerobic digester. The biogas produced is combusted in a combined heat and power plant to generate electricity. The fermentation residues, which contain considerable amounts of nutrients, are returned to the field and used as fertilizer. The heat produced during the biogas combustion is used to meet the heat requirements of the biogas plant.

2.4 | Life cycle inventory

2.4.1 | Agricultural systems

Data for the substrate cultivation were taken from a field trial conducted at the University of Hohenheim, southwest Germany. In this field trial, different WPM establishment procedures were tested for their long-term methane yields over a 5-year cultivation period (2014–2018; von Cossel, Steberl, et al., 2019). Although further biogas cropping systems were assessed in this trial, the present study focused on a single WPM (BG90; Saaten-Zeller, 2016), as it performed best in terms of dry matter (DM) and methane yield. The standard establishment procedure (WPM E1) and the simultaneous sowing of maize and WPM (WPM E2) were evaluated. In addition, mono-cropped maize was included as a reference.

For all three BSPS, soil preparation included ploughing and harrowing, followed by sowing. In ‘Maize’ and ‘WPM E2’, the maize was sown at a density of 90,000 seeds per...
hectare. For ‘WPM E2’, 10 kg WPM seeds were sown immediately afterwards. In ‘WPM E1’, 10 kg seeds of WPM were sown alone (Table 1). The WPM systems included the additional step of rolling to ensure sufficient soil contact of the small seeds. In the field trial, weed management was conducted by hand. As this is unrealistic in commercial plantations, this study assumed the application of pesticides by field sprayers. The respective pesticide amounts were taken from a comparable field trial also performed at the University of Hohenheim (Kiesel et al., 2017; Table 1). In line with this study, two plant protection procedures were considered during the establishment period. The application of plant protection agents was assumed to take place in the first year only in WPM, as perennial plants effectively suppress weeds once established. In maize, an annual application was assumed.

The harvest of the biogas substrates was assumed to be conducted by maize choppers and self-loading trailers, as is typical for silage production (Wernet et al., 2016). In the establishment year 2014, all biogas substrates were harvested in October. From the second year onwards, harvest in the WPM systems took place in August, while the harvest date for maize remained in October. In the maize BSPS, harvest was followed by stubble ploughing each year. For WPM, it was assumed that stubble ploughing took place after the last harvest in 2018 only to prepare the field for further cultivation. The agricultural procedures for the silage production are summarized in Table 2.

For this study, the average annual yields of the field trial cultivation period (2014–2018) were taken. These are given in Table 3, together with average methane yield and content of the biogas substrates.

Table 1: Summary of agricultural inputs. Yearly average over 5-year cultivation period

| Seed | WPM E1 | WPM E2 | Unit |
|------|--------|--------|------|
| Maize | 90 | — | 18 | 1,000 seeds ha$^{-1}$ × a$^{-1}$ |
| WPM | — | 2 | 2 | kg ha$^{-1}$ × a$^{-1}$ |
| Stomp Aquab | 2.00 | 0.40 | 0.40 | ha$^{-1}$ × a$^{-1}$ |
| Spektrumb | 1.00 | 0.20 | 0.20 | ha$^{-1}$ × a$^{-1}$ |
| MaisTer powerb | 1.00 | 0.20 | 0.20 | ha$^{-1}$ × a$^{-1}$ |
| Laudisb | 1.70 | 0.34 | 0.34 | ha$^{-1}$ × a$^{-1}$ |
| Buctrilib | 0.35 | 0.07 | 0.07 | ha$^{-1}$ × a$^{-1}$ |
| Nitrogena | 90.0 | 77.0 | 77.0 | kg N ha$^{-1}$ × a$^{-1}$ |
| Phosphorusa | 17.6 | 17.6 | 17.6 | kg P$_2$O$_5$ ha$^{-1}$ × a$^{-1}$ |
| Potassiuma | 35.2 | 35.2 | 35.2 | kg K$_2$O ha$^{-1}$ × a$^{-1}$ |

avon Cossel, Steberl, et al. (2019).
bKiesel et al. (2017).
TABLE 2 Summary of agricultural procedures. Yearly average over 5-year cultivation period

