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Can Energy Cropping for Biogas Production Diversify Crop Rotations? Findings from a Multi-Site Experiment in Germany

Christoph Strauß[1] · Christiane Herrmann[2] · Christian Weiser[1] · Peter Kornatz[3] · Monika Heiermann[2] · Joachim Aurbacher[3] · Janine Müller[3] · Armin Vetter[1]

Abstract

During the last years, a demand for regionally produced biogas feedstocks was created by government subsidies to biogas production in Germany—contrary to the trend of specialization of agricultural production towards global commodity markets. The question arose whether this trend could contribute to an increased cultivation of uncommon crops and diversification of cropping patterns, owing to comparably different and less restricted feedstock requirements. In the cooperative research project "EVA," a multi-site experimental crop rotation field trial was conducted over 8 years at eight sites, representing the variety of soil-climatic conditions in Germany. The aim of the trial was to assess a variety of established and novel crops for anaerobic digestion. This paper presents the key findings of the trial. Special emphasis is given to biomass productivity and profitability. The chances for the approach "diversification of cropping patterns via energy cropping" are discussed. Results show that maize (average 4-year dry matter yield varied site-specific between 14.22 and 25.12 t ha^{-1}) is clearly the most efficient crop for biogas production in Central Europe. Some cropping options for biogas feedstock production, such as winter triticale (whole crop, average yield of 6.71 to 15.17 t ha^{-1}) or perennial fodder mixtures (average yield of 7.51 to 19.44 t ha^{-1}) are feasible choices for farmers in some regions, which could contribute to diverse cropping systems.

Keywords Energy crops · Biogas feedstocks · Double-cropping · Maize · Sorghum · Perennial mixtures

Introduction

Farmers in Europe have largely renounced mixed farming systems with diverse cropping patterns in crop production and turned towards more specialized farming systems [1], with a small number of high yielding crops on arable land [2]. This is triggered by globalization of agrarian commodity markets on the demand side, and success in breeding and the development of operating resources, e.g., plant protection, on the production side.

In Germany, as in other European countries, regional differences in specialization of crop production accompanied by highly simplified crop sequences are apparent. On the one hand, a shift towards maize (*Zea mays*) can be observed in regions of intensive livestock farming, mainly based on breeding successes in temperate maize production. On the other hand, intensive production of conventional cereals, mainly wheat, occurs in regions focusing on international grain markets.

Despite this trend, there has recently been increased interest in crop rotation-related topics [3]. This is, firstly, driven by the growing concern of policy, administration, farmers, and research that an ongoing simplification of crop sequences might lead to problems that cannot be fully compensated by agrotechnical innovation. This includes, for example, the increase of herbicide-resistant weeds [4]. Secondly, an increasing public awareness of the ecological aspects of cropping decisions develops, which is for example reflected by stricter ecologic conditions for agricultural subsidies ("greening") [5].

In Germany, public incentives for the production of electricity from renewable resources are set by the EEG (Renewable Energy Law). From 2004 onwards, this comprised special

✉ Joachim Aurbacher
Joachim.aurbacher@agrar.uni-giessen.de

[1] Department of Plant Production, Thuringian State Institute for Agriculture, Naumburger Straße 98, 07743 Jena, Germany

[2] Leibniz Institute for Agricultural Engineering and Bioeconomy e.V, Max-Eyth-Allee 100, 14469 Potsdam, Germany

[3] Justus Liebig University Gießen, Senckenbergstraße 3, 35390 Giessen, Germany

remunerations for electricity production via energy crop biomethanation. The legislation was the most important driver for a change of decision patterns in crop choice. In total, the cropping of feedstocks for biogas production currently covers approx. 12.3% of the arable land in Germany, and the number of biogas plants exceeded 9300 [6, 7].

For biogas production, a variety of feedstocks can be utilized [8] such as animal manure, organic waste, and crop biomass, mainly preserved whole crops as silage. The residues, so-called digestates, are deployed as valuable fertilizer in agricultural production systems. The low transportability of in- and output material brings forward decentralized concepts [9].

The full-scale biomethanation process in Germany is mainly based on maize silage, making up around three quarters of renewable resources input of biogas plants [6]. The “biogas-boom” accelerated the trend towards simplified crop rotations in regions with high proportions of maize production. Hence, questions arose addressing agronomic and eminent environmental issues related to intensive maize cropping [10].

Numerous recent cropping experiments have aimed at carving out the chances for the diversification of crop rotations. Various biogas feedstock-cropping options for anaerobic digestion were conducted within the scope of applied research approaches (e.g., [11–14]). The most relevant options tested as alternatives to maize and suitable to be included into typical crop rotations are as follows:

Whole-Crop Cereals Winter barley (*Hordeum vulgare*), winter rye (*Secale cereale*) and winter triticale (*X Triticosecale*), and in some cases, oat (*Avena sativa*) are suggested for cropping. A good integration into agricultural working regimes as well as relatively low production costs are reported as advantages of whole-crop cereal cropping [13, 15].

Sorghum In Central Europe, sorghum breeds are discussed as “new” crops that might be relevant in future energy cropping system. Advantages comprise high water efficiency as C_4-crop and intensive utilization of soil water as well as an excellent suppression of weeds [11, 16].

Perennial Fodder Crops Alfalfa (*Medicago sativa*), clover (*Trifolium* species), and mixtures of those with grasses are traditional options of fodder production in Central Europe. Features such as weed suppression and nitrogen fixation are of central importance for cultivation and nutrient supply. Cropping perennial crops is advantageous to biodiversity in arable systems [17, 18] and lead to low erosion risks as well as positive impacts on the increase of soil organic carbon [19].

Intercrops/Double-Cropping Integration of intercrops and an efficient combination of winter- and subsequent summer annual crops in the so-called double-cropping system are further promising options to diversify crop rotations for biogas production. Specific aims are a higher yield via better exploitation of the vegetation span as well as positive effects such as lower nutrient leaching, reduced erosion risks, and active suppression of weeds. This approach offers multiple possibilities for combinations of crops [20, 21]. Sequences with forage rye (early cut in late April/beginning of May) as winter crop have been intensively tested. Forage rye is characterized by good growth ability already in colder spring conditions and leaves time for the development of a subsequent crop (e.g., maize or sorghum).

One of the largest multi-site field trials in Germany is the crop rotation trial of the cooperative project “EVA” (Development and Comparison of Optimized Cropping Systems for the Production of Energy Plants under the Variety of Regional Conditions in Germany). The broad character of the project’s aims was set to draw an extensive picture of the variety of possibilities of energy cropping for methane-rich biogas production. It further enabled to concomitantly assess relevant parameters for a broad evaluation. This includes the experimental testing of biomass types, yields, and the conversion into methane [22].

This paper focuses on crop production of appropriate crops and the feasibility of their cropping in farming. Aspects of feedstock characteristics with regard to methane yields as well as economic performance are considered. It complements published results of the EVA-project on the impacts of energy crop rotation design on multiple aspects of resource efficiency [23] and integrative evaluation efforts, comprising the ecological validation of entire crop rotation [24], and builds up on findings of biogas feedstock characteristics [25, 26].

Objectives of the presented paper are focused on the:

(a) Assessment and comparison of biomass yields of a variety of partially well known, partially less known crops in different rotational positions at the eight sites of the field trial.
(b) Testing feedstocks with regard to their suitability for biogas production.
(c) Economic performance under the variety of site conditions.
(d) Evaluation of crop rotation effects onto the yield of subsequent wheat cropping.

