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Silage Maize and Sugar Beet for Biogas Production in Rotations and Continuous Cultivation: Dry Matter and Estimated Methane Yield

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Abstract: Since silage maize is the main crop grown for biogas production (biomass crop) in Germany; its increasing cultivation is critically discussed in terms of social and agronomical aspects. To investigate if sugar beet is suitable as an alternative biomass crop to silage maize; three-year field trials with both biomass crops in rotations with winter wheat (food crop) and continuous cultivation were conducted at three highly productive sites. Dry matter (DM) yield per hectare was measured via field trials whereas methane yield per hectare was estimated via a calculation. Higher annual DM yield was achieved by silage maize (19.5–27.4 t·ha^{-1}·a^{-1}) compared to sugar beet root (10.7–23.0 t·ha^{-1}·a^{-1}). Dry matter yield was found to be the main driver for the estimated methane yield. Thus; higher estimated methane yield was produced by silage maize (6458–9388 Nm^3·ha^{-1}) with overlaps to sugar beet root (3729–7964 Nm^3·ha^{-1}). We; therefore; classify sugar beet as a suitable alternative biomass crop to silage maize; especially when cultivated in crop rotations with winter wheat. Additionally; we found that the evaluation of entire crop rotations compared to single crops is a more precise approach since it includes rotational effects.

Keywords: biomass; bioenergy; winter wheat; highly productive sites; Central Europe

1. Introduction

In the European Union, 20% of the total energy production has to be of renewable origin by 2020. In order to achieve this target, member states were supposed to set up National Renewable Energy Action Plans which define individual goals and tasks [1]. Thus, the German Renewable Energy Sources Act (EEG 2004 and subsequent amendments) [2] was implemented to achieve a sustainable development of the energy supply via reducing fossil resources consumption, and promoting bioenergy use. Moreover, Germany fixed its target by increasing the amount of heat and electricity generated from renewable energy sources to 14% and 30%, respectively [3]. One option of bioenergy use is the production of biogas from biomass crops, which is of special interest in Germany and, thus, regulated in the EEG as well, but also in other biogas producing countries. Currently, the amendment to the EEG in 2014 [4] aims to significantly reduce the use of biomass crops for biogas production in favor of residues and wastes. However, in the coming years, there will still be a significant portion of biomass crops fed to biogas plants which were put into operation before the latest amendment.

Silage maize (*Zea mays* L.) is the main biomass substrate for biogas production in Germany [5,6] according to its actual high yield. Moreover, cultivation and ensiling techniques are well known by farmers [7,8]. Further, silage maize is suitable for continuous cultivation due to its self-compatibility. As a consequence, silage maize cultivation increased strongly in some regions in Germany and was associated with a narrow cropping sequence which was assumed to decrease yield [9] and, moreover, the social acceptance of biogas production [10]. Nevertheless, cultivating silage maize for biogas production in regions with dominating cash-crop cultivation might increase regional diversity of crop rotations [11]. However, this does not contribute to a higher diversity on the field scale when silage maize is grown in continuous cultivation [12]. Therefore, alternative biomass crops with a high yield level and a material composition suitable for biogas production are urgently needed. Sugar beet (*Beta vulgaris* L.) is recommended as such an alternative biomass crop at sites favorable for crop rotations with cereals [13,14] and, in addition, Weiland [15] classified it as having a high biogas potential.

In contrast to silage maize, sugar beet is cultivated in crop rotations, e.g., with winter wheat (*Triticum aestivum* L.) [16], due to its self-incompatibility. Crop rotations are known to improve soil fertility and crop yield and to increase biodiversity. Thus, they are an instrument of sustainable crop cultivation [17]. Moreover, Amon *et al.* [18] and Zegada-Lizarazu and Monti [17] pointed out the necessity of biomass crop cultivation "in versatile and sustainable crop rotations". Hence, optimal combinations of biomass and non-biomass crops should be developed [17]. Thus, crop rotations with sugar beet (as biomass crop) and winter wheat (as food crop) can provoke positive ecological effects, as well as a higher social acceptance of biomass crop production.

Even if sugar beet was proposed for biogas production, there are very few internationally published data and concerning its methane yield per hectare, some studies lack a scientifically-defendable approach. Nevertheless, no study has been, so far, conducted comparing directly the methane yield per hectare of silage maize and sugar beet root when grown in various crop rotations in the same experiment on highly productive sites. Therefore, we assessed silage maize and sugar beet root as biomass crop in rotations with winter wheat as a food crop. We thereby focused on highly productive sites for exploiting the maximum attainable yield of these crops in Central Europe.