| Procedure       | Maize | WPM E1 | WPM E2 | Unit          |
|-----------------|-------|--------|--------|---------------|
| Ploughing       | 0.2   | 0.2    | 0.2    | procedures × ha⁻¹ × a⁻¹ |
| Stubble ploughing| 0.8   | 0.2    | 0.2    | procedures × ha⁻¹ × a⁻¹ |
| Rotary harrowing| 2.0   | 0.4    | 0.4    | procedures × ha⁻¹ × a⁻¹ |
| Sowing          | 1.0   | 0.2    | 0.4    | procedures × ha⁻¹ × a⁻¹ |
| Rolling         | 0.0   | 0.2    | 0.2    | procedures × ha⁻¹ × a⁻¹ |
| Herbicide spraying | 2.0 | 0.4 | 0.4 | procedures × ha⁻¹ × a⁻¹ |
| Fertilizing     | 1.0   | 1.0    | 1.0    | procedures × ha⁻¹ × a⁻¹ |
| Harvesting      | 1.0   | 1.0    | 1.0    | procedures × ha⁻¹ × a⁻¹ |
| Ensiling        | 1.0   | 1.0    | 1.0    | procedures × ha⁻¹ × a⁻¹ |

TABLE 3 Average yield data according to von Cossel, Steberl, et al. (2019)

| Crop          | Maize | WPM E1 | WPM E2 | Unit          |
|---------------|-------|--------|--------|---------------|
| DM yield      | 20.10 | 11.28  | 15.32  | t × ha⁻¹ × a⁻¹ |
| FM yield      | 56.53 | 29.10  | 34.71  | t × ha⁻¹ × a⁻¹ |
| CH₄ yield     | 6,376.38 | 2,694.63 | 3,800.60 | m³ × ha⁻¹ × a⁻¹ |
| CH₄ content   | 52.83 | 53.55  | 53.14  | %             |

It was assumed that the biomass from all cultivation systems is transported to a nearby (distance 10 km) farm by tractor. There, the biomass is first ensiled and then fed into the digester by means of a wheel loader (Wernet et al., 2016). These steps are assumed to be accompanied by a DM loss of 5%.

Fertilization is vital for biomass production and was conducted in the field trial by means of mineral fertilizers, and nutrient quantities applied are given in Table 1. As in practice, nutrients are usually supplied through fermentation residues, this procedure was assumed for the assessment. 100% of the potassium and phosphorus in the digestate were considered plant available, while it was only 60% for nitrogen. The difference between the plant available nutrients in the digestate (after spreading) and the amounts applied in the field trial was assumed to be covered by mineral fertilizers. The environmental impacts associated with the application of fermentation residues and mineral fertilizers were estimated using the following models. Nitrate emissions were calculated by the SALCA-NO3 model taking into consideration the monthly balance of N mineralization, N uptake by the crops, the risk of nitrate leaching from fertilizer application and the intensity of soil tillage (Richner et al., 2014). Ammonia emissions from the spreading of fermentation residues were calculated assuming a volatilization of 20% of the plant available nitrogen in the digestate (IPCC, 2006). Direct N₂O and NO emissions were based on IPCC (2006) and include indirect N₂O from harvest residues (IPCC, 2006). Phosphorus and phosphate emissions were calculated according to Nemeczek and Kägi (2007). It was assumed that the pesticides applied are released to agricultural soil (Wernet et al., 2016).

The cultivation of perennial plants on arable land can constitute a change of land use. Potential effects, such as changes in soil organic carbon content (SOC), need to be considered in bioenergy assessments (Agostini et al., 2019). Due to the unknown fate of the carbon stored in the soil, it is recommended that CO₂ removal through a change in SOC is shown separately in the results graphs (ISO 2018). The estimates of SOC changes used in this study were based on the Roth C model (Coleman et al., 1997). An initial field soil carbon content of 59 t carbon (C)/ha was assumed, which is representative of the regional conditions (Jacobs et al., 2018). The amounts of C added to the soil during the cultivation period (crop residues, root biomass) were estimated using data on carbon allocation in plants from a recent report by Jacobs et al. (2018). The considered carbon allocation factors are reported in Data S1. It was assumed that the biomass left on the field at the end of the cultivation period in 2018 remained there and was accounted as carbon input in the RothC model. In addition, the C input from fermentation residues was considered in all three systems. The calculation of the fermentation residues’ carbon content is described in Section 2.4.2. Main assumptions and detailed information on the SOC modelling are provided in Data S1.