Materials and Methods

Cultivation Experiments Since 2005, plot experiments comprising various types of energy crops were conducted on eight sites, chosen to represent varying soil-climate conditions of field cropping in Germany (Fig. 1, Table 1).

One distinctive feature of the field trials was the incorporation of the tested crops in several 4-year crop rotations (CR),

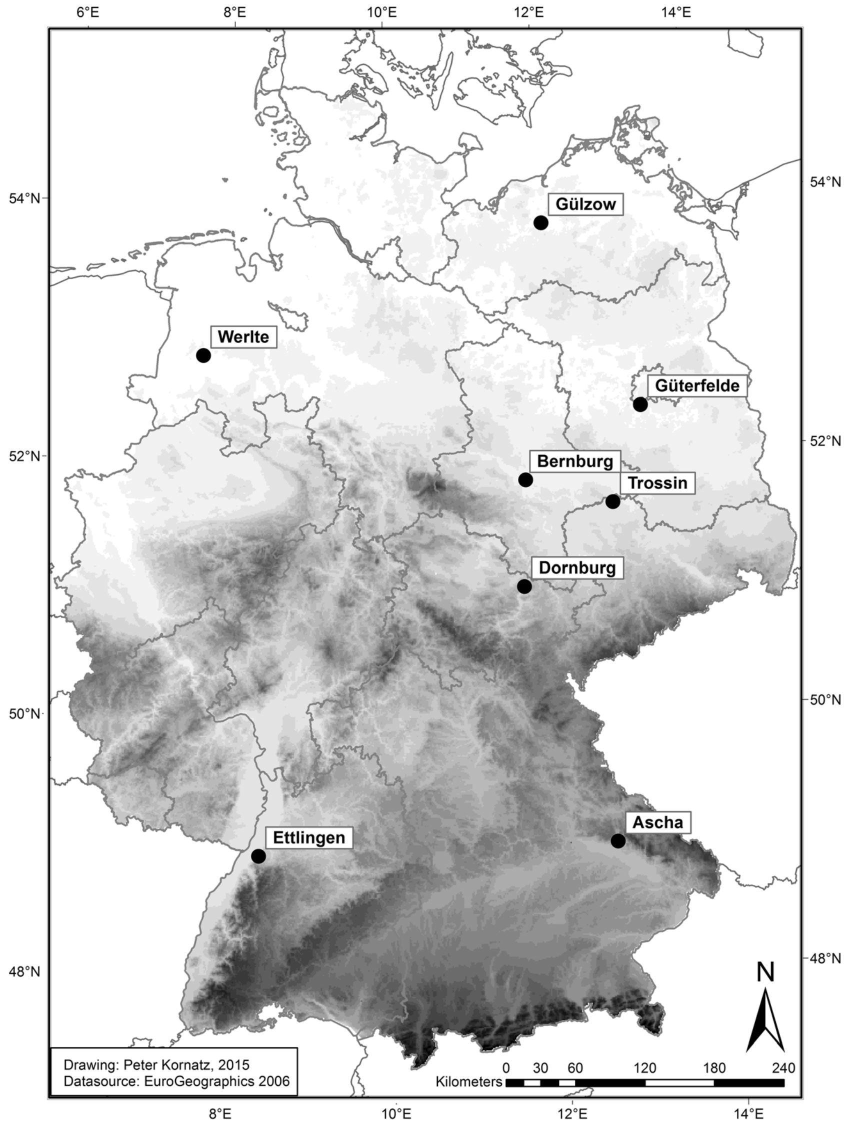

Fig. 1 Geographical position of the sites of the crop rotation experiment summarized in Table 2

which consisted of a different (but usually large) share of potential energy crops. The high share of energy crops was chosen to allow for testing a wide range of crops while making the best use of limited experimental time and area. Five crop rotations were started in 2005 and repeated identically in a second trial in 2006 in order to take effects of varying weather conditions into account. Two runs of the crop rotations were conducted, the second starting in 2009 and 2010 (Table 2). In the fourth year of each rotation, experiments were finalized with the cultivation of winter wheat for quantifying rotation effects of the designed rotations and the different energy crops.

During the trial period, a set of parameters was measured and determined, including soil chemistry characteristics, weather, crop phenology, biomass accumulation, final yield and quality, crop diseases and pests, weed flora, and management practices (see also [23]). All investigations followed a uniform, standardized protocol. Any of the participating institutions are today certified according to the rules of good experimental practice of Directive EU 284/2013 [27].

The experiments were mainly established in randomized block design or in split plot design [28] as marked in Table 1. As a common standard, four replications of plots, each with side plots, were established. At the sites with split plot design, strips were included as replicated check plots to account for eventual soil variability. The size of single plots ranged from 9 to 31 m^2, depending on the site and available technique. For the evaluation, all values were calculated as dry matter (DM) mass units; defective values in yield measurement (e.g., due to damage by wild hogs) were erased.

Methodical features of the experiment were oriented towards questions of practical relevance for advisory purpose. Crop choice, the selection of a tillage system with plowing before the establishment of main crops and production aims (such as a relevant dry matter content for ensiling biogas crops at 28–35% DM), was specified for all sites. Selection of

Table 1 Sites of the crop rotation experiment “EVA” and specific site characteristics [23, modified]

Location name	Federal State	Average precipitation (mm)[a]	Average annual temperature (°C)[a]	Soils (FAO)[b]	Soil value[c]	Predominant crops[d]	Plot experimental design
Ascha	Bavaria	807	7.5	Stagnic Cambisol	47	Wheat (w), potatoes, forage	Randomized
Bernburg	Saxony-Anhalt	511	9.7	Chernosem	90	Wheat (w), sugar beets, oilseed rape	Randomized
Dornburg	Thuringia	584	8.3	Luvisol	65	Wheat (w), barley (w), oilseed rape	Split plot
Ettlingen	Baden-Wuerttemberg	771	10.3	Regnosol	75	Maize, wheat (w), barley (w)	Randomized
Gülzow	Mecklenburg-Western-Pommerania	560	8.9	Planosol	51	Wheat (w), oilseed rape, barley (w)	Split plot
Güterfelde	Brandenburg	570	8.9	Alveluvisol	29	Rye (w), maize, potatoes	Split plot
Trossin	Saxony	554	8.9	Gleyic Cambisol	31	Wheat (w), maize, potatoes	Split plot
Werlte	Lower Saxony	769	9.0	Stagnic Cambisol	40	Maize, cereals (w)	Split plot

[a] 30-year average (1961–1990). [b] According to FAO classification. [c] Soil rating value (max. 120 points). [d] Data from the official statistics. *(w)* = winter

cultivar, fertilizer amounts, and crop protection as well as the scheduling of measures were applied site-specific according to the recommendations and guidelines for farmers of the participating regional institutions. Compared to a strict uniform choice of measures, this kind of grouping of factors into a complex factor “site/optimum choice according to regional guidelines” poses a higher responsibility on regional participating institutions and does not exclude divergences in decision behavior (e.g., risk aversion) between those. According to Eckner et al. [29], a higher value and transferability for practical agriculture could be expected.

Data collection was performed in Microsoft Excel and Microsoft Access. The R software environment (version R-3.1.1 [30]) was applied for statistical analysis. Descriptive statistics (relative frequencies and means) were calculated for each categorical variable. Linear mixed-effects regression analysis (R package lme4, version 1.1-6 [31]) was used to investigate the difference between maize and an alternative crop, accounting for location and annual as random effects. The best model was chosen based on Akaike’s information criterion (AIC) and likelihood ratio tests. Confidence intervals were estimated by bootstrapping [32]. Additionally, a simple analysis of variance (one-way ANOVA) for the yield comparison between maize and the alternatives was conducted for each year and site.