As one part of our joint project, the present study aimed to investigate if sugar beet root is suitable as an alternative biomass crop to silage maize for biogas production. For this purpose, we (i) assessed the dry matter (DM) yield per hectare of both biomass crops as affected by different preceding crops and of entire crop rotations, and (ii) estimated the methane yield per hectare of both crops.

2. Results

2.1. Annual DM Yield of Crop Rotation Elements and Triennial DM Yield of Entire Crop Rotations

In Aiterhofen, annual DM yield of silage maize was significantly highest (27.4 $t \cdot ha^{-1} \cdot a^{-1}$) when cultivated in the rotation (catch crop mustard (*Sinapis Alba* L.)—) silage maize—winter wheat—winter wheat (Table 1). Highest annual DM yield of sugar beet root (23.0 $t \cdot ha^{-1} \cdot a^{-1}$) occurred in the rotation (catch crop mustard—) sugar beet—winter wheat—winter wheat, and was significantly lower than highest annual DM yield of silage maize.

In Harste, the highest annual DM yield of silage maize was 21.0 $t \cdot ha^{-1} \cdot a^{-1}$ when cultivated in the rotation (catch crop mustard—) silage maize—sugar beet—winter wheat. Compared to this, the highest sugar beet root annual DM yield was significantly lower (17.7 $t \cdot ha^{-1} \cdot a^{-1}$) and was obtained when winter wheat was the preceding crop. Nevertheless, this sugar beet root yield was not significantly lower compared to silage maize grown in the rotation (catch crop mustard—) silage maize—winter wheat—winter wheat and under continuous cultivation.

In Etzdorf, under continuous cultivation, considerable differences of annual DM yield occurred between silage maize (22.7 $t \cdot ha^{-1} \cdot a^{-1}$) and sugar beet root (10.7 $t \cdot ha^{-1} \cdot a^{-1}$).

Table 1. Annual and triennial dry matter yield per hectare of crops investigated per crop rotation/continuous cultivation at three experimental sites in Germany; mean values and standard deviation (2011–2013). Biomass crops: SM = silage maize; SB = sugar beet root; food crop: WW = winter wheat grain.

Site	Crop	Annual Dry Matter Yield (t·ha^{-1}·a^{-1})	Triennial Dry Matter Yield (t·ha^{-1}·a^{-1})
Aiterhofen	SM	$27.4^{a} \pm 4.8$	
	WW	8.6 ± 0.8	$44.2^{B} \pm 4.3$
	WW	8.2 ± 1.3	
	SB	$23.0^{bc} \pm 3.2$	
	WW	8.7 ± 0.6	$40.1^{C} \pm 2.7$
	WW	8.4 ± 1.1	
	SM	$25.2^{b} \pm 5.6$	
	SB	$21.7^{c} \pm 2.4$	$55.4^{A} \pm 5.9$
	WW	8.5 ± 0.4	
Harste	SM	$19.5^{ab} \pm 1.5$	
	WW	8.6 ± 1.2	$36.3^{C} \pm 1.6$
	WW	8.2 ± 1.5	
	SB	$17.7^{bc} \pm 1.1$	
	WW	8.7 ± 0.7	$34.6^{C} \pm 2.0$
	WW	8.3 ± 1.7	
	SM	$21.0^{a} \pm 3.0$	
	SB	$17.0^{c} \pm 1.6$	$46.6^{B} \pm 2.5$
	WW	8.6 ± 1.0	
	SM (continuous)	$19.8^{ab} \pm 3.2$	$59.4^{A} \pm 2.5$
	SB (continuous)	$15.4^{c} \pm 3.3$	$46.2^{B} \pm 7.2$
	WW (continuous)	8.3 ± 1.2	$24.8^{D} \pm 0.3$
Etzdorf	SM (continuous)	$22.7^{a} \pm 5.4$	$68.1^{A} \pm 8.3$
	SB (continuous)	$10.7^{b} \pm 6.9$	$32.2^{B} \pm 5.4$
	WW (continuous)	7.4 ± 1.3	$22.3^{B} \pm 2.1$

Different lowercase letters indicate significant differences at $p \leqslant 0.05$ (Tukey) between biomass crop rotation elements (SM, SB; n adjusted due to experimental setup: Aiterhofen = 12, Harste = 9, Etzdorf = 12). Different uppercase letters indicate significant differences at $p \leqslant 0.05$ (Tukey) between triennial dry matter yield of entire crop rotations (n adjusted due to experimental setup: Aiterhofen = 12; Harste crop rotations = 9, Harste continuous cultivation = 3; Etzdorf = 4). Sites were assessed separately.

