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Replacing silage maize for biogas production by sugar beet – A system analysis with ecological and economical approaches

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ABSTRACT

In a holistic methodological approach, we linked field trial data with different modeling approaches to answer the question if sugar beet roots offer an ecological and economical efficient alternative to silage maize as a substrate for biogas production. Field trials were conducted at highly productive sites in Germany, representative for Central Europe, and tested both biomass crops in continuous cultivation and in crop rotations with winter wheat. In these trials, estimated methane yield of silage maize was generally higher (6837 to 8782 $Nm^3\ ha^{-1}\ a^{-1}$) than of sugar beet roots (3206 to 7861 $Nm^3\ ha^{-1}\ a^{-1}$) and both biomass crops reached highest yield in crop rotations. Under the nonobservance of technical effects, substrate production costs (€ per Nm^3 methane) were higher for sugar beet roots and a nationwide modeling showed that, in most of the German districts, it would need to be reduced by 10 to 25% in order to reach economical competitiveness with silage maize. However, at a farm level, sugar beet for biogas production was economically advantageous when introduced with a share of 10 to 16% into the individual farm's cultivation program mainly due to high yield stability reducing the economical risk. However, a decrease in gross margin (€ ha^{-1}) was likely to occur. In the field trials, different ecological impacts of crop cultivation were assessed but did not highlight one of the two biomass crops in comparison. However, it was evident that cultivating them in three years long crop rotations with two years of winter wheat provoked lower risks of loss of soil organic matter (−122 to −20 kg humus-C $ha^{-1}\ a^{-1}$) or N-leaching (40 to 62 kg N ha^{-1} in three years) than in continuous cultivation. In contrast, the continuous cultivation of silage maize and sugar beet showed lower greenhouse gas emission (7652 to 11,074 kg C-dioxide-equivalents ha^{-1} in three years) than the crop rotations with winter wheat. Overall, we conclude that sugar beet roots can offer an efficient alternative to silage maize as a substrate for biogas production. However, to raise sugar beet's competitiveness, dry matter yields should be increased without increasing production costs and ecological impacts.

1. Introduction

The European Union set itself the goal to produce 20% of the total energy production from renewable resources by 2020. One technology used among member states is the production of biogas, especially in Germany with about 3905 MW installed capacity followed by Italy with 1000 MW (Bacenetti et al. 2016; EurObserv'er, 2014). A current survey for Europe categorized 81% and 82% of the German and Italian, respectively, biogas plants to be of an agricultural type (European Biogas Association, 2015). In Germany, 52% (mass related) of the substrate used for biogas production was classified as renewable primary products which includes arable crops (DBFZ, 2015). Like all arable systems, the production of biogas from biomass crops needs to reach economical, ecological, and social standards in order to contribute to a sustainable development of energy production (European Commission, 2010; Tilman et al., 2002). This target applies for the entire production chain including the field and its cultivation system, the agricultural farm, and the biogas production itself. However, it is debatable if the sustainability of a production chain is scientifically measureable

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due to various scales, system boundaries, functional units, and trade-offs between variables measured (van Ittersum et al., 2008; Tilman et al., 2002). Moreover, policy decisions, e. g. concerning the development of bioenergy production in the European Union Member States, risk to be led by simplifications and to ignore local or farm's circumstances (Plevin et al., 2014). Nevertheless, among others, the German government pointed out some criteria in the Biomass Action Plan (BMU and BMELV, 2009) which are, so far, not legally binding. These sustainability criteria which the biogas production, including the biomass crop cultivation, should achieve are: Viable and secure energy supply, (local) employment and value creation, socio-economical development of developing countries, avoidance of conflicts with e. g. food production as well as with conservation of biodiversity, soil fertility, and valuable landscapes, prevention of water and air pollution, and reduction of greenhouse gas emission (BMU and BMELV, 2009). Even if the current amendment to the German law on renewable energy (EEG; Anon., 2014) aimed to significantly reduce the use of biomass crops for biogas production, there will be still a significant portion of biomass crops used in those biogas plants which started operating before this latest amendment. However, the biomass crop cultivation needs to be as efficient as possible in order to be competitive with food production and fossil fuels (Patterson et al., 2008).

At present, silage maize (*Zea mays* L.) is the most important substrate among the renewable primary products for biogas production in Germany as reported with a share of 73% in a nationwide survey (DBFZ, 2015) but also stated for Austria by Bauer et al. (2010). The reasons are a high yield, low production costs (Wünsch et al., 2012; Graebig et al., 2010), and uncomplicated cultivation management. The high acreage of its cultivation, currently around 894,000 ha in Germany (FNR, 2015), is linked to a trend of cultivating silage maize continuously on one field (continuous cultivation). Several reviews (Karpenstein-Machan and Weber, 2010; Ruppert et al., 2013; Zegada-Lizarazu and Monti, 2011) already discussed the various social and ecological problems coming along with continuous cultivation systems, as loss of biodiversity (Sauerbrei et al., 2014), of soil health, and of biomass yield (Nevens and Reheul, 2001). This clearly contradicts the above mentioned sustainability criteria. Thus, there is a call for alternative substrates which increase the biodiversity of biomass crop cultivation systems and, at the same time, achieve a similar, or even higher, energy and economical efficiency without increasing environmental impacts (Amon et al., 2007a; Zegada-Lizarazu and Monti, 2011). Sugar beet (*Beta vulgaris* L.) is a high yielding crop with a high content of easily fermentable carbohydrates (Starke and Hoffmann, 2011) and has, therefore, a high potential as a substrate for biogas production (Sieling et al., 2013; Starke and Hoffmann, 2011; Weiland, 2010). Currently, sugar beet hold a share of 2% (DBFZ, 2015) on the substrates for biogas production in Germany. Moreover, sugar beet needs to be cultivated in crop rotations, classically with cereals. This offers the opportunity to diversify biomass crop rotations by the combination with food production which increases the flexibility of the farmer and reduces the competition for productive land. However, scientific approaches investigating sugar beet roots as a substrate for biogas production are very rare. Further, to the best of our knowledge, assessments of the entire production chain, including the crop's cultivation system, were not done so far.