Presented yield data of the major alternatives (triticale whole crop, sorghum, perennial fodder crops, and double-cropping options) were compared with maize cropping on eight sites using 4 years each.

For better interpretation, the results of winter wheat, which was grown in the fourth year of the rotation (Table 2), are presented in an aggregated form. The yields were transformed to relative values for each set of site-year combinations. The denominator of this transformation was the mean value of wheat yields in CR 1 to 5, which were conducted on all sites in parallel. Based on this, relative wheat yield differences due to rotational effects were compared across all sites.

Ensiling and Biogas Production Potential

In order to test the suitability of different crop species from crop rotations for biogas production, samples of harvested material were taken and ensiled in 1.5-l preserving jars as described by [25]. Ensiling was conducted in triplicates per harvested crop material. The jars were stored for 90 days at

Table 2 Cropping plan of the crop rotation experiment, crop rotations 1 to 5 (CR 1–5) conducted on all sites in parallel

Year of cropping	CR 1[c]	CR 2	CR 3	CR 4[c]	CR 5[c]
2005/2006 / 2009/2010	Spring barley fodder radish (SZF)	*Sorghum*	*Maize*	Oats[a]	Spring barley alfalfa- or clover-grass-mixture (US)
2006/2007 / 2010/2011	*Maize*	*Forage rye (WZF)* *Maize (ZF)*	Forage rye (WZF) Sorghum (ZF)	*Winter Triticale*	*Alfalfa- or clover-grass-mixture*
2007/2008 / 2011/2012	Winter triticale Sorghum (SZF)	**Winter triticale**	Winter triticale annual ryegrass (SZF)	**Rapeseed**	Alfalfa- or clover-grass-mixture (US)
2008/2009[b] / 2012/2013[b]	***Winter wheat***	***Winter wheat***	***Winter wheat***	***Winter wheat***	***Winter wheat***

Italicized: yield comparisons presented. Bold: utilization as cash crop. *SZF*, summer intercrop/catch crop; *US*, undersown crop; *WZF*, winter intercrop; *ZF*, second crop

[a] Mixture of breeds. [b] Final crop in crop rotations at the sandy and dry sites Güterfelde und Trossin Winter: Rye. [c] Some changes were made from this set-up from 2009 onwards; these changes are not of relevance to the comparisons of this paper

25 °C. Silages were then tested for biogas and methane yields according to VDI-Guideline 4360 [33]. For each test, ensiled crop material and inoculum were filled into 2-l lab-scale reactors at an average organic dry matter (ODM) ratio $ODM_{Substrate}$ to $ODM_{Inoculum}$ of 0.5. The inoculum consisted of digestate from previous anaerobic digestion tests that were run with crop feedstocks. Reactors were incubated under anaerobic conditions at 35 °C over a period of 30 days. Biogas was collected in wet gas meters and the gas volume was determined daily by displacement of a barrier solution [33]. Biogas composition including methane and carbon dioxide concentration was analyzed using a portable gas analyzer (GA94, Ansyco). Methane yields were expressed as the sum of methane produced during the 30-day period and normalized to standard conditions (dry gas, 273.15 K, 1013.25 hPa), with reference to the ODM content of the digested crop material. A detailed description of the procedure of the batch anaerobic digestion tests is given by [26].

DM content of the silages was measured by oven drying at 105 °C, and ODM was analyzed by ashing of the dried samples at 550 °C according to [34]. By taking into account dry matter correction for losses of volatile compounds during oven drying [35] and by multiplying with yield results, methane yields per hectare could be derived.

Economic Evaluation

The results of the experiments that were determined at plot experiment and laboratory scale were transferred to calculate methane hectare yields to serve as a basis for an economic evaluation at commercial scale. To account for commercial level processes, an estimation of 12% dry matter losses during harvest and ensiling was assumed. For biomass that had to be wilted for proper ensiling (perennial fodder crops, forage rye), additional 10% DM losses were included for the extra process.

The values of biogas yields used for the economic evaluation were derived as explained above. To provide an estimation of commercial scale yields, in the first step, the values determined in batch tests were aggregated for each crop species specific to the position within the crop rotation, the cutting regime, the range of DM content, and to the stage of growth at harvest. In the second step, these biogas potential values were set into relation to the values for maize silage. In the third step, these relative values were applied to calculate a commercial scale estimation by multiplying them with the well-known standard value of the maize silage methane-potential deducted from experiences of commercial scale biogas plants ($338\ L_N\ kg_{ODM}^{-1}$) [36]. To estimate the monetary output of the production process, the value of silages was not solely based on mass units, but on the overall methane production potential of the production per hectare. The value for methane was estimated at $0.33\ €\ m^{-3}$ (which equals a price of maize silage of $33.5\ €\ t^{-1}$ fresh matter—and results in an equivalent contribution margin to a wheat production system with a product price of $192.5\ €\ t^{-1}$).

The benefit of each crop production process was then used to calculate a contribution margin per hectare, which serves as an overall criterion of economic feasibility. Standard methods were used [37] with the peculiarity that in contrast to general contribution margin calculations, we also included the fixed costs of machinery, as they may differ from crop to crop.[1] All direct costs such as seed plant protection and fertilizer costs as well as all labor costs that can be attributed to the production system were subtracted from the calculated benefit. The data for the production procedure costs were taken from KTBL databases [36, 38]. These values allow for a differentiated comparison between cropping options.

Data Availability The data that support the findings of this study are available from the participating institutions but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. However, data are available from the authors upon reasonable request and with permission of the participating institutions.

Results

Single Cropping Options: Winter Triticale as Whole Crop for Ensiling

At all sites, the yield level of winter triticale was lower than the yield level of maize (Fig. 2). On average, the calculated significant ($P < 0.001$) yield deficit of winter triticale in comparison to maize across all sites accounted for $-8.12\ t\ ha^{-1}$.

Significant calculated yield deficit ($P = 0.05$) varied considerably between all sites. While the shortfall was highest in Ettlingen ($-10.3\ t\ ha^{-1}$), the differences in yield ($-4.11\ t\ ha^{-1}$) were less distinct on the relatively cool and dry loess site Dornburg (Fig. 2, bottom). At this site, result can be explained by the high variation of maize yields between the years.

In Trossin and Güterfelde, both dry and sandy eastern German sites, also high variations of maize yields between the years were observed. Overall, a minor variation of triticale yields (between the years) is noticeable.

Sorghum as Whole Crop

Sorghum yields were lower than maize yields. The mean yield of sorghum over all years and sites was $13.32\ t\ ha^{-1}$ while the average yield of maize shows a higher level ($17.59\ t\ ha^{-1}$). The difference was significant at all sites, except for

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[1] However, other overhead costs like machinery shelter were not included but assumed to be constant.