In general, the most constant annual DM yield was obtained by winter wheat (mean 7.4–8.7 t·ha^{-1}·a^{-1}), whereby yield was higher when silage maize or sugar beet was the preceding crop (8.5–8.7 t·ha^{-1}·a^{-1}) compared to winter wheat as preceding crop (7.4–8.4 t·ha^{-1}·a^{-1}).

In Aiterhofen, significantly highest triennial DM yield was produced by the rotation (catch crop mustard—) silage maize—sugar beet—winter wheat (55.4 t·ha^{-1}·a^{-1}).

In Harste, silage maize under continuous cultivation reached the significantly highest triennial DM yield (59.4 t·ha^{-1}·a^{-1}). Here, the triennial DM yield of the rotations with either silage maize or sugar beet followed by two-fold winter wheat were at a similar level (36.3 t·ha^{-1}·a^{-1} and 34.6 t·ha^{-1}·a^{-1}, respectively).

In Etzdorf, under continuous cultivation, very low triennial DM yield of sugar beet root (32.2 t·ha^{-1}·a^{-1}) differed significantly from the one from silage maize (68.1 t·ha^{-1}·a^{-1}).

2.2. Estimated Methane Yield of Silage Maize and Sugar Beet Root

In Aiterhofen (Figure 1a), the significantly highest estimated methane yield of silage maize was 9388 Nm^{3}·ha^{-1} when cultivated in the rotation (catch crop mustard—) silage maize—winter wheat—winter wheat. The highest estimated methane yield of sugar beet root was 7964 Nm^{3}·ha^{-1} when cultivated in the rotation (catch crop mustard—) sugar beet—winter wheat—winter wheat and was significantly lower than the highest estimated methane yield of silage maize.

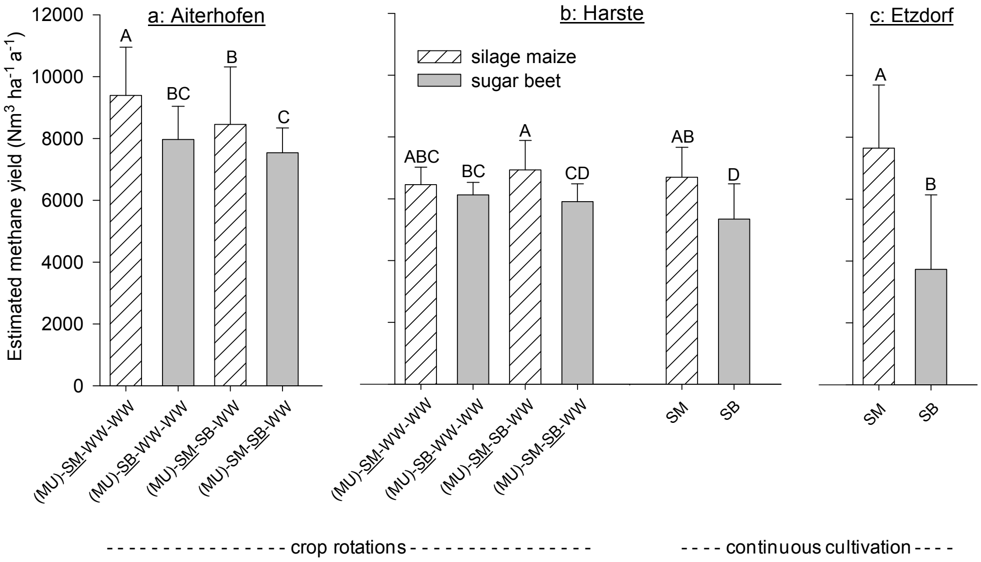

Figure 1. Estimated methane yield per hectare of biomass crops silage maize (SM) and sugar beet root (SB) in different crop rotations with catch crop mustard (MU) and winter wheat (WW, food crop) and continuous cultivation at three experimental sites in Germany; mean values and standard deviation (2011–2013). Respective crop rotation element underlined. Different letters indicate significant differences at $p \leqslant 0.05$ (Tukey) between biomass crop rotation elements (n adjusted due to experimental setup: Aiterhofen = 12; Harste = 9; Etzdorf = 12). Sites were assessed separately.

