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Silage maize and sugar beet for biogas production in crop rotations and continuous cultivation – energy efficiency and land demand

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ABSTRACT

Empirical data on energy performance (net-energy yield, energy efficiency, land demand) of biomass crop cultivation are needed for policy and agronomic decision making. Energy input and energy performance of the cultivation of silage maize (SM), sugar beet (SB), and winter wheat (WW) in crop rotations and continuous cultivation were evaluated on the basis of three field experiments on highly productive sites in Germany. Silage maize and SB root were considered as crops for biogas production and WW as a food crop. Even if SM cultivation needed the largest energy input across sites and years (19–22 GJ ha^{-1} a^{-1}), the energy output compensated for it and largest net-energy yield (212–317 GJ ha^{-1} a^{-1}), energy efficiency (11.4–17.1 GJ GJ^{-1}), and smallest land demand (33–48 m^2 GJ^{-1}) were observed. For SB cultivation, energy input (15–19 GJ ha^{-1} a^{-1}) and energy performance were lower (119–266 GJ ha^{-1} a^{-1}, 9.1–14.7 GJ GJ^{-1}, 38–279 m^2 GJ^{-1}, respectively). Differences between both crops were significant ($p \leq 0.05$), but not in all cases. Winter wheat cultivation required an energy input of 13–18 GJ ha^{-1} a^{-1} and showed the lowest energy performance (103–119 GJ ha^{-1} a^{-1}, 6.6–8.6 GJ GJ^{-1}, 84–102 m^2 GJ^{-1}, respectively). The net-energy yield and land demand values presented are among the largest and the lowest, respectively, for rainfed Central European conditions. As the preceding crops, SB induced a higher energy performance of the subsequent WW than SM. When taking such crop rotation effects into account for the overall evaluation, we concluded that SB root as a biomass crop is a suitable alternative to SM.

1. Introduction

One aim of arable crop cultivation is to reach the largest energy output (yield) via the smallest input (agronomic management) since this ratio of energy efficiency (output:input) is one possible proxy for the respective economic and ecologic performance of the cultivation system (Franzluebbers and Francis, 1995; Hülsbergen et al., 2001; Kiley-Worthington, 1981; Pelletier et al., 2011; Rathke and Diepenbrock, 2006): The use of energy sources (except sunlight) is costly and emits climate relevant greenhouse gases (Khaledian et al., 2010). Thus, the more energy efficient a cultivation system is, the more it contributes to a sustainable agricultural production (Herrmann, 2013; Reineke et al., 2013; Schroll, 1994). Especially for arable crops which serve for biogas production (biomass crops), energy efficiency is the key factor to mitigate the strong competition with fossil energy sources and with food production (Patterson et al., 2008). Hereby, the larger the energy efficiency is, the more units of fossil energy are replaced. In the context of current European statements (European Commission, 2014) and amendments to the German Renewable Energy Sources Act (Anon, 2014), we suggest that it will be even more important for farmers to cultivate biomass crops as energy efficiently as possible also in order to raise their monetary income.

Generally, reliable values on energy efficiency in arable crop cultivation, especially from Central Europe, are scarce (Camargo et al., 2013; Hülsbergen et al., 2001). Moreover, energy output and input are driven by crop- and site-specific yield parameters as well as by regional characteristics, like soil properties, socio-economic characteristics of the farm, cultivation system chosen, and by agri-

Abbreviations: K_2O, potassium oxide; MgO, magnesium oxide; MU, mustard; P_2O_5, phosphorous pentoxide; SB, sugar beet; SM, silage maize; WW, winter wheat.

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cultural legislation etc. (Hülsbergen et al., 2001; Kuesters and Lammel, 1999; Reineke et al., 2013; Tzilivakis et al., 2005). Climatic conditions are also of concern since irrigation is quite energy intensive (Franzluebbers and Francis, 1995; Reineke et al., 2013). We thus consider studies from rainfed conditions and Central European socio-economic agricultural structures only. We further evaluate silage maize (*Zea mays*) and sugar beet (*Beta vulgaris*) root as biomass crops and winter wheat (*Triticum aestivum*) as a food crop. For the energy input of silage maize cultivation, few, but homogenous values (12–18 GJ ha^{-1} a^{-1}) were reported (Boehmel et al., 2008; Felten et al., 2013; Gissén et al., 2014). For sugar beet cultivation, a large variation in energy input (8–37 GJ ha^{-1} a^{-1}) was shown (Gissén et al., 2014; Hülsbergen et al., 2001; Kuesters and Lammel, 1999; Reineke et al., 2013; Tzilivakis et al., 2005) as well as for winter wheat cultivation (5–23 GJ ha^{-1} a^{-1}; Arvidsson, 2010; Deike et al., 2008a, 2008b; Hülsbergen et al., 2001; Kuesters and Lammel, 1999; Rosenberger et al., 2001). In Central Europe, silage maize is usually reported as the biomass crop with the largest energy output via methane (Bauer et al., 2010) ranging between 85 and 271 GJ ha^{-1} a^{-1} (Felten et al., 2013; Gerin et al., 2008; Gissén et al., 2014; Martínez-Pérez et al., 2007; Patterson et al., 2008). Sugar beet root for biogas production was less investigated and net-energy yield of 94–153 GJ ha^{-1} a^{-1} out of methane was published (Gissén et al., 2014; Martínez-Pérez et al., 2007; Patterson et al., 2008). However, some values cited included losses via processing and conversion (Felten et al., 2013; Martínez-Pérez et al., 2007), some did not (Gerin et al., 2008; Gissén et al., 2014; Patterson et al., 2008) and few studies were based on field trials (Felten et al., 2013; Gissén et al., 2014). The social dilemma of hectares taken away from food production in favor of biomass crop production (Patterson et al., 2008) asks for empirical values on the land demand per unit of energy produced which should be as low as possible (Bauer et al., 2010). To reduce the competition for valuable land, past studies mainly discussed the suitability and availability of so called surplus or abandoned land (Campbell et al., 2008; Dauber et al., 2012; Kappas, 2013; Offermann et al., 2011). However, reliable data are also required for highly productive sites in order to draw comparisons.