Our joint project ('The sugar beet as an energy crop in crop rotations on highly productive sites – an agronomic/economic system analysis') posed the question if and where sugar beet roots as a substrate for biogas production offer an ecological and economical efficient alternative to silage maize. Within five subprojects (Jacobs et al., 2014), we implemented a holistic systematic methodological approach linking reliable data from field trials with different modeling approaches focusing on district-specific yield levels, individual farms, and biogas plants in Germany. The aim of this paper was to integrate the results into an interdisciplinary and multi-level assessment in order to give a broad view on pros and cons of using sugar beet roots as a substrate for biogas production. In detail, we compared (i) the methane yield and (ii) the substrate production costs of both biomass crops in field trials and in a nationwide modeling, respectively. (iii) Moreover, we assessed the economical consequences of introducing sugar beet for biogas production into the cultivation program of a farm. (iv) We further evaluated the ecological impacts of biomass crop cultivation on soil fertility (soil organic matter, soil compaction risk), N-leaching, and greenhouse gas (GHG)-emission in the field trials.

2. Materials and methods

As a reliable database, we used three field trials located on highly productive sites in different Federal States of Germany, representative for high yield potentials under rainfed conditions in Central Europe: (i) Aiterhofen (Luvisol; 48°85′ N, 12°63′ E; Bavaria), (ii) Harste (Luvisol; 51°61′ N, 9°86′ E; Lower Saxony), and (iii) Etzdorf (Haplic Chernozem; 51°43′ N, 11°76′ E; Saxony-Anhalt) all conducted from 2010 to 2014 (Fig. 1). All sites had a silt loam soil texture, mean temperature of > 8.5 °C and a precipitation of >450 mm (DWD, 2014; own data). Organic C content of the soils were (measured in 0 to 30 cm in 2010) 1.0% (Aiterhofen), 1.3% (Harste), and 1.9% (Etzdorf), respectively. Further exact values on e. g. field size, nutrient contents in soil are given in Brauer-Siebrecht et al. (2016). Silage maize and sugar beet were cultivated in crop rotations with winter wheat (*Triticum aestivum* L.) and in continuous cultivation which enabled us to investigate the entire cultivation system as well as the single crop apart from rotational effects: (i) continuous cultivation of silage maize (Aiterhofen, Harste, Etzdorf), (ii) continuous cultivation of sugar beet (Harste, Etzdorf), (iii) (catch crop: mustard; *Sinapis alba* L.) - silage maize - winter wheat - winter wheat (Aiterhofen, Harste), (iv) (catch crop: mustard) - sugar beet - winter wheat - winter wheat (Aiterhofen, Harste), and (v) (catch crop: mustard) - silage maize - sugar beet - winter wheat (Aiterhofen, Harste). All crop rotation elements were cultivated each year. Number of field replicates was four in Aiterhofen and Etzdorf and three in Harste. The agronomical management (e. g. varieties, fertilizer strategies) followed the respective site-specific recommendations. Amounts of mineral N-fertilizer varied across years and crop rotations and ranged as follows (2010 to 2014): (i) Aiterhofen: silage maize: 180 to 255 kg N ha^{-1}, sugar beet: 80 to 160 kg N ha^{-1}, winter wheat: 180 to 235 kg N ha^{-1}, mustard: 40 kg N ha^{-1}; (ii) Harste: silage maize: 105 to 145 kg N ha^{-1}, sugar beet: 60 to 135 kg N ha^{-1}, winter wheat: 180 to 230 kg N ha^{-1}, mustard: 50 kg N ha^{-1}; (iii) Etzdorf: silage maize: 140 kg N ha^{-1}, sugar beet: 100 kg N ha^{-1}. Further details on the agronomical management are given in Brauer-Siebrecht et al. (2015, 2016). All harvest residues remained in the field. In contrast to silage maize, the continuous cultivation of sugar beet has no relevance in agricultural practice and needs rather to be seen as a methodological approach here. For several assessments (see below), we set up region-specific virtual scenarios characterizing the socio-economical circumstances of crop cultivation, farm management, and of biogas production as being typical region where the field trials were conducted (Table 1).

In an interdisciplinary and multi-level approach, we used certain economical (i-iv) and ecological (v-vii) indicators to compare silage maize and sugar beet roots as substrates for biogas production:

(i) On a field trial level, the methane yield per ha of silage maize and of sugar beet roots as cultivated in the different crop rotations was estimated according to Weißbach (2008, 2009) based on the dry matter yield and the content of fermentable organic matter gained in 2011 to 2014. Mean dry matter yield of silage maize and sugar beet roots across crop rotations, years, and field replicates was: (i) Aiterhofen: silage maize: 25 t ha^{-1}, sugar beet: 22 t ha^{-1}; (ii) Harste: silage maize: 21 t ha^{-1}, sugar beet: 17 t ha^{-1}; (iii) Etzdorf: silage maize: 21 t ha^{-1}, sugar beet: 9 t ha^{-1}. The mean content of fermentable organic matter was: (i) Aiterhofen: silage maize: 812 g per kg dry matter, sugar beet: 926 g per kg dry matter; (ii) Harste: silage maize: 798 g per kg dry matter, sugar beet: 919 g per kg dry matter; (iii) Etzdorf: silage maize: 792 g per kg dry matter, sugar beet: 921 g per kg dry matter. For further and

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