In Harste, the highest estimated methane yield of silage maize was 6937 Nm^3·ha^{-1} when cultivated in the rotation (catch crop mustard–) silage maize—sugar beet—winter wheat (Figure 1b), although it was not significantly different from silage maize in the other crop rotation and under continuous cultivation. Highest estimated methane yield of sugar beet root was 6126 Nm^3·ha^{-1} when cultivated in the rotation (catch crop mustard–) sugar beet—winter wheat—winter wheat and differed significantly from highest silage maize yield and lowest sugar beet root yield which was obtained under continuous cultivation.

In Etzdorf, under continuous cultivation, differences were most distinct between silage maize (7649 Nm^3·ha^{-1}) and sugar beet root (3729 Nm^3·ha^{-1}) (Figure 1c).

3. Discussion

3.1. Dry Matter Yield of Silage Maize and Sugar Beet Root Cultivated in Different Crop Rotations

Among all sites, mean annual DM yield was highest for silage maize (19.5–27.4 t·ha^{-1}·a^{-1}) followed by sugar beet root (10.7–23.0 t·ha^{-1}·a^{-1}; lowest values obtained under continuous cultivation), whereas winter wheat yield was lowest (7.4–8.7 t·ha^{-1}·a^{-1}) (Table 1). The yield level of silage maize in our trials was slightly higher compared to results of Graß *et al.* [7], Grieder *et al.* [19], and Herrmann *et al.* [20], who reported a silage maize DM yield between 19.1 and 21.8 t·ha^{-1}·a^{-1} but not exclusively for highly-productive sites. Our mean DM yield of sugar beet root in crop rotations (Aiterhofen and Harste: 17.0–23.0 t·ha^{-1}·a^{-1}) was in the lower range in comparison to results of Starke and Hoffmann [14] who detected DM yield of different varieties between 17 and 27 t·ha^{-1}·a^{-1}. Mean annual DM yield of all three crops was considerably higher (104%–161%, excluding sugar beet under continuous cultivation) when comparing with the local yield recorded by *Statistische Ämter des Bundes und der Länder* [21] for the years investigated in this study, especially in Aiterhofen. This confirmed our sites to be "highly productive", but was, for sure, also driven by usually more precise agronomic management of field trials compared to agricultural practice.

Despite the general outcomes discussed above, we found some specific effects on the DM yield with regard to sites and years: Firstly, the year 2012 appeared to be favorable for sugar beet in Aiterhofen and root DM yield was at a similar level as of silage maize (not shown). Moreover, one has to consider that harvest of sugar beet root in Harste was relatively early (Table 2) and that sugar beet root is suggested to increase yield with an extended growing period [22]. We, thus, conclude that, considering site- and year-specific circumstances, the difference between sugar beet root and silage maize DM yield can be somewhat lower. Secondly, some crop rotational effects on the annual DM yield of biomass crops occurred: the highest DM yield of silage maize and of sugar beet root generally occurred at both sites in crop rotations with two-fold winter wheat. An exception was silage maize in Harste, driven by a strong yield decrease in 2012, for which we have no explanation. In our study, strong yield losses of sugar beet root under continuous cultivation and, thus, lower DM yield (Harste 15.4 t·ha^{-1}·a^{-1}; Etzdorf: 10.7 t·ha^{-1}·a^{-1}) occurred mainly due to infestation with *Cercospora beticola* and root rots. Anyway, this appeared in Harste to be dominant in one field replication and was boosted in Etzdorf by insufficient fungicide application. Moreover, yield losses can be caused by a possible infestation with Rhizoctonia solani or nematodes [23–25], too, which, however, was not observed during the years investigated. Nevertheless, our methodological approach confirmed the high pest infestation risk of sugar beet under continuous cultivation, supporting the general assumption that sugar beet requires cultivation in crop rotations.

Table 2. Sowing and harvest dates as well as degree days and sums of global radiation for the cultivation of biomass crops, silage maize (SM) and sugar beet (SB), at three experimental sites in Germany (2011–2013).