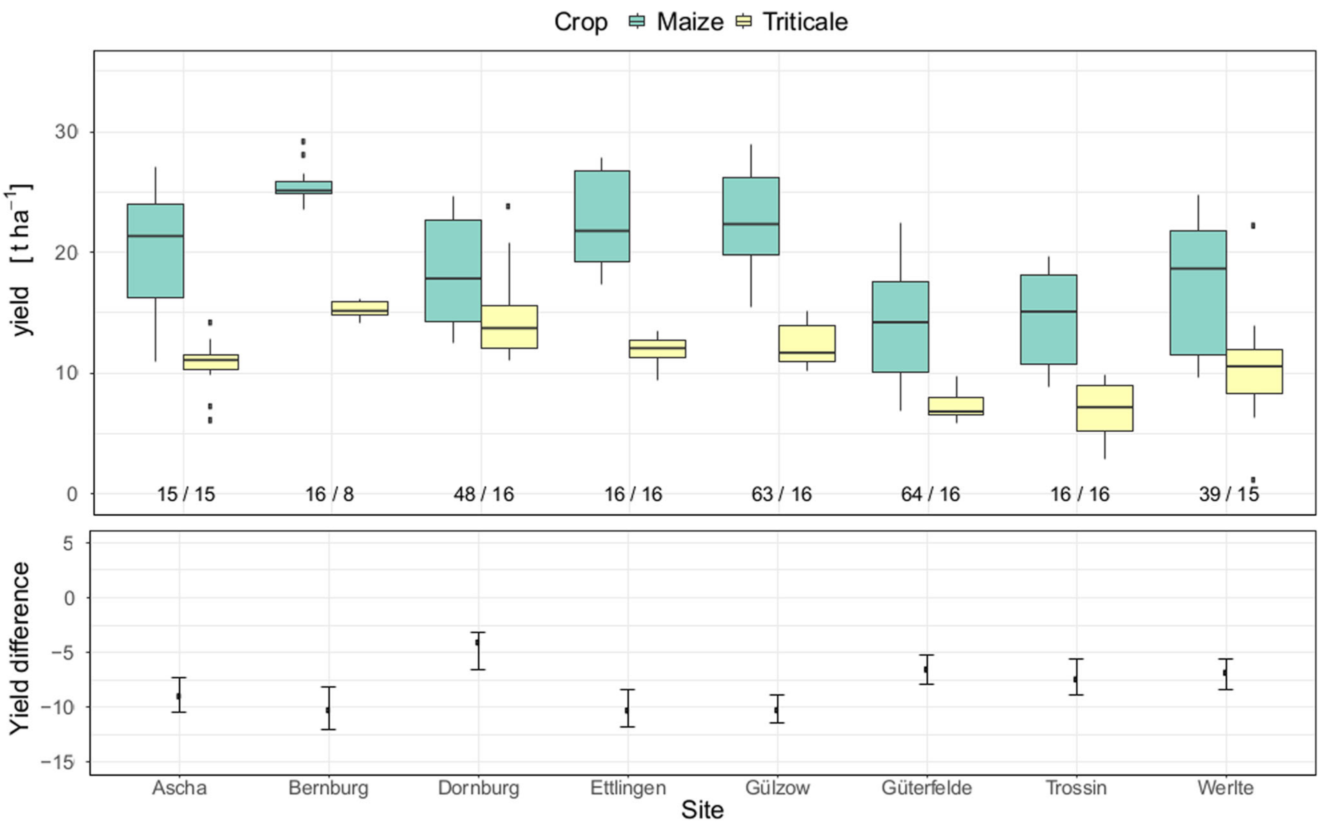

Fig. 2 Observed dry matter yields for maize and triticale (top) and calculated mean yield difference for triticale in comparison with maize (bottom) at different sites of cultivation. Values below zero represent yield deficit of triticale in comparison to maize and error bars show the 95% confidence interval. Numbers represent total number of repetitions for maize/triticale. Four-year comparison, Bernburg only 2 years. Maize yields from CR 1, triticale from CR 4/5, see Table 2

Güterfelde. Yield differences in Dornburg and Trossin reveal relatively small deviations. This indicates that on dry sites characterized by soils with low water-holding capacity, sorghum yields are closest to maize. At the sites with high differences to maize yields (Ascha, Bernburg, Ettlingen, Gülzow, and Werlte), the yield relation is mainly determined by the high yield level of maize. In this regard, the results on the site Ettlingen, south-western Germany, are most remarkable, where maize yields reached levels of 17.83 t ha^{-1} to 23.31 t ha^{-1} (Fig. 3). Low yields of sorghum can serve as an explanation only in the case of Werlte, possibly due to a low adaption to cool summer temperatures of available sorghum cultivars.

Perennial Fodder Crops

Clover-grass and alfalfa-grass mixtures showed moderate yields (average of all sites and years 11.86 t ha^{-1}) in comparison to maize (19.56 t ha^{-1}). In view of the entire 4-year trial, nearly all sites revealed significantly lower yields of perennial forage mixtures compared to maize (Fig. 4). As in the presented comparison between maize and winter triticale yields, the only exception was the site Dornburg. At this site, an alfalfa-grass-mixture showed significantly higher yields than maize in 2010. At the sites with higher precipitation (Ascha and Werlte), the yield of clover-grass mixtures was not significantly lower than the yield of maize in 1 of the 4 years.

Winter Intercrops Complementing Maize and Sorghum Cropping

Before sowing the C$_4$-crops maize and sorghum, forage rye can be grown and harvested to complement the yield quantity during the growing season. The average yield over all sites and years was 19.53 t ha^{-1} for forage rye-maize, 16.53 t ha^{-1} for forage rye-sorghum, and 19.27 t ha^{-1} for maize without previous winter intercrop (Fig. 5). A significant 4-year yield surplus in comparison to maize without winter crop was determined with the combination forage rye-maize at the north-western site Werlte, which is characterized by milder winter months (mean 4-year yields, 22.07 t ha^{-1} and 18.04 t ha^{-1}, respectively). On almost all other sites, the yield relations were balanced, which means that yield surpluses of the extra rye yield resulted in lower yields of the subsequent maize. On the dryer loess-sites Dornburg and Bernburg, significantly minor yields of both double-cropping options were measured.

In general, the combination of forage rye plus sorghum showed lower yield (3.0 t ha^{-1}) than maize. The disadvantage

