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Greenhouse gas emission of biogas production out of silage maize and sugar beet – An assessment along the entire production chain

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HIGHLIGHTS

- GHG-emission, bioenergy yield, GHG-saving potential based on field trial data.
- Results complement the absence of default values, especially for sugar beet.
- Results represent Central European conditions of crop and biogas production.

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ABSTRACT

The study delivers values on greenhouse gas (GHG)-emission via cultivation of silage maize and sugar beet and of GHG-saving potential of electricity produced from biogas out of both biomass crops. Data are based on three rainfed crop rotation field trials in Germany (2011–2014) representative for Central Europe and can serve as default values. It was found that GHG-emission via crop cultivation was driven mainly by nitrous oxide emission from soil and mineral N-fertilizer use and was 2575–3390 kg carbon dioxide equivalents (CO_2eq) per hectare for silage maize and 2551–2852 kg CO_2eq ha^{-1} for sugar beet (without biogas digestate application). Integrating a GHG-credit for surplus N in the biogas digestate reduced total GHG-emission via crop cultivation to 65–69% for silage maize but only to 84–97% for sugar beet. The GHG-saving potential of electricity production from biogas was calculated for three biogas plants differing in technical characteristics. The GHG-saving potentials were generally >70% (silage maize: 78–80%, sugar beet: 72–76%) and the authors concluded that the technical setting of the biogas plant had a slight impact only. Overall, the authors assumed that the major potential for GHG-emission's reduction along the bioenergy production chain were N-management during crop cultivation and methane losses at the biogas plant. Finally, sugar beet, if cultivated in crop rotation, was shown to be an efficient alternative to silage maize as a biomass crop in order to achieve a higher diversity in biomass crop cultivation.

1. Introduction

By the year 2020, 20% of the total energy production in the European Union is to be from renewable resources. Biogas, as ane technology of a high importance in Germany [1,2], is mainly produced under agricultural circumstances and, currently, 52% of the mass of substrate used for biogas production are renewable primary products, including arable crops [3]. One of the major environmental impacts of arable crop cultivation is the emission of climate relevant gases (greenhouse gases = GHG). Among others, the main relevant GHG in this

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context are CO_2, CH_4, and N_2O. Carbondioxide is mainly emitted via the production and application of agronomic means during crop cultivation (fertilizer, diesel etc.) [4]. The main sources for CH_4 and N_2O are animal husbandry (including manure storage) and denitrification processes in soil, respectively. Thus, the agronomic management chosen strongly determines the GHG-emission and the environmental impact of crop cultivation [5]. Further, site-specific characteristics, such as climate conditions, soil properties, socio-economical structure of the farm, and agricultural legislation are of concern. Especially for the cultivation of arable crops which serve for biogas production (biomass crops), the accounting of GHG-emission is a key factor since the major goal of bioenergy production is to reduce GHG-emission. When accounting the GHG-emissions, two steps of the bioenergy production chain are of concern: (i) the GHG-emission via crop cultivation and the respective biomass crop's yield and (ii) the GHG-emission and the energy loss through the conversion process at the biogas plant. They both merge into the aggregated GHG-intensity (ratio of GHG-emission to energy yield) of the entire bioenergy production chain and the GHG-saving potential in comparison to a fossil energy source [6]. The GHG-saving potential of electricity, heating, or cooling from biogas is expressed as a percentage related to the same energy form but gained from a fossil source and needs to reach a certain threshold [7]. The latter was recommended to be the same than for bioliquids and biofuels [7] as it currently is at 35% but will increase to 50% in 2017 and 60% in 2018 [8]. However, the European Commission stated that 70% GHG-saving is desirable as a standard of 'good practice' for bioenergy production from biogas [6].

Nowadays, silage maize is the most important biomass crop in Germany with a share of 73% [6] but also stated for Austria by Bauer et al. [9] and the high acreage of its cultivation provokes social and ecological problems on the regional and on the arable field scale [10–12]. Thus, there is a strong call for alternatives which increase the diversity of biomass crops but achieve a similar GHG-saving potential as silage maize [6,12,13]. Sugar beet (*Beta vulgaris* L.) root was reported to have a CH_4-yield potential close to silage maize [14–17]. Moreover, sugar beet needs to be cultivated in crop rotations, classically with cereals, and can thus further increase the diversity of biomass crop cultivation systems.