Year		Site					
		Aiterhofen		Harste		Etzdorf	
		SM	SB	SM	SB	SM	SB
2011	Sowing	04-18	03-29	04-18	03-24	04-18	04-07
	Harvest	09-12	10-13	09-14	09-28	09-22	10-05
	Degree days (°Cd)	2448	3056	2339	2764	2542	2842
	Global radiation ((MJ m^{-2}) days)	2817	3465	2560	3107	2680	2970
2012	Sowing	04-25	03-29	04-19	03-28	04-24	04-02
	Harvest	09-18	10-15	09-13	09-28	09-06	10-09
	Degree days (°Cd)	2534	3029	2565	2927	2270	2847
	Global radiation ((MJ m^{-2}) days)	2812	3430	2409	2798	2386	2990
2013	Sowing	04-27	04-17	04-25	04-16	04-26	04-25
	Harvest	09-17	10-09	09-13	09-24	10-01	10-21
	Degree days (°Cd)	2392	2756	2368	2616	2547	2759
	Global radiation ((MJ m^{-2}) days)	2695	3083	2414	2646	2572	2701

Our study stabilized the findings of Amon *et al.* [18] and Weiland [15] who characterized silage maize as the biomass crop with the highest yield, in our case also compared to sugar beet root. Other studies investigated further alternative biomass crops and showed e.g., lower annual DM yield for sorghum of 13.3 t·ha^{-1}·a^{-1} as the mean of several sites in Germany [26] compared to the yield found for silage maize and sugar beet root in our study. However, it needs to be considered that the highest yield of crops is generally achieved at sites with favorable agronomic conditions only.

3.2. Dry Matter Yield Evaluated in Terms of Entire Crop Rotations

When evaluating entire crop rotations, highest triennial DM yield (Table 1) was performed under continuous cultivation of silage maize (Harste: 59.4 t·ha^{-1}·3a^{-1}; Etzdorf: 68.1 t·ha^{-1}·3a^{-1}) or in the rotation (catch crop mustard—) silage maize—sugar beet—winter wheat (Aiterhofen: 55.4 t·ha^{-1}·3a^{-1}; Harste: 46.6 t·ha^{-1}·3a^{-1}). As expected, the more of our high yielding biomass crops were in a rotation, the higher was the triennial DM yield. Differences between crop rotations with either silage maize or sugar beet followed by twofold winter wheat occurred mainly because of the higher annual DM yield of silage maize discussed above. However, the effect of annual DM yield is partly neglected when considering the entire crop rotation. Few evaluations of entire crop rotations are published so far, but the need got increased attention in more recent studies [7,13,26]. Overall, our results highlight as well that the current practice of comparing single crops is not sufficient for a systematic and holistic evaluation of crop cultivation since it excludes rotational effects.

3.3. Estimated Methane Yield of Silage Maize and Sugar Beet Root as Driven by Dry Matter Yield

Our finding of a strong influence of DM yield on estimated methane yield (Table 1, Figure 1) was confirmed by Graß *et al.* [7], Grieder *et al.* [19], Mayer *et al.* [27], and Sieling *et al.* [13]. Consequently, we recognized highest estimated methane yield of silage maize in Aiterhofen when cultivated in the rotation (catch crop mustard –) silage maize—winter wheat—winter wheat (9388 $\text{Nm}^3 \cdot \text{ha}^{-1}$) and lowest in this rotation in Harste (6458 $\text{Nm}^3 \cdot \text{ha}^{-1}$). These results were in a similar range to those of Amon *et al.* [18] who reported possible methane yield of about 7500–10,200 $\text{Nm}^3 \cdot \text{ha}^{-1}$ when silage maize was cultivated under suitable climatic conditions. Lower methane yield of silage maize was observed by Grieder *et al.* [19] as 3990–7120 $\text{Nm}^3 \cdot \text{ha}^{-1}$. Estimated methane yield of sugar beet root in our study was lower (3729–7964 Nm^3 ha^{-1}; lowest values gained under continuous cultivation) compared to silage maize due to lower annual DM yield. Amon *et al.* [28] detected a methane yield of sugar beet root of about 3770 $\text{Nm}^3 \cdot \text{ha}^{-1}$ whereby they measured a lower DM yield and biochemical methane potential. Results of German variety tests (SV-B 2012–2014) predicted a methane yield of about 6100 $\text{Nm}^3 \cdot \text{ha}^{-1}$ [29]. Considering that methane yield of e.g., cereals was 3200–4500 $\text{Nm}^3 \cdot \text{ha}^{-1}$ [18], estimated methane yield of our biomass crops was on a high level.