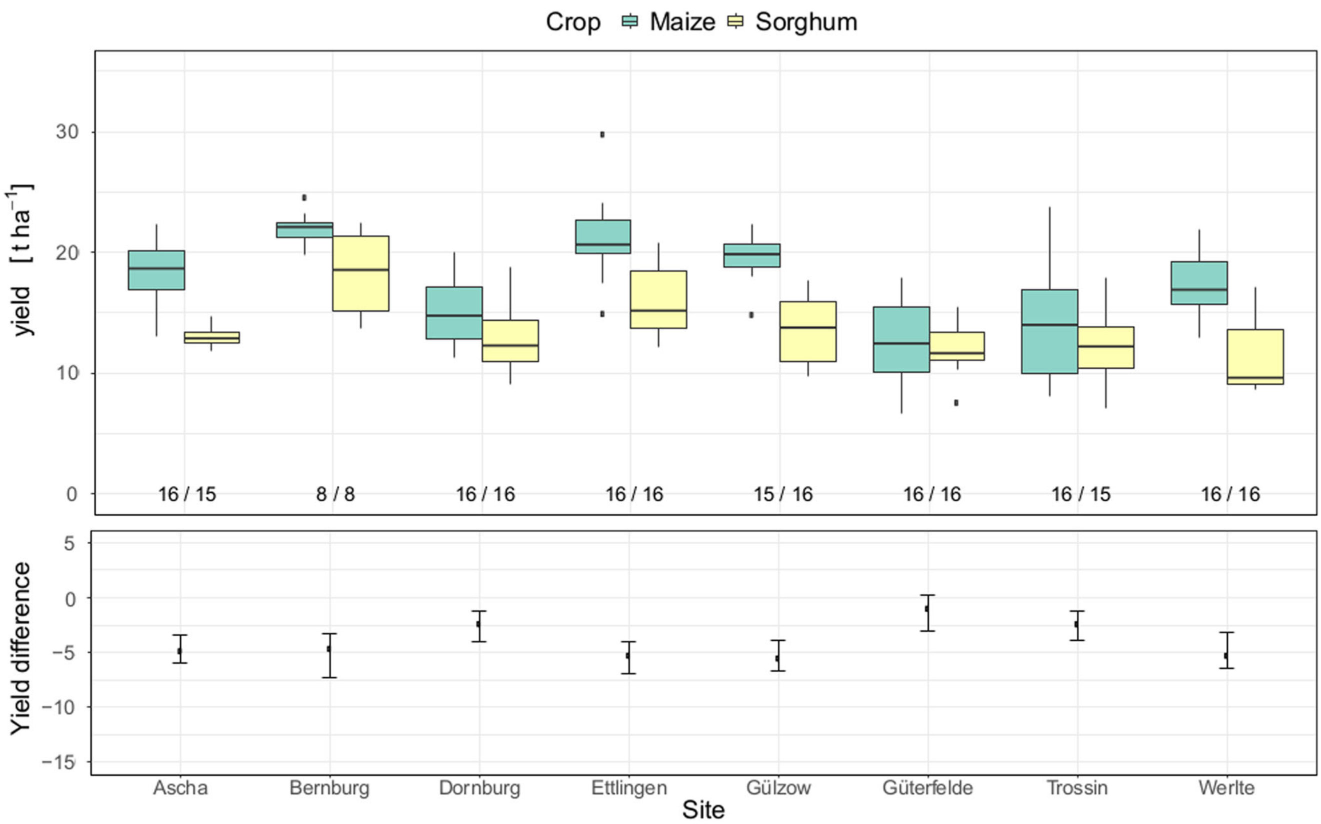

Fig. 3 Observed dry matter yields for maize and sorghum (top) and calculated mean yield difference for sorghum in comparison with maize (bottom) with respect to different sites of cultivation. Values below zero represent the yield deficit of sorghum in comparison to maize and error bars show the 95% confidence interval. Numbers represent the total numbers of repetitions for maize/sorghum per site. Four-year comparison, Bernburg only 2 years. Maize yields from CR 3, Sorghum from CR 4/5, see Table 2

in relation to maize systems is less marked, if set into relation to yield differences without winter crop. If more productive breeds for sorghum are going to be available, probably competitiveness to maize cropping might initially be achieved on sites with winter intercropping.

Biogas Yields

The conversion of the energy stored in the biomass to methane via anaerobic digestion differs from feedstock to feedstock (Fig. 6). The experiments reveal that most feedstocks indicate a methane yield per kilogram of dry matter lower than that of maize. Grasses/cereals cut in a vegetal state of growth are an exceptions. Harvested in a later growth state, whole-crop cereals produce at least similar methane yields as maize. Sorghum shows lower yields compared to maize silage.

Economic Evaluation

Table 3 shows contribution margins (including fixed costs for machinery) for the crop-site combinations (Figs. 2, 3, 4, and 5), for which the alternative to maize was regarded as most promising.

As presented in Table 3, even these most promising crop-site combinations reveal economic disadvantages compared to maize cropping without winter intercrop. This also applies to the combination of maize with forage rye in Werlte/Lower Saxony, which showed comparatively higher yields. The yield surplus, which can be achieved by the additional forage rye intercrop, cannot make up for the much higher cost of the entire production system of two crops. Despite a surplus yield of 4 t ha^{-1}, a difference of more than 130 € ha^{-1} is to be expected, which can be explained by the higher cost of intercropping and the lower yield of the second-crop maize.

Winter cereal cropping as whole crops is less disadvantageous than the double-cropping system compared to maize cropping. For example, the minor difference in the contribution margin in Dornburg/Thuringia is approx. 37 € ha^{-1}. This can be explained by the much lower production cost in triticale cropping (e.g., seed cost).

Alfalfa-grass-mixtures, contrastingly, provide a low contribution margin of 190 € ha^{-1} and a difference of 228 € ha^{-1} to maize cropping. Based on this, competitiveness with maize cropping for biogas is not in reach. Even more, the cost during the first year of cropping (sowing under spring barley) was not included and could be subtracted from the revenues in the main cropping years, which were evaluated here. If—as in

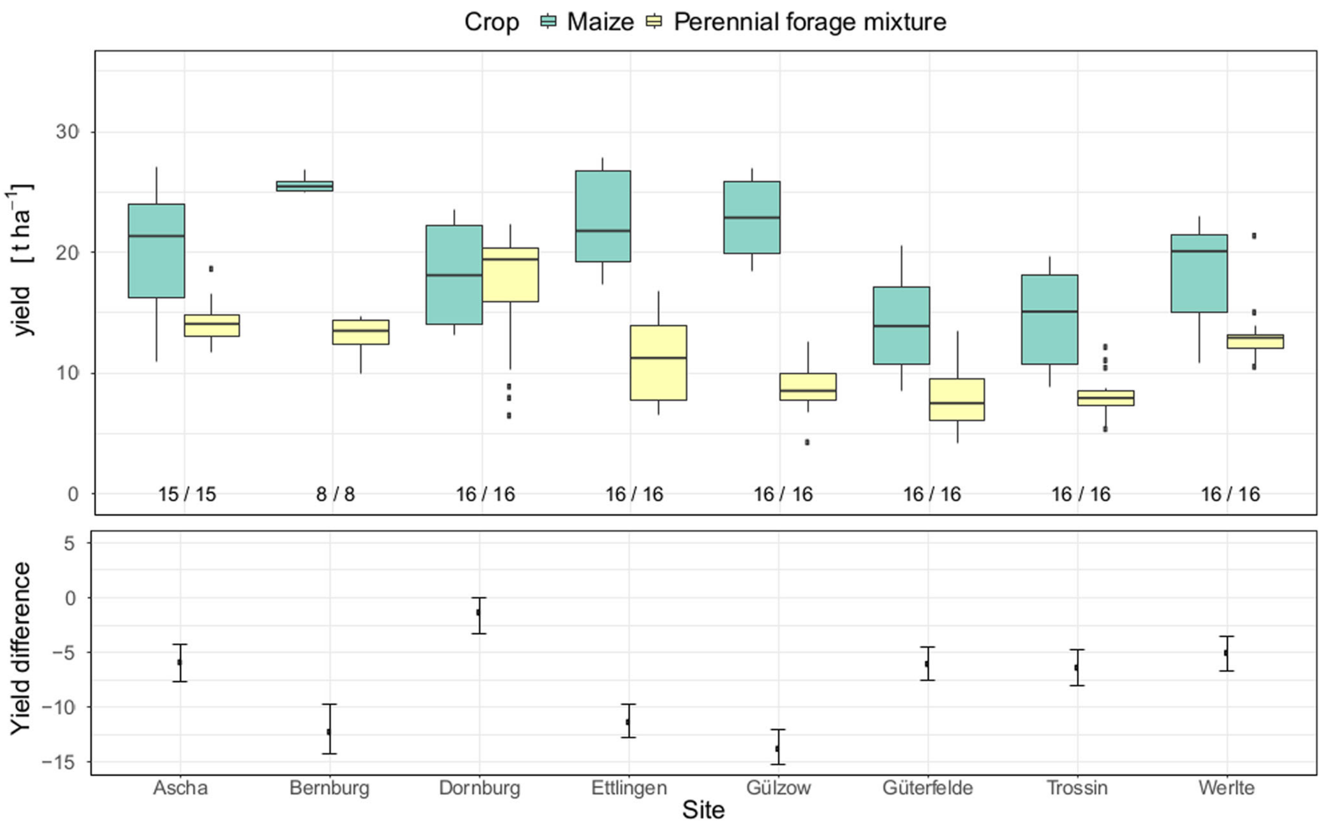

Fig. 4 Observed dry matter yields for maize and perennial forage crops (top) and calculated mean yield difference (bottom) at different sites of cultivation. Values represent the yield deficit of perennial forage mixtures in comparison to maize and error bars show the 95% confidence interval. Numbers represent the total numbers of repetitions for perennial fodder mixtures/maize. Four-year comparison, Bernburg only 2 years. Maize yields from CR 1, perennial forage mixtures from CR 5/4, see Table 2