2.4.2 Anaerobic digestion and electricity generation

The biomass yield data were complemented by data from laboratory analyses on the potential biogas yield and composition (CH₄:CO₂ ratio) of each substrate (Table 2). It was assumed that the substrates are anaerobically digested in a biogas plant with an electrical output of 500 kWh. Data for the infrastructure and related impacts of the anaerobic digestion plant were taken from the ecoinvent database (Wernet et al., 2016). Furthermore, it was assumed that the biogas produced is combusted in a combined heat and power generation unit with an electrical efficiency of 40% and a thermal efficiency of 43%. Emissions associated with the biogas combustion were modelled in accordance with ecoinvent standard processes (Wernet et al., 2016). It was assumed that 18% of the total heat and 10% of the total electricity production are used internally to cover the plant’s heat and electricity demand. The residual heat was assumed lost, although it could be used to supply nearby buildings. For this reason, additional results for the use of 50% of the remaining heat are reported in Data S1.

As mentioned above, it was assumed that fermentation residues are recycled to the fields. The mass of the residues was calculated as the mass of the substrate minus the mass
of biogas (CO₂ and CH₄) produced (Wernet et al., 2016). As explained above, it was assumed that phosphorus and potassium contents are unchanged by the fermentation process, but that only 60% of the nitrogen in the residues is available for plants (Giuntoli, Agostini, Edwards, & Marelli, 2017). Emissions from digestate storage were calculated according to EMEP/EEA (2013) for NH₃, NO and N and according to IPPC (2006) for N₂O. Emissions from the biogas combustion, including methane, N₂O and NOₓ, were modelled according to Wernet et al. (2016). Methane emissions from the biogas plant, including all production steps, were assumed as 2% of the total biogas production.

2.4.3 Fossil reference system

The marginal German electricity mix (Lauf, Memmler, & Schneider, 2019) was taken as fossil reference using standard ecoinvent inventory data (Wernet et al., 2016). In addition, a comparison with the European fossil fuel comparator is reported within a sensitivity analysis.

2.4.4 Life cycle costing

The total production costs of the electricity production, including biogas substrate production, anaerobic digestion, and the heat and power cogeneration, were calculated based on the LCC methodology (Swarr et al., 2011). All costs occurring over the 5-year cultivation period were accounted for. The system boundaries were the same as in the environmental assessment. For each substrate scenario, the following costs were taken into consideration: land rent, CAP contribution, costs of machinery, diesel, agricultural inputs (e.g. pesticides) and labour costs. For the land costs, average land rents for the studied region in southwest Germany of 270 €/ha were taken (Statistisches Landesamt Baden-Württemberg, 2017). Costs of machinery and diesel were based on the KTBL database (KTBL, 2019), while cost data for pesticides were taken from typical consumer sources. Labour costs of 17 €/hr were assumed as a representative average estimate for the German agricultural sector (Wagner et al., 2019).

For the biomass conversion process, costs for the construction of the biogas plant and the cogeneration unit were included, assuming an electrical plant output of 500 kWh. Maintenance and operating costs for both units were based on Leible, Kälber, Kappler, Oechsner, and Mönh-Tegeder (2015). Average labour costs of 17 € were assumed, similar to those for the substrate production. To include a temporal dimension, a discount rate of 6% was applied to discount all costs to their present value. Data S1 reports assumed costs, including corresponding references, as well as results of additional sensitivity analyses regarding the discount rate, heat use and land prices.

2.4.5 Sensitivity analysis

To assess the influence of certain important parameters on the final results of the environmental assessment, three sensitivity analyses were performed. Methane losses at combined heat and power plants vary widely (Liebetrau, Reinelt, Agostini, & Linke, 2017). To assess the sensitivity of the results with regard to this aspect, the first sensitivity analysis assumed increased methane losses. The second scenario assessed the result’s sensitivity to the fate of the carbon seques-trated in the cultivated soil. In the third sensitivity analysis, potential impacts of indirect land use change (iLUC) were assessed. Considering the required arable land per functional unit as well as the relative net primary productivity of this land, potential impacts from land use changes on a global level were assessed in line with Schmidt, Weidema, and Brandão (2015). Due to the major relevance of iLUC for GWP, the sensitivity analysis focused on this impact category only. Although the results will also be sensitive to other aspects, such as the choice of by-product and ammonia emissions from application of fermentation residues, these were not considered here as they do not influence the conclusions with respect to the ranking of the biogas substrates.