To sum up, we found that sugar beet root had a slightly higher estimated biochemical methane potential than silage maize (not shown), but the main driver for the estimated methane yield was the DM yield. This is in consensus with Schumacher *et al.* [30] who stated that a low biochemical methane potential can be compensated by a high DM yield. However, our results show that estimated methane yield of sugar beet root can reach levels close to those of silage maize. Additionally, several further aspects influence the yield of the biogas production chain, like feedstock ration or time management, but were not included in our analysis and may alter the respective conclusions. Moreover, ecologic and economic parameters are of concern. Therefore, further aspects, like energy balances, greenhouse gas emissions, soil health, economic competitiveness, and production costs will be analyzed and discussed in other parts of the joint project [31].

4. Experimental Section

4.1. Field Trials

Crop rotation field trials were conducted at the sites Aiterhofen near Straubing (48°85′ N, 12°63′ E; Bavaria), Harste near Göttingen (51°61′ N, 9°86′ E; Lower Saxony) and Etzdorf near Halle (51°43′ N, 11°76′ E; Saxony-Anhalt). We classified them as highly productive sites representative for Central Europe. First harvest was 2010, but harvests evaluated in this study were 2011–2013 to consider preceding crop effects. Detailed site information is reported in Table 3.

Table 3. Site characteristics of the three crop rotation trials in Germany (2011–2013).

	Site		
	Aiterhofen	Harste	Etzdorf
Soil	Luvisol	Luvisol	Haplic Chernozem
Soil texture	Silt loam	Silt loam	Silt loam
Ø temperature (°C) [a]	8.6	9.2	9.1
Ø precipitation (mm) [a]	757	651	466
Field size (ha)	5.3	4.9	0.6
Plot size (m^2)	420	230	70
Field replications	4	3	4
P_2O_5 (mg 100 g^{-1}) [b]	39.3	17.1	31.5
K_2O (mg 100 g^{-1}) [b]	16.2	14.7	23.0
MgO (mg 100 g^{-1}) [b]	17.5	15.9	21.0
pH value *	7.3	7.2	7.4
Soil organic C (%) [b]	1.0	1.3	1.9

[a] Long-term mean value 1981–2010 (Aiterhofen, Harste: [32]; Etzdorf: own measurements); [b] Content in soil in 2010 (0–30 cm); CAL-extraction for P_2O_5, K_2O; $CaCl_2$-extraction for MgO, pH-value.

In Aiterhofen and Harste, the following crop rotations were investigated (Figure 2): (i) (catch crop mustard—) silage maize—winter wheat—winter wheat; (ii) (catch crop mustard—) sugar beet—winter wheat—winter wheat, and (iii) (catch crop mustard—) silage maize—sugar beet—winter wheat. Every crop within one rotation was considered as a crop rotation element. In addition, to test the crops apart from rotational effects, we conducted continuous cultivation of (iv) silage maize; (v) sugar beet; and (vi) winter wheat in Harste and Etzdorf (Figure 2). There is no practical relevance of sugar beet under continuous cultivation due to its self-incompatibility but it was cultivated here as part of the methodological approach. In Aiterhofen, silage maize under continuous cultivation could be realized in 2012 and 2013 only. This was due to regulatory constraints in Bavaria at that time which prohibited silage maize cultivation for more than two consecutive years [33]. In 2011, we cultivated sorghum instead. Thus, Aiterhofen's silage maize under continuous cultivation was not included in this study. Winter wheat was taken into account as a food crop. When winter wheat was the preceding crop, the following winter wheat was sown end of September whereas winter wheat after silage maize or sugar beet was sown end of October with a seed density adapted (350 grains m^{-2} instead of 270 grains m^{-2}). At all sites, soil tillage was conducted with a cultivator (15–25 cm deep).

