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Impact of Energy Crop Rotation Design on Multiple Aspects of Resource Efficiency

Biogas production can cause environmental problems due to a biased alignment of one energy crop used as a feedstock, e.g., maize in Germany. Diversification of crop rotations and resource-efficient management can be the key to sustainable crop management. Four crop rotations on eight sites across Germany were evaluated in terms of their resource efficiency (area use, energy, and economic efficiency) to derive options. Analysis revealed high variation in all indicators under review, with a high variance explanation by the interaction between crop rotation and regional characteristics. Furthermore, results indicate that high area-specific methane yields do not equate to high energy efficiency. Crop management adaptation is a useful tool for optimizing resource efficiency.

Keywords: Anaerobic digestion, Biogas production, Cropping system, Methane, Regional crop management

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1 Introduction

A well-considered development of bioenergy production is assumed to improve the sustainability of energy generation by reducing greenhouse gas emissions and contributing to a secure energy supply [1]. However, the dynamic expansion of bioenergy production can cause environmental concerns, as in the case of maize-based bioethanol production in the USA, sugarcane bioethanol production in Brazil [2], or biogas production in Germany. Recently, arable land used for energy crop (EC) cultivation as biomass feedstock for anaerobic digestion amounted to over one million hectares (ha), representing approximately 8.3 % of the total arable land in Germany [3]. In addition to legal regulations, this trend has accelerated due to pressures for resource-efficient farming and specialization, encouraging maize cultivation in short rotations up to monoculture. Such practices result in diversification losses of crop rotation (CR), which can generate potential environmental damages [4]. Although the amended German Renewable Energy Sources Act [5] restricted the expansion of biogas plants fed with ECs by a reduction of the feed-in tariff system, approximately 7500 biogas plants installed in Germany [3] are under grandfathering and will run for the next 20 years, with sustained demand on crop biomass feedstock.

In general, long and diversely structured CR can improve soil fertility (by enhancing soil structure, reducing soil erosion, and maintaining sufficient content of soil organic matter), nutrient use efficiency (through reduced and demand-oriented fertilizer use), and biodiversity. Effective CR tends to reduce the input of crop protection agents and increase yields [6]. Thus, the benefits of diverse CRs along with improved resource-efficient management are key to sustainable EC management [7].

A large number of arable and novel crops (perennial, annual) can be grown as ECs. Crops with rapid growth, high yield of usable biomass, ability to grow under adverse weather and poor soil conditions, and with high resistance against pests and diseases are favored [8, 9]. ECs may involve altered harvest and sowing dates, as well as pesticide and nutrient needs, compared with conventional food crops, and can be implemented in traditional food CRs or in self-contained CRs. However, establishing new cropping systems comprises agronomic, ecological, and economic uncertainties and risks for farmers. On the other hand, there is growing pressure on farmers to prove the sustainability of their EC system to society. Moreover, to meet future land demands for food, feed, chemicals, and energy, it is important to prioritize production systems that are resource-efficient with regard to land area used, energy requirements, and cost per unit of product [10]. Hence, there is a growing demand for scientific research and long-term experiments on EC systems to provide knowledge and advice for sustainable

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energy CR management. It is a central issue for biogas production pathways to use resource efficiency as a focal indicator to detect the most efficient production lines for the global energy supply, including sustainable EC systems.

Multiple aspect sustainability analysis of EC systems should be performed based on empirical data, e.g., data from a German joint research project called EVA (Site-Adapted Cropping Systems for Energy Crops) [11]. The focus of the project was on the development of economically successful, resource-efficient, and environmentally friendly EC production systems with special regard to CRs, with the aim of providing suitable agricultural alternatives to the dominant cultivation of maize for biogas production. This project has been carried out in eight different regions to evaluate different CRs for biomass production in extensive field trials. The aim of this paper is to evaluate four CRs on eight sites in terms of multiple relevant aspects of their resource efficiency (area use, energy, and economic efficiency) to derive options for sustainable EC management for biogas production. The analysis results are expected to be valid for energy cropping in Germany, as well as for other regions, at least in Europe.

2 Materials and Methods

2.1 Plot Experiments

The plot experiments were performed at eight sites across Germany run by regional authorities (Fig. 1). The sites differed in edaphic conditions and represented typical agricultural growing conditions of different arable regions (Tab. 1). At each site, the same five standard and four optimized regional-specific four-year energy CRs were established as a randomized plot experiment. The experiments were run with four replicated plots for each CR type, and the entire experiment was replicated four times in parallel starting in 2005, 2006, 2009, and 2010. For our analysis, we selected four standard CRs as follows: two management-intensive CRs (CR 01 and CR 02), including maize as the main crop and a sudangrass hybrid double-cropping system, one extensive perennial field forage CR (CR 04), and one mixed CR (CR 03) with 50 % ECs and 50 % cash crops (Tab. 2). All CRs included winter wheat as the final crop, to detect CR effects, except in Brandenburg and Saxony, where the final crop was winter rye. The perennial field forage CR varied among the sites according to the cultivated forage species mix: alfalfa/grass, alfalfa/clover/grass, or clover/grass. The management of particular crops was optimized according to the regional praxis. Thus, variation in crop management was mainly related to differences in precrops, seeding dates, and harvest targets (whole crop harvest, green manuring, grain harvest, and straw harvest).