3 RESULTS

3.1 Life cycle impact assessment

The following sections present the potential environmental impacts of the electricity production scenarios assessed. All results are given per kWh of electricity produced, ready to be fed into the national grid. For each category, impacts were attributed to the following contributors: substrate production (silage production), related changes in soil carbon contents (dLUC), biomass transport, biogas and electricity production (biogas plant). In each category, the main drivers are identified and the alternative substrate scenarios are compared. In addition, the results of each impact category are compared to the fossil reference.

3.1.1 Global warming potential

The GWP results emphasize the importance of biogas production for the overall impacts. This phase represented the major contributor of impacts in all substrate scenarios (Figure 2a). Related emissions can mainly be attributed to methane emissions. Overall, WPM E2 had the lowest net impacts (78 g CO₂eq/kWh), followed by WPM E1 (183 g CO₂eq/kWh) and maize (236 g CO₂eq/kWh). Both WPM systems had higher impacts in the substrate provision phase than the maize system. The GWP of this phase was dominated by N₂O emissions from the nitrogen application and CO₂ emissions from the
harvesting procedures in all systems. For WPM E1 and E2, these additional impacts were counteracted by the carbon sequestration in the cultivated soil (dLUC), underlining the importance of dLUC considerations. It should be noted that the high dLUC contribution per functional unit in the WPM-based BSPS is also due to their lower productivity and thus higher land use (2.3 times the area of maize for WPM E1 and 1.5 times for WPM E2), which gives more room for soil carbon sequestration.

3.1.2 | Eutrophication potential (freshwater and marine)

Both freshwater (FE) and ME impacts were dominated by the substrate production (Figure 2b,c). This was more pronounced for ME (Figure 2c); for FE, some impacts were also related to biogas plant procedures (Figure 2b). Impacts from silage production were mainly due to phosphorus and nitrogen emissions from the application of fermentation residues and mineral fertilizers. Maize and WPM E2 had similar FE impacts, while those of WPM E1 were higher (Figure 2b). This was mainly due to the fact that the models for the phosphorus and phosphate emissions were predominantly based on the area considered, which was higher for the WPM E1 system. For ME, the WPM-based BSPS (WPM E1 and E2) were more favourable than maize (Figure 2c), mainly due to reduced nitrate losses over the cultivation period. This resulted from the constant vegetation cover, which prevents leaching during the growth period.

3.1.3 | Terrestrial acidification

Biogas and substrate production contributed an almost equally high share of the total acidification potential. Most of the impacts could be attributed to ammonia emissions associated with digestate storage and the application of fermentation residues. The lower land use efficiency of WPME E1 led to higher ammonia emissions and consequently higher impacts in the silage production than for WPM E2 and maize.

3.1.4 | Fine particulate matter formation and ozone formation

As with TA, the results for PM were dominated by the secondary aerosol ammonia. Particulate matter emitted by agricultural machinery contributed some additional PM impacts. Most of the OF impacts were due to the emission of nitrogen oxides from these machines. In sum, more than two-thirds of both the PM and OF impacts could be traced back to the agricultural stage.
Comparison of biogas options with fossil reference

Figure 3 presents the comparison of the environmental impacts of the biogas systems assessed with those of the marginal German electricity mix. The biogas systems were clearly able to contribute to the mitigation of global warming impacts under the conditions and assumptions of the study. The GWP of maize, WPM E1 and WPM E2 were 24%, 19% and 8% those of the marginal electricity mix. Similarly, the bioenergy systems resulted in lower impacts for FE and OF than the fossil reference, which had substantial impacts from lignite mining and combustion. By contrast, the fossil systems fared better in the other impact categories assessed (ME, TA and PMF). Taking all impact categories together, the biogas alternatives were clearly more favourable in terms of GHG emission mitigation, FE and OF, but these reductions come at the expense of additional burdens in three other impact categories.

3.2 Life cycle costing

Figure 4 presents the total costs of electricity production in the biogas systems assessed. In general, the results reflect the yield differences between the biogas substrate systems. Maize was the cheapest option at 0.138 €/kWh, followed by combined maize and WPM cultivation at 0.143 € (WPM E2). The standard WPM system (WPM E1) was the most expensive at 0.156 € (Figure 4). The costs of biomass supply accounted for less than of the total costs in the WPM systems, with harvesting procedures having the most influence. This was also due to the lower specific methane yield of WPM. In addition, land costs were responsible for almost a quarter of the biomass supply costs for WPM systems, while for maize, these accounted for less than 20%, harvesting and pesticide application being the major cost driver. Accordingly, higher land costs would have a much stronger effect on WPM systems due to their less efficient use of agricultural land.
3.3 | Scenario analysis

Three sensitivity analyses were performed varying (a) methane emissions at the biogas plant, (b) the duration of carbon storage and (c) the potential influence of iLUC considerations.