There is limited data on GHG-emission from the biogas production chain which can serve as defaults. Those which are available [7,18] do not consider site-specific circumstances, such as yield level, cultivation management, biogas plant characteristics, and, concerning biomass crops, are focused on silage maize (*Zea mays* L.). However, Felten et al. [19] and Claus et al. [20] published respective data for individual production systems in Germany but, anyway, limited to silage maize. Moreover, no scientifically reliable data on the aggregated GHG-intensity and the GHG-saving potential of bioenergy from biogas out of sugar beet root are available, neither for Germany nor for Central Europe. In order to close these research gaps and to provide reliable default values, the aims of this study were (i) to quantify the GHG-emission via the cultivation of silage maize and sugar beet based on reliable data of crop rotation field trials in Germany and (ii) to calculate the aggregated GHG-intensity and the GHG-saving potential of the entire production chain of electricity production from biogas subject to different feedstock compositions with silage maize and sugar beet. The authors thereby provide a concept of GHG-accounting respecting site-specific aspects such as the crop's yield level, the cultivation management, and the biogas plant's characteristics. Further, this study gives implication on potentials of increasing the GHG-saving potential.

2. Materials and methods

2.1. Site-specific data basis

Data of three field trials in Aiterhofen (Luvisol; 48°85′ N, 12°63′ E; Bavaria), Harste (Luvisol; 51°61′ N, 9°86′ E; Lower Saxony), and Etzdorf (Haplic Chernozem; 51°43′ N, 11°76′ E; Saxony-Anhalt) in Germany of the years 2011–2014 were evaluated. Experimental details are found in Brauer-Siebrecht et al. [17]. All sites were of a silt loam soil texture, had a mean temperature of >8.5 °C, a yearly precipitation of >450 mm, and were not irrigated. The soil nutrient status differed between sites. Silage maize and sugar beet were cultivated in different cultivation systems (crop rotations, continuous cultivation) but were not orthogonally replicated across sites (Table 1). All crop rotation elements were cultivated every year on a separate plot per field replication. Continuous cultivation occurred every year on the same plot. In Aiterhofen and Etzdorf, there were four field replications and in Harste, there were three. Field replications apply for the yield of the crops only.

Plots were of 420 m^2 in Aiterhofen, 230 m^2 in Harste, and of 70 m^2 in Etzdorf. The agronomic management (e. g. variety, fertilizer strategy) followed the respective site-specific recommendations (for details, see [17]).

The continuous cultivation of sugar beet, as done here in Etzdorf, generally has no practical relevance and is to be interpreted here with an explicit experimental background: Sugar beet root yield showed a strong decrease during field trial conduction [17] and indicates the relevance of a proper agronomic management also for bioenergy production purpose.

The maximum attainable energy yield was estimated as the CH_4-yield per dry matter yield of silage maize and sugar beet root as described by Brauer-Siebrecht et al. [17]. The CH_4-yield was multiplied by the energy content of 35.9 MJ Nm^{-3} [21]. Maize stubbles, beet leaves and belowground residues were not considered as energy yield since they remained in the arable field for soil fertility purposes. As the mean value of crop rotation elements, field replicates, and years (2011–2014; data not shown, see Table 1), the specific CH_4-yield of silage maize was 341 $Nm^3\,Mg^{-1}$ dry matter (Aiterhofen), 335 $Nm^3\,Mg^{-1}$ dry matter (Harste), and 333 $Nm^3\,Mg^{-1}$ dry matter (Etzdorf); of sugar beet root, it was 347 $Nm^3\,Mg^{-1}$ dry matter (Aiterhofen), 346 $Nm^3\,Mg^{-1}$ dry matter (Harste), and 345 $Nm^3\,Mg^{-1}$ dry matter (Etzdorf).

2.2. System boundary 'crop cultivation': Calculation of greenhouse gas emission

For the accounting of the GHG-emission via crop cultivation, the spatial system boundary was outlined as follows: it included the production of agronomic means, their transportation to the farm and further to the arable field as well as all agronomic operations in the field. Further, GHG-emission developed in the field as well as the transportation of the crops to the biogas plant and the backward transportation of biogas digestates were contained. The temporal system boundary was one crop cultivation season starting with the first agronomic operation after the preceding crop's harvest and ending with the harvest of the crop investigated. The functional unit was the GHG-emission, as kg CO_2 equivalents (CO_2-eq) per hectare and year where one year was equivalent to one crop cultivation season.

The GHG-emission was calculated following the field trials' documentation (application of agronomic means) which needed to be modified in terms of machinery used and arable field size in order to be in line with real region-specific cultivation situations (for further details, see [22]). The application of agronomic means was then allocated to the default values provided in the database