In summary, crop-specific and reliable baseline data are still needed. However, energy output and input (e.g. amount of N-fertilizer, tillage passes) depend on the respective preceding crop in the rotation. Thus, to avoid allocation mistakes, we suggested that an assessment of the entire cultivation system, e. g. crop rotation, is generally needed (Franzluebbers and Francis, 1995; Nemecek and Erzinger, 2005). Sugar beet is not self-compatible and needs to be cultivated in crop rotations, classically with cereals. Among the latter, wheat can reach high yield and quality in crop rotations with silage maize and sugar beet. Anyway, cultivating crops in rotations is part of the concept of a sustainable crop cultivation (Zegada-Lizarazu and Monti, 2011) which applies as well for biomass crops.

The present study had the following objectives to be assessed via reliable field trial data under Central European conditions: (i) Publish baseline data on the energy input for the cultivation of silage maize, sugar beet, and winter wheat. (ii) Point out the main agronomic factors as options for a reduction of the energy input. (iii) Evaluate the energy performance as the triangle of net-energy yield, energy efficiency, and land demand of crops in crop rotations or in continuous cultivation. Overall, we intended to compare silage maize and sugar beet root as biomass crops.

2. Methods

Generally, the evaluation of energy input and output was conducted following the method of Hülsbergen et al. (2001). In order to avoid interaction and allocation mistakes with the technical settings of the crop's use (biogas plant, flour mill), our study focused on the cultivation system and, thus, the spatial system boundary was the field. It included the farm-to-field-traffic, but neither the construction and maintenance of farm-buildings, nor the on-farm traffic, nor the occasional drying of winter wheat, nor a backflow of nutrients via biogas digestates for the biomass crops. However, consequences of biogas digestate use are discussed in Section 4.1. The temporal system boundary was one season of crop cultivation starting with the first agronomic operation after the preceding crop's harvest and ending with the harvest of the crop investigated. Hereby, catch crop cultivation was evaluated as being an individual crop in the rotation. However, our results were expressed per hectare and year where one year was equivalent to one cropping season.

Table 1
Crops investigated in different cultivation systems (different crop rotations, continuous cultivation) at three sites in Germany (2011–2013).

	Aiterhofen n = 4	Harste n = 3	Etzdorf n = 4
crop rotations			
(catch crop: mustard) – silage maize – winter wheat – winter wheat	x	x	
(catch crop: mustard) – sugar beet – winter wheat – winter wheat	x	x	
(catch crop: mustard) – silage maize – sugar beet – winter wheat	x	x	
continuous cultivation			
silage maize	x[a]	x	x
sugar beet		x	x
winter wheat		x	x

[a] Cultivated in 2012, 2013 only.

2.1. Data basis

In our study, 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 2011–2013 were evaluated. Experimental conditions are described in detail in Brauer-Siebrecht et al. (2016). All sites had a soil texture of a silt loam, a mean temperature of >8.5 °C and a precipitation of >450 mm. The soil nutrient status differed between sites. The crops investigated were silage maize, sugar beet, and winter wheat and were cultivated in different cultivation systems (crop rotations, continuous cultivation) but were not orthogonally replicated across sites (Table 1). In crop rotations, every crop rotation element was cultivated every year on a separate plot per field replication of which there were four in Aiterhofen and Etzdorf and three in Harste. In continuous cultivation, every crop was cultivated every year on the same plot. Plot sizes were 420 m^2 in Aiterhofen, 230 m^2 in Harste, and 70 m^2 in Etzdorf. The agronomic management (e.g. variety, fertilizer strategy) was done following the respective regional recommendations (for details, see Brauer-Siebrecht et al., 2016). These differences in experimental setup did not allow a statistical comparison between sites. In Aiterhofen, continuous cultivation of silage maize was realized in 2012 and 2013 only and could be evaluated for the energy input only.

2.2. Energy output

The energy output of crops was calculated based on the yearly yield of every crop in the different cultivation systems (different crop rotations and continuous cultivation; Table 1) and for every field replicate. The energy output of silage maize and sugar