3.3.1 | Methane emissions at the biogas plant

In the baseline scenario, methane emissions at the biogas plant were assumed as 2% of the total production. According to Liebetrau et al. (2017), methane emissions can vary immensely and thus strongly affect the comparison of the biogas alternatives with electricity production from fossil resources. An increased methane loss of 4% led to a surge of the total GWP by 46%, 59% and 134% for maize, WPM E1 and WPM E2, respectively (Figure 5). Despite these increased emissions, the biogas systems still performed more favourably in terms of GWP than the fossil references—GHG emissions were at least 65% lower than for the marginal German electricity mix. However, it needs to be noted that under the high-methane-emission scenario only WPM E2 would achieve a 70% reduction based on the fossil fuel comparator as suggested by the EU (SWD258, 2014).

Duration of soil carbon sequestration

In the results presented above, the GWP favourability of WPM E1 and E2 in comparison with maize very much depended on the soil carbon sequestration. The assessment was based on the assumption that the carbon sequestered during the cultivation period would be indefinitely withdrawn from the atmosphere. In reality however, the fate of the carbon would strongly depend on the consecutive cultivation techniques and systems. For this reason, it was tested how the length of the carbon storage influences the overall GWP results. This was achieved by considering soil carbon sequestration as a temporary storage only. Storage periods between one and 100 years were tested by the introduction of correction flows for delayed emissions, as suggested in ILCD (2010). Figure 6 depicts the potential GWP impacts of the maize, WPM E1 and WPM E2 systems plotted against the length of time the carbon is stored in the soil. Based on this assessment, it can be concluded that the full amount of carbon needs to remain in the soil for at least 51 years for WPM E1 and 17 years for WPM E2 to ensure lower GWP impacts than maize (Figure 6).

Effects of potential indirect land use changes

It has been shown that iLUC can strongly influence impact assessment results of agricultural product systems. The potential additional impacts for GWP when these effects were included in our study are shown in Figure 7. The iLUC impacts accounted for a substantial share of the overall GWP results. They were quantified in accordance with Schmidt and Muños (2014) and included the transformation of land not used as cropland (34.5%) and the intensification of land already in use (65.5%). Impacts of the intensification comprised the additional consumption of nitrogen fertilizers and the associated N₂O emissions according to IPCC (2006). As the results were highly sensitive to whether iLUC impacts occur or not, this aspect is crucial for decision support. For WPM E1, the inclusion of iLUC effects results in substantially higher impacts than for the more productive biogas substrate maize. This is due to the extensive land use (maize: 0.372 m²/kWh; WPM E1: 0.892 m²/kWh) and thus greater

![Figure 5](https://example.com/figure5.png) Global warming potential (GWP) of generation of 1 kWh produced from maize, wild plant mixtures (WPM), and two fossil references: Marginal German electricity mix (Lauf et al., 2019) and European Union’s fossil fuel comparator (SWD258, 2014). For biomass systems, low methane emissions (2% of methane production; low methane emissions) as well as higher methane emissions (4% of methane production; high methane emissions) were compared.
land use transformation and intensification of WPM E1. If the potential iLUC impacts are factored into the extent assumed, they could outweigh the carbon sequestration related to the direct LUC. However, even under this assumption, WPM E2 would result in a lower GWP than maize and WPM E1.

4 | DISCUSSION

This study assessed the environmental and economic performance of a potential path for the extensification of biogas production by the replacement of the conventional biogas substrate maize (Z. mays L.) with perennial WPM. Two establishment approaches for WPM were assessed: (a) a standard procedure for WPM alone (WPM E1) and (b) WPM undersown with the use of cover crop maize (WPM E2). First, the results of the environmental assessment are critically reviewed with respect to the main contributors and sensitivity considerations. Second, potential methodological shortcomings are discussed, which may affect the decision between the extensive WPM system and maize for use as biogas substrate. Finally, the economic perspective is included to identify the conditions under which WPM cultivation could be a promising alternative to conventional biogas substrates.