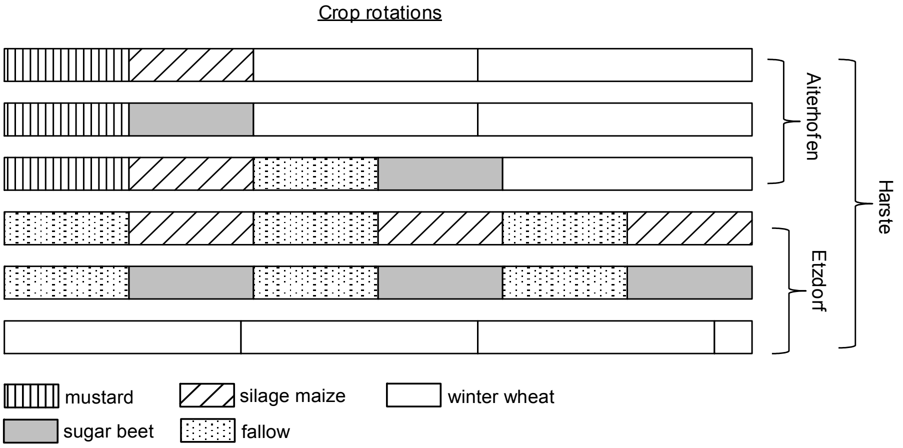

Figure 2. Crop rotations and continuous cultivation at sites investigated.

Crop varieties were chosen according to the site conditions (Table 4). All crop residues (sugar beet tops and leaves, winter wheat straw) remained in the field. The mineral nitrogen fertilizer was applied according to the target value and to the yearly mineral nitrogen content in the soil in spring

("Sollwert") of the respective crops in Aiterhofen and Harste, whereas a constant rate was applied in Etzdorf (Table 4). The use of pesticides was carried out following local optimum recommendations and according to the personal experience of the technician responsible for the respective trial. To determine the yield of the crops, a core part of each plot was harvested. The area for yield determination differed per site and crop and was determined by the machinery available: (i) 30 m^2 (Aiterhofen), 21 m^2 (Harste), and 9.2 m^2 (Etzdorf) for silage maize; (ii) 12 m^2, 10.8 m^2, and 18.4 m^2, for sugar beet root, respectively; and (iii) 25 m^2, 16.8 m^2, and 15.3 m^2, for winter wheat, respectively. Furthermore, sugar beet was topped manually in Aiterhofen and Harste and mechanically in Etzdorf.

Table 4. Characteristics of cultivated varieties and mean (min-max) mineral nitrogen fertilizer rate of test crops silage maize (SM), sugar beet (SB) and winter wheat (WW) at three experimental sites in Germany (2011–2013).

Site	Variety Characteristics			Mineral Nitrogen Fertilizer Rate ($kg{\cdot}N{\cdot}ha^{-1}$)		
	SM	SB	WW	SM	SB	WW
Aiterhofen	FAO 280	Rhizomania tolerant	High baking quality	200	105 (80–135)	220 (210–225)
Harste	FAO 240	Rhizomania tolerant, nematode tolerant	High baking quality	125 (110–145)	90 (60–120)	205 (180–230)
Etzdorf	FAO 300	-	Baking quality	140	100	160

Sowing and harvest dates as well as degree days (sum of daily mean temperature, base temperature 0 °C) and the sums of global radiation for the cultivation of biomass crops are displayed in Table 2. Silage maize harvest was realized at physiological maturity. Due to technical organization, sugar beet root harvest in Harste was conducted 1–4 weeks earlier compared to the other sites.

4.2. Calculation of the Estimated Methane Yield

To compare the estimated methane yield out of fresh crop material of silage maize (Equation 1) and sugar beet root (Equation 2) by the same approach, we used the method of Weißbach based on the calculation of the parameter "fermentable organic matter" (FOM) [34,35]:

$$\mathrm{FOM}\,(\mathrm{g}\,(\mathrm{kg\,DM})^{-1}) = 984 - (\mathrm{XA}) - 0.47\,(\mathrm{XF}) - 0.00104\,(\mathrm{XF})^2 \tag{1}$$

$$\mathrm{FOM}\,(\mathrm{g}\,(\mathrm{kg\,DM})^{-1}) = 991 - (\mathrm{XA}) - 0.70\,(\mathrm{XF}) \tag{2}$$