the cropping experiment—only two main usage years are considered, an additional 77 € ha^{-1} of costs has to be taken into account. Sorghum on the dry site Güterfelde/Brandenburg, where yields are almost comparable to maize, showed an economic disadvantage compared to maize of 116 € ha^{-1}. This disadvantage can be explained by the lower methane yields of the feedstock and the relatively low dry matter content—which leads to higher transport cost during harvest and digestate spreading operations.

Crop Rotation Effects

Yields of wheat after different pre-crops indicate a relatively high variation within the tested energy crop rotations (Fig. 7, relative values).

It becomes obvious that rapeseed and sorghum depict good properties as pre-crops (mean value, 106.3% of winter wheat mean yield at each site and 107.1%, respectively). Winter triticale as a pre-crop, harvested as grain, showed the risk of lower yields of a following winter wheat with 95.5% mean yield compared to each site's mean yield, whereas whole crop harvest of triticale in combination with a summer catch crop merely showed a minor yield deficit of subsequent wheat cropping with a mean value of 98.9% and just slightly below the yields of wheat after perennial fodder crops (100.4%) and maize (102.6%).

Discussion

Options for Diversification of Crop Rotations

Whole-Crop Cereals Findings from literature reveal that under certain Central European conditions, whole-crop cereals reach yield quantities of maize silage with dry matter yields up to 20.0 t ha^{-1} [12, 14]. Yields in the presented EVA field trial were on the fertile loess-sites at on average 15.0 t ha^{-1} and on the less productive diluvial sites at approx. half of this amount which was below maize yields at all sites. One explanation for the lower yields compared to other specific trials was that the harvest had to take place at the beginning of milk ripeness to provide good biomass qualities for ensiling (DM content between 28 and 35%). At the time of milk ripeness, maximum yield is not yet achieved, especially on dry and sandy sites.

The methane production potential of whole-crop cereal feedstocks is appropriate for biogas production. In addition, production costs are relatively low which increases the

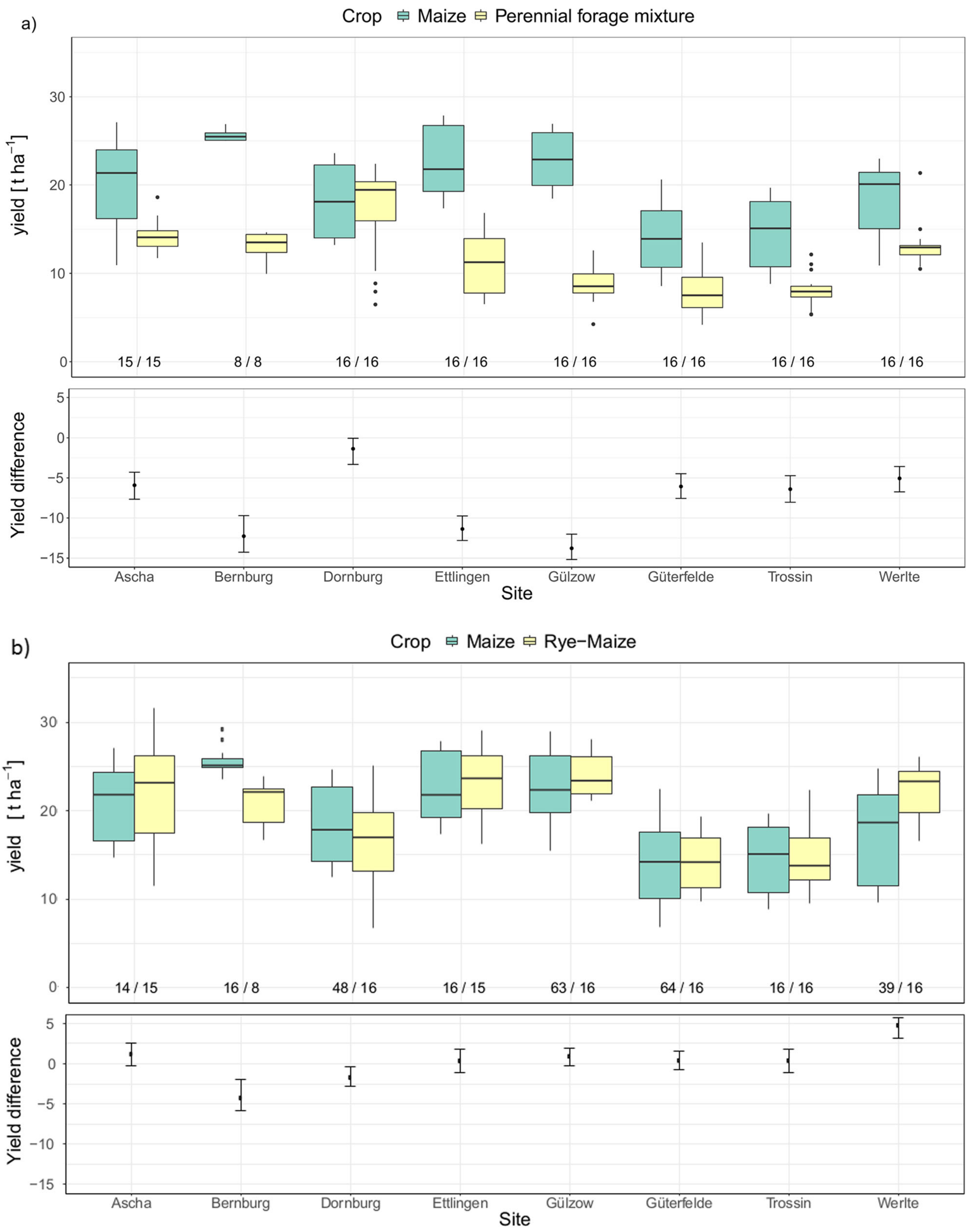

Fig. 5 Observed dry matter yields for maize and double-cropping options forage rye + sorghum (**a**) and forage rye + maize (**b**) (top in both a and b) and calculated mean yield difference (bottom in both a and b) at different sites of cultivation. Values represent the yield differences of double-cropping options with respect to maize and error bars show the 95% confidence interval. Numbers represent total numbers of repetitions for maize/double-cropping options per site. Four-year comparison, Bernburg only 2 years. Maize yields from CR 1, double-cropping: forage rye + sorghum from CR 3 (a) and forage rye + maize from CR 2 (b), see Table 2