4.1 | Environmental performance

The results of the environmental analysis reveal that both the maize and the two WPM systems have a better performance than the fossil reference in the impact category GWP. This observation is in line with other studies on alternative biogas substrates (e.g., Kiesel et al., 2017; Wagner et al., 2019). Judging from the results of the baseline scenario alone, WPM E2 appears to be a better option in the assessed categories as it represents a good combination of the advantages of the mono-cropped maize and WPM systems. The results emphasize the importance of both biomass and methane yields in all impact categories, and this is also one of the reasons why WPM E2 is more favourable than WPM E1 in the assessed impact categories. This finding is in line with similar studies on bioenergy, which highlight the importance of biomass yield (Lask, Wagner, Trindade, & Lewandowski, 2019; Meyer, Wagner, & Lewandowski, 2017; Wagner et al., 2019). The advantages of perennial systems with regard to the nitrate leaching risk become apparent when considering ME. In this impact category, WPM E1 and WPM E2 have substantially fewer impacts than the maize system.
The importance of land use change factors needs to be emphasized in the comparison of the maize and WPM systems, as the cultivation of perennial crops can have a tremendous influence on the soil carbon stock. In general, including dLUC benefits the environmental performance of the WPM biogas systems in terms of GWP. Per se, environmental impacts from the substrate production of WPM E1 and E2 are higher per functional unit than for maize, but these effects are outweighed by soil carbon sequestration. It should be noted that soil carbon dynamics very much depend on site-specific characteristics (e.g. initial SOC content, clay content, former land use) and on the modelling approach (Harris, Spake, & Taylor, 2015). The present study relied on RothC simulations, which use site-specific data on climate, soil features and carbon input. For these reasons, it is considered a more reliable approach than, for instance, the default emission factors proposed in the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) commonly applied in LCA (Peter, Fiore, Hagemann, Nendel, & Xiloyannis, 2016). Calibration of the model using SOC data representative of multi-annual WPM cultivation could further improve its reliability. In addition, the fate of the sequestered carbon is uncertain; it could be released with the subsequent land use and thus become GWP relevant again. As shown in the scenario analysis (Figure 6), the soil carbon sequestration would need to be ensured over at least 51 and 17 years, respectively, to render WPM E1 and WPM E2 valid alternatives to maize in terms of greenhouse mitigation. However, WPM cultivation systems could be particularly advantageous if planted on degraded lands with low SOC, since they can effectively increase the local soil carbon content.

The sensitivity analysis on the methane emissions at the biogas plant showed their strong influence on the absolute GWP of the systems under consideration. It was shown that, even under the assumption of higher methane emissions, electricity produced from the biogas substrates analysed can contribute to GWP mitigation when replacing the marginal German electricity mix. The comparison with the EU fossil fuel comparator underlines however that the substrates should ideally not be digested alone but rather in combination with manure, as has previously been suggested (Agostini et al., 2015).

The consideration of iLUC impacts that may arise due to a substrate change is also of high relevance. The third sensitivity analysis emphasized the importance of acknowledging related risks in the decision-support scheme. Although these impacts are highly uncertain, the magnitude of their implications for GWP justifies their inclusion in the environmental assessment. Although modelling approaches for iLUC impacts vary widely, the iLUC results of this study are in line with other studies on agricultural produce such as wheat, maize silage, barley and milk products (Brinkman, Wicke, & Faaij, 2017; Chobtang, McLaren, Ledgard, & Donaghy, 2017; Gerssen-Gondelach, Wicke, & Faaij, 2017; Schmidt & Muños, 2014). The sensitivity analysis applied in this study focused primarily on GWP impacts. However, iLUC and related land-transforming activities could also have impacts on the soil and habitat quality of the affected areas, and this should be addressed in future research (Gerssen-Gondelach et al., 2017). The consideration of iLUC impacts in this study is based on the assumption that the increase in land demand is entirely met by transformation of land and intensification of arable land use. However, it should be noted that a decline in German biogas production is expected in the near future. This is due to the withdrawal of political incentives, which will eventually result in a lower demand for biogas substrates and thus arable land for this application. It could be argued that the higher amount of land required for the WPM cultivation in comparison to maize could be partially offset by a reduction in demand. However, if this does not materialize, additional effects need to be considered and these are reviewed in the last section of the discussion.