where XA was crude ash and XF was crude fiber, both given in g $(kg\,DM)^{-1}$. The FOM content describes the fraction of the organic matter degradable by microorganisms under anaerobic conditions in a biogas fermenter [34]. Crude ash content was determined by incineration (550 °C, 5 h) of the dried (105 °C) biomass material. Crude fiber content of silage maize was determined by near-infrared-spectroscopy (Perstop Analytical Model 5000-C, Foss, Rellingen; external laboratory) since we assumed a considerable variability. The XF content of sugar beet root is of a very high stability [36,37] and, therefore, a constant XF content of 54 g $(kg{\cdot}DM)^{-1}$ [36] was assumed. The methane production potential of silage maize was estimated in previous studies of Weißbach as 0.420 $Nm^3{\cdot}(kgFOM)^{-1}$ and of sugar beet root as 0.375 $Nm^3{\cdot}(kg{\cdot}FOM)^{-1}$ [34,35], and was stoichiometrically validated for several crops in a praxis trial [38]. This methane production potential multiplied with the respective FOM resulted in the estimated biochemical methane potential ($Nm^3{\cdot}(kg{\cdot}DM)^{-1}$). The crop's biochemical methane potential multiplied with the respective annual DM yield ($t{\cdot}ha^{-1}$) gave, in turn, the estimated methane yield ($Nm^3{\cdot}ha^{-1}$). This approach was proven to fit well to results of batch and Hohenheimer biogas yield tests whereas former calculation methods [39,40] resulted in underestimated methane yields [34,41]. Yield losses through transportation, storage, and conversion were not included because we solely focus on the field scale. This enabled a comparison of the crops and crop rotations apart from settings of their technical use, giving also an estimation of the maximal energetic output [42].

4.3. Statistical Analyses

Since the experimental setup of the sites investigated was not uniform, all sites were analyzed separately. Analysis of variance (ANOVA) was performed to determine the effect of "crop rotation" and "crop rotation element" as fixed factors. There were some individual adjustments to the model due to the experimental setup: (i) For the comparison of the biomass crops silage maize and sugar beet, we skipped the food crop winter wheat from the model because it was not the target of the analysis. To compare the biomass crops in different crop rotations in terms of DM and estimated methane yield, fixed factors were "crop rotation element" and "year of investigation". Due to the fact that every crop rotation element was cultivated on a separate plot within one field replication every year in Aiterhofen and in Harste, "field replication" was treated as a random factor in which the "year of investigation" was nested. This model did not fit for continuous cultivation in Harste since the crops were cultivated constantly on one plot per field replication across years. Nevertheless, this model was applied anyway for comparing crop rotations with continuous cultivation at that site. For the site Etzdorf, where only continuous cultivation was assessed, "field replication" was a random factor; (ii) To compare the triennial DM yield of entire crop rotations, data of each crop rotation element per crop rotation for 2011–2013 were summed up including winter wheat (food crop). Due to the fact that every crop rotation element was cultivated every year on a separate plot per field replication, there were three year-plot combinations: e.g., the crop rotation silage maize—winter wheat—winter wheat had the combinations "2011: silage maize—2012: winter wheat—2013: winter wheat", "2011: winter wheat—2012: winter wheat—2013: silage maize" and "2011: winter wheat—2012: silage maize—2013: winter wheat". For Harste and Aiterhofen, this "year-plot" combination was the random factor. Such year-plot combinations were not available for continuous cultivation and the yield of three years (2011, 2012, 2013) per field replication was summed up. This resulted in an unbalanced dataset for Harste (crop rotations: $n = 3$ year-plot combinations × 3 field replications; continuous cultivation: $n = 3$ field replications). Additionally, no random factor for Etzdorf was applied.

Statistical analyses were carried out with SAS 9.3 (SAS Institute Inc., Cary, NC, USA) with the procedure "mixed". Tukey's test was used to compare mean values and normal distribution of residuals was tested with the procedure "univariate". The level of significance was $\alpha = 5\%$.

5. Conclusions

Yield performance of sugar beet root was 5%–15% lower compared to silage maize when cultivated in crop rotations with winter wheat. We concluded that yield differences were low in some years and could be even lower by a later sugar beet root harvest in autumn. Altogether, we observed effects of the year as well as of the crop rotation on DM and estimated methane yield. We concluded that the assessment of entire crop rotations, including rotational effects, is needed for a comprehensive evaluation of crops. Further, a higher diversity of crop rotations on field scale might achieve positive agronomical and social effects. Overall, we consider sugar beet, when cultivated in crop rotations with cereals, to be a promising crop for biogas production, especially when it is required to "dilute" continuous cultivation of silage maize.

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