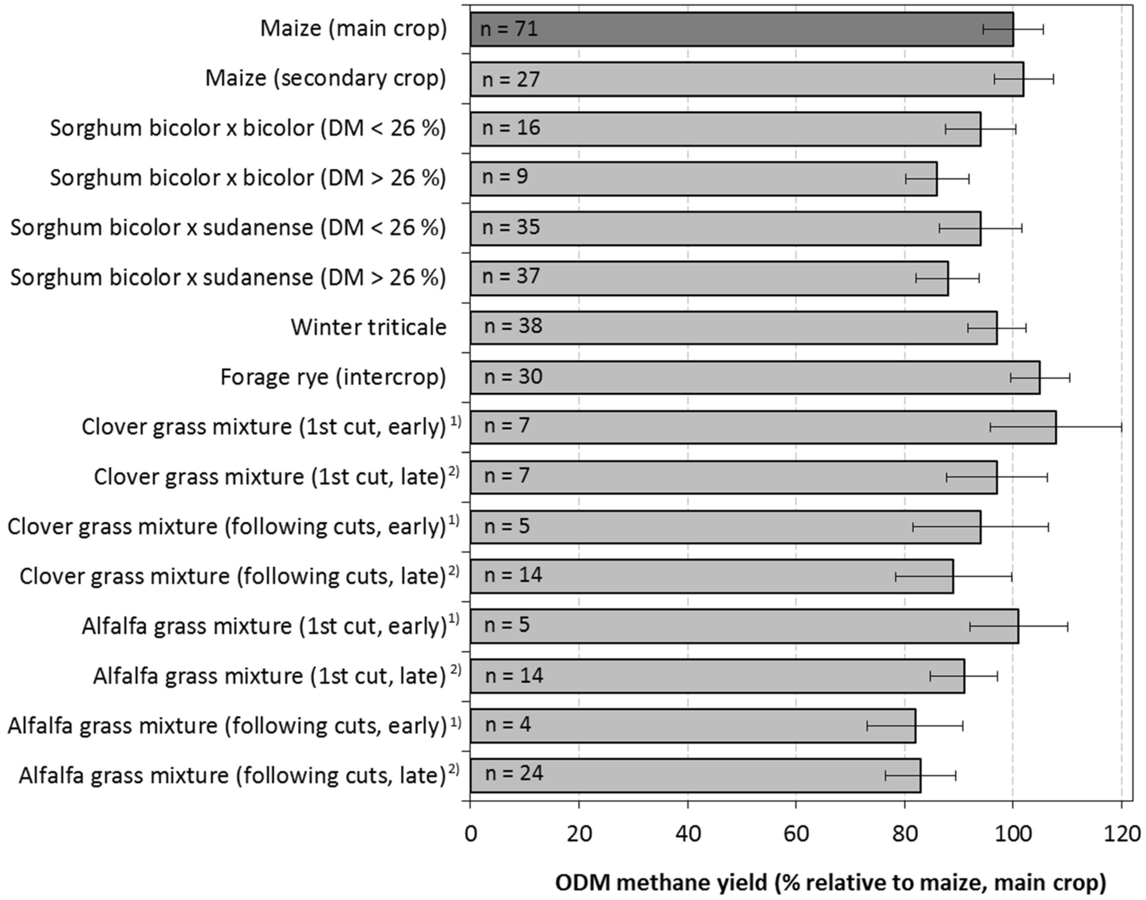

Fig. 6 Methane yields of different crop feedstocks from the EVA-experiment. Only silages with good or very good ensiling quality were considered (boxplot: median, quartiles, and extreme values, mean. *n* = number of tested silages, for every silage 2 to 6 repeated measurements; ODM = Organic dry matter) [25]

suitability of whole-crop cereals on cool temperate and productive sites.

Compared to grain cereal production for market purposes, cost reduction potential exists with regard to insecticide and fungicide applications. Less fungicide application is an option due to a less progressed infestation of fungal diseases at the time of earlier harvest and lower quality requirements for biogas production [13]. Compared to maize, lower seed cost plays an important role.

Sorghum Sorghum showed better results than whole-crop-cereals from a yield perspective. However, compared to multiple-year mean yield of maize, sorghum could not provide higher yields on any of the sites investigated. On the sandy diluvial eastern German sites, a comparable yield potential is confirmed. We conclude that sandy soils and insufficient precipitation during the vegetation period (i.e., water deficits during growth) diminish the relative disadvantages of sorghum. Nevertheless, ripening patterns of most of the commercially available and not fully adapted breeds on Central European sites are unfavorable. Given systematic breeding efforts for adaptation to Central European conditions are relatively young, it may be expected that a higher suitability for cropping on sites with low water-holding capacity and precipitation sums of less than 600 mm is possible in the medium term. In the future, higher specific methane yields and an adaptation to temperate climate and, thus, a better ripening process in temperate autumn conditions might lead to a better economic performance. However, water availability is of central importance for provision of biomass yields. Despite the higher soil water utilization capacity of sorghum compared to maize [11, 21], water was clearly identified as yield-limiting factor.

Perennial Fodder Mixtures Perennial fodder mixtures were associated with relatively low yields except for Dornburg. At Dornburg, alfalfa cropping provided high yields and is regarded as an ecologically valuable alternative with respect to humus, nitrogen, and biodiversity [17, 18] effects. Not all of the sites had selected fodder mixtures representing the most productive mixtures available: In a parallel experimental trial, higher yields with perennial fodder crops were achieved on some of the EVA-sites [39].

Moreover, perennial fodder mixtures are able to provide resource-efficient biomass with large greenhouse gas

Table 3 Economic key figures of the most promising site-cropping option-combinations shown in Figs. 2, 3, 4, and 5. Calculated on the base of determined biomass yield figures and methane yield (Fig. 6) [36]

	Dornburg, Thuringia			Güterfelde, Brandenburg		Werlte, Lower Saxony			
	W. triticale, main crop	Alfalfa grass, main crop[b]	Maize, main crop	Sorghum	Maize, main crop	Green rye, catch crop	Maize, catch crop	Total	Maize, main crop
Crop yield (t ha^{-1})	38.6	52.3	62.1	44.3	40.3	28.5	49.3	77.8	57.8
Crop yield, dry matter (t ha^{-1})	14.7	15.4	18.2	12.1	12.5	6.1	15.9	22.0	18.1
Dry matter content (%)	38	31	29	28	30	23	32		32
Silage yield (t ha^{-1})[a]	33.9	46.0	54.6	39.0	35.4	25.0	43.3	68.3	50.9
Silage yield, dry matter (t ha^{-1})[a]	13.0	13.6	16.0	10.6	11.0	5.4	14.0	19.4	16.0
Methane yield (m^3 ha^{-1})	4031	3759	5056	2902	3228	1741	4430	6171	5049
Total benefit (€ ha^{-1})	1330	1241	1668	958	1065	575	1462	2036	1666
Seed costs (€ ha^{-1})	74		160	141	129	45	160	205	160
Fertilizer costs (€ ha^{-1})	180	74	207	154	143	107	185	292	206
Plant protection costs (€ ha^{-1})	23	3	90	74	89	41	46	87	73
Harvesting costs (€ ha^{-1})	317	680	402	338	323	280	356	636	387
Digestate dispersion costs (€ ha^{-1})	93	143	159	120	101	80	123	203	146
Misc. labor costs (€ ha^{-1})	262	151	232	214	200	159	78	237	187
Total cost (€ ha^{-1})	949	1051	1250	1041	985	712	948	1660	1159
Contribution margin (€ ha^{-1})	381	190	418	− 83	80	−137	514	376	507
Margin to maize cultivation (€ ha^{-1})	37	228		164		131			

[a] 12% silage loss. [b] Only the first year after year of establishment without costs of establishment

mitigation potential [40]. Owing to their positive effects on environmental parameters, small-grained legumes (alfalfa, clover) are suitable crops to comply with "greening"-requirements of EU agricultural policy.