### 4.2 Potential methodological shortcomings

Biodiversity conservation is one of the major arguments in favour of WPM cultivation as the local biodiversity could substantially benefit from the provision of habitat, breeding space and feed for open-land birds and small game (von Cossel, Steberl, et al., 2019). This is in line with the general recognition that perennial second-generation bioenergy crops tend to contribute positively—or at least less negatively—to biodiversity conservation than first-generation bioenergy crops such as maize (Immerzeel, Verweij, van der Hilst, & Faaij, 2014). At the same time, it should be noted that the expansion of arable land is the most pressing threat to biodiversity conservation on a global scale (Ceballos et al., 2015). In this study, the risks associated with iLUC were only assessed with respect to GWP. However, they also need to be acknowledged for biodiversity aspects. This is of particular relevance since iLUC effects are likely to take place in locations of higher biodiversity potential. It is important that local biodiversity conservation in European agricultural landscapes is not counteracted by global effects. Unfortunately, conventional LCA frameworks do not consider these aspects sufficiently. In recent years, a number of methods have been proposed (Winter, Lehmann, Finogenova, & Finkbeiner, 2017) but these are only rarely used and still need to be validated for perennial crops such as WPM. Similar to biodiversity, soil health and quality aspects—advantages of WPM systems—are commonly overlooked in LCA practice. In particular for WPM systems containing legumes, aspects such as potential soil quality improvement need to be considered.
4.3 Economic aspects

It can be concluded from the economic analysis that, of the systems assessed, the conventional biogas substrate maize is the cheapest option for the farmer, who is ultimately the decision-maker. The lower costs for maize are mainly due to the high biomass productivity, which results in low farm-gate production costs of 25.65 € per t fresh matter, compared to 27.71 € for WPM E1 and 25.65 € for WPM E2. The figures for maize are substantially lower than those previously reported for silage production in northern Italy (Agostini et al., 2016), mainly due to differences in the costs taken into account for agricultural procedures. The WPM E1 and E2 costs are comparable to German figures for miscanthus (24.2 € per t fresh matter; Wagner et al., 2019).

The total costs of electricity generation per kWhel produced are 0.138 € for maize, 0.156 € for WPM E1 and 0.143 € for WPM E2, which corresponds to 38.45 €, 43.42 € and 39.72 € per GJel, respectively. For WPM systems in particular, land costs are the major contributor. The land rents assumed in this study are average values for the German federal state of Baden-Württemberg, but in typical biogas regions land costs are usually significantly higher than the average at 750 €/ha (Statistisches Landesamt Baden-Württemberg, 2017). The assumption of these higher values would widen the economic imbalance between the systems with the costs of the alternative systems exceeding maize (0.158 €) by 28% (WPM E1: 0.202 €) and 11% (WPM E2: 0.175 €; Figure S4). Consequently, a switch to WPM systems in these regions cannot be recommended to the farmer from an economic point of view, if no political incentives are in place and only direct costs are accounted for. This becomes even more apparent when the German legislation on renewable energy is considered. Plant operators receive up to 0.1690 €/kWh if their plant (>150 kW) was operational before 2017. For newer plants, a maximum value of 0.1488 €/kWh was set for 2017 with a yearly decrease of 1%. This compares to the 0.2500 €/kWh guaranteed in the first phase of the biogas-supporting schemes in Germany (Renewable Energy Sources Act, 2014).

4.4 Wild plant mixtures: A sustainable, alternative biogas substrate? Conditions and requirements

The environmental assessment reveals the higher-yielding WPM E2 system as the more promising of the extensive systems in terms of the categories considered here. However, its economic performance is still lower than that of the maize system. Thus, agricultural practices for WPM cultivation need further optimization. The importance of finding alternative biogas substrates such as WPM is highlighted by the requirements of the German renewable energy legislation, which aims at a continuous decline in the share of maize in the overall feedstock composition. From 2021 on, the maximum proportion is set at 44% of maize silage, compared to 69% in 2016 (FNR, 2019). Further improvement of the WPM systems seems feasible, as these predominantly contain undomesticated species, which have not been the subject of breeding efforts (Kuhn, Zeller, Bretschneider-Herrmann, & Drenckhahn, 2014; Schmidt, Lemaigre, Delfosse, von Francken-Welz, & Emmerling, 2018). However, maize would still be the more economic biogas substrate. The maize yield (20.1 t DM/ha) in the present study is rather high, exceeding the regional average of 15.8 t DM/ha by more than 25% (Statistisches Landesamt Baden-Württemberg, 2020). When comparing the biogas substrates, it is worth noting that the WPM E1 yield (11.3 t DM/ha) exceeded yields of other WPM cultivation trials in southern Germany (8.9 t DM/ha) by a similar percentage (Vollrath et al., 2016). As the yields of both biogas substrates were on an equally high level, the conclusions regarding the feedstock comparison can be considered robust. In general, lower yields, in practice, would result in higher environmental impacts and costs than reported in this study. The maize system assessed in the here achieved these high DM yields under moderate N inputs of 90 kg/ha, resulting in lower environmental impacts for the maize silage than in comparable studies. For instance, Kiesel et al. (2017) reported DM yields of 18.9 t when applying 240 kg N/ha under similar conditions. Likewise, the ecoinvent process for the integrated production of silage maize in Switzerland (Wernet et al., 2016) suggests DM yields of 17.2 t can be achieved with fertilizer inputs of 98 kg N/ha.

Yields are also important in determining the amount of land required for the production systems under assessment, with the WPM systems requiring substantially larger areas. This could lead to additional greenhouse gas emissions as a result of a geographical shift of agricultural production, as reported in the iLUC scenario analysis. The scenario analysis showed that these effects could partially outweigh the reported carbon-related advantages of the WPM systems such as increased soil carbon accumulation. Accordingly, critical assessment of WPM cultivation, including the handling of potential iLUC effects, is crucial for it to be able to offer a favourable alternative to maize in terms of greenhouse gas mitigation.

A range of iLUC mitigation measures, such as the use of marginal land, have been discussed in the literature (Wicke et al., 2015). In general, marginal lands are characterized by a number of limitations that constrain agricultural productivity. The total marginal agricultural land area in Europe has been estimated at 464,833 km² (von Cossel et al., 2019). The cultivation of WPM on such land is considered feasible and would benefit from the substantial potential for adaptability, stress resistance and resilience...
achieved through the wide range of plant species in the seed mixtures. Once established, the deep rooting systems and perennial nature of WPM provide an advantage over maize and allow successful adaptation to the conditions characterizing marginal agricultural lands (Vollrath et al., 2012; von Cossel & Lewandowski, 2016). Degraded land could considerably benefit from the effective soil-carbon build-up in WPM cultivation systems, thus contributing to the capture of CO₂ from the atmosphere. WPM could likewise be used in strip cultivation or buffer systems, as already suggested for other perennial crops (Ferrarini, Serra, Almagro, Trevisan, & Amaducci, 2017). The perennial polycultures could also meet the requirements of ecological focus areas in the near future. In all these situations mentioned above, the agricultural system could benefit from the advantages of WPM cultivation, including carbon storage, biodiversity conservation, reduced nutrient leaching and other ecological services at landscape level.

The electricity generation from biogas produced from WPM resulted in lower impacts than for maize in two of the six impact categories assessed. The maize system seems more favourable from an economic perspective, which is a major decision criterion for farmers. It has been suggested that the goal of using WPM for biogas production is not to achieve the same level of productivity as maize, but to justify a change of feedstock through a combination of economic and environmental factors (Vollrath et al., 2012). Nevertheless, under current conditions, the adoption of WPM cultivation should only take place if long-term soil carbon sequestration can be ensured. In addition, large-scale adoption of stand-alone WPM cultivation should not take place on good quality land but should instead be reserved for low-yielding land. This recommendation needs to be emphasized where deployment would result in a geographical shift of agricultural production, as shown in the iLUC scenario analysis. The uncertainty in dLUC considerations and the potential occurrence of iLUC impacts could affect the relative ranking of the GWP results, underlining the importance of acknowledging these aspects in the assessment of agricultural extensification strategies. The adoption of WPM systems will most likely depend on the management of soil carbon storage as well as of the trade-offs between iLUC-associated risks and higher costs, which are ultimately related to the question of productivity. Agricultural biogas facilities in Germany usually use a substrate combination of energy crops and manure. WPM from non-cultivated, marginal agricultural land, ecological focus areas and buffer strips could complement substrate mixes, while enriching agricultural landscapes.

**DATA AVAILABILITY STATEMENT**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

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

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