Double-Cropping Systems/Integration of Intercrops The field trial results showed significant yield benefits due to an additional integration of intercrops (or double-cropping with two equally yielding crops) on only one of the sites, Werlte, which is sufficiently supplied with water and characterized by mild conditions during the winter period. Nevertheless, this yield benefit is insufficient to provide an economic profit, given the additional cost caused by the laborious productions system. Production systems with high yields and high costs might gain attractiveness in market situations with very high land prices.

Systems that aim at a later transition between the first and second crop leads to a more or less "equal" yield amount of both crops harvested in 1 year and possibly to a higher overall yield. With respect to the late establishment of the second crop, ripening and reaching adequate silage qualities are not safeguarded [20]. As the performance of double-cropping systems largely depend on water availability, a slightly better suitability of double-cropping systems compared to the sole cropping of maize can be achieved by irrigation [41]. In general, the cropping of intercrops is often based on further motivations, like erosion prevention.

Crop Rotation Effects on Winter Wheat Yield Regarding the entire cropping systems or crop rotations, in addition to yield and economic performance of individual cropping options, further effects on yields of subsequent crops have to be considered. In the presented trial, sorghum and rapeseed indicated good properties as pre-crops for winter wheat. Enhancing effects of rapeseed are well known and attributed to good nutrient supply for winter wheat [42]. To some extent, they are exploited in farming practice [43]. The observed positive effects of sorghum as pre-crop are rather unexpected: Analysis of the winter wheat after sorghum did not show significant differences in fungal infections [44] and the reasonably late harvest of most sorghum breeds under German conditions is usually not beneficial for a following winter crop—due to limitations in seedbed preparation and sowing times.

Relatively low yields of winter wheat after winter triticale are due to the close relatedness of the crops. A lower risk of such pre-crop-induced yield decline can be assumed if winter triticale is harvested as whole crop followed by a summer intercrop/catch crop. The low suitability of alfalfa-grass and clover-grass mixtures as pre-crops is contrary to expectations based on nitrogen fixation, remaining nitrogen-rich root biomass, and thus a good soil aggregate quality [45]. Observations may be explained by a well-adapted fertilizer application and relatively intense soil water utilization. Pre-crop suitability is not higher than that of silage maize, which

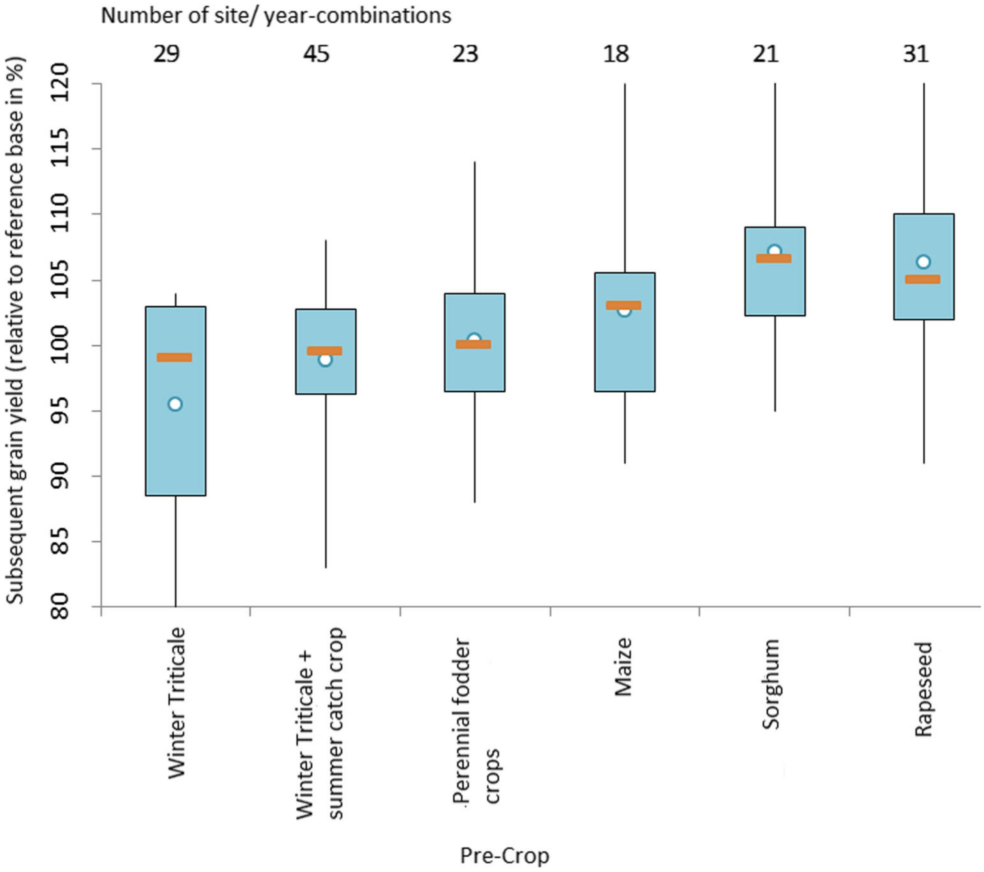

Fig. 7 Relative yields of winter wheat after different pre-crops/ pre-crop combinations in %. Reference base: 100% is the mean value of wheat for each site-year combination of wheat in CR1-CR5 (Table 2). The figure shows min/max, quartiles, median (lines), and mean value (circles)

again showed average to slightly above average pre-crop suitability for the succeeding winter wheat.

Limitations of the Crop Rotation Experiments and Evaluation

Evaluation of crop performance based on plot experimental data abstracts from a broad variety of choice situations in practical farming. Consequently, presented data does not reflect certain challenges, for example in work organization, storage management, plant protection, or fertilizer management given in large-scale farming.

Maize has been found to be the most efficient crop for biogas production. However, more comprehensive maize cropping has already raised herbicide intensity with a regionally increased focus on "problem weeds" [46]. With regard to fertilizer management, the chosen evaluation models cannot provide for regional or farm specific conditions. In regions with high organic fertilizer amounts and extended maize production, surplus fertilizer from biogas production even increases cost [47], while in other production systems (e.g., stockless organic farming), the management of digestates and crop rotations that facilitate nutrient supply provide for major benefits [48]. Specific subsidy regulations such as for legumes on "ecological priority areas" (greening) [5] can also be of relevance to economic preferences, but are not considered in the presented evaluation.

Conclusion and Outlook

Silage maize is clearly the most productive crop for biomethanation in Central Europe. Other cropping options go along with relevant disadvantages with regard to yield performance, substrate qualities, and/or economic performance. This also applies to the complementation of maize cropping with intercrops. In most cases, the performance of the main crop was weakened by the intercrop and additional production efforts lead to a much lower economic performance.

Still, the results suggest several agronomically feasible options to be included into typical crop rotations. Although the economic performance of the energy crop alternatives is at least slightly lower compared to maize, their property as "flowering plants" and contribution to increased biodiversity should not be neglected, as these benefits play a large role in political debates [49, 50] .

Future opportunities lie in focusing on the breeding and technical potential with regard to biomethanation of crops characterized by low digestibility but high yield expectations. These proposed options could promote diversity and help to mitigate environmental problems in the intensively used agrarian landscape.

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