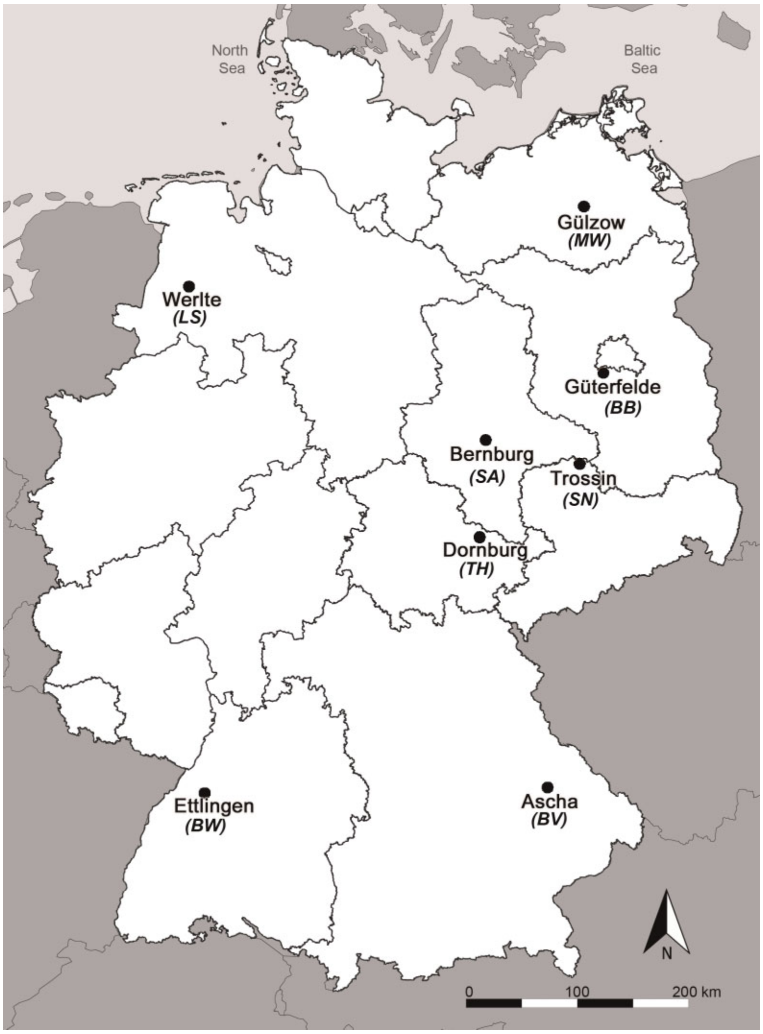

Figure 1. Location of EVA experiments in Germany.

2.2 Measured Parameters and Indicators Used

The sites were characterized by an extensive site investigation that described soil profiles and soil samplings up to 2 m depth with 6–8 replications. During the trial period, the following groups of parameters were observed: soil chemistry characteristics, weather, crop phenology, biomass accumulation, final yield and quality, specific methane yield of various ECs, crop diseases and pests, weed flora, and management practices. All investigations followed a uniform, standardized protocol.

To evaluate resource efficiency, three indicators were selected: area use efficiency, energy efficiency, and economic efficiency (Tab. 3). To avoid over-interpretation of individual aspects, the selected indicators were ranked equally and were not weighted.

Table 1. Site description of the EVA plot experiments.

Location name	Federal state	Climate precipitation [mm][a)] and average annual temperature [°C]		Soils (FAO)[b)]	Soil value[c)]	Predominant crops[d)]
Ascha (BV)	Bavaria	807	7.5	Stagnic Cambisol	47	wheat (w), potatoes, forage
Bernburg (SA)	Saxony-Anhalt	511	9.7	Chernosem	90	wheat (w), sugar beets, oilseed rape
Dornburg (TH)	Thuringia	584	8.3	Luvisol	65	wheat (w), barley (w), oilseed rape
Ettlingen (BW)	Baden-Wuerttemberg	771	10.3	Regosol	75	maize, wheat (w), barley (w)
Gülzow (MW)	Mecklenburg-Western Pomerania	560	8.9	Planosol	51	wheat (w), oilseed rape, barley (w)
Güterfelde (BB)	Brandenburg	570	8.9	Albeluvisol	29	rye (w), maize, potatoes
Trossin (SN)	Saxony	554	8.9	Gleyic Cambisol	31	wheat (w), maize, potatoes
Werlte (LS)	Lower Saxony	769	9.0	Stagnic Cambisol	40	maize, cereals (w)

[a)] 30 year average (1961–1990); [b)] according to FAO classification; [c)] soil rating value (max. 120 points); [d)] data from official statistics; (w) = winter.

Table 2. EVA CR description.

CR	Year 1	Year 2	Year 3	Year 4
CR 01	winter barley[a),] sudangrass hybrid [a)]	maize[a)]	winter triticale[a)], phacelia[c)]	winter wheat[b)],[d)]
CR 02	maize[a)]	winter rye[a)], sudangrass hybrid[a)]	winter triticale[a)], annual ryegrass[a)]	winter wheat[b)],[d)]
CR 03	oats mixture[a)]	winter triticale[a)]	winter oilseed rape[b)]	winter wheat[b)],[d)]
CR 04	summer barley[a)], undersown by field forage[a)]	field forage[a)]	field forage[a)]	winter wheat[b)],[d)]

[a)] biomass production; [b)] cash crop production, [c)] cover crop; [d)] in Brandenburg and Saxony winter rye instead of winter wheat.

Table 3. Overview of efficiency indicators, their focus, and literature source.

Indicator name	Focus	Source
area use efficiency [CH_4 yield Nm^{3}ha^{-1}]	methane yield per hectare	batch anaerobic digestion tests VDI 4630 [12]
energy efficiency (EROI) [output in MJ input MJ^{-1}]	efficiency of energy input	VDI 4600 [15], Ecoinvent [16] and KTBL [17] database
economic efficiency [Nm^3€$^{-1}$ha^{-1}]	methane yield per costs of production	KTBL [17] database and DLG [18]

2.2.1 Area Use Efficiency

Area use efficiency was determined by calculating potential methane yields from the harvested biomass of one ha, including only biomass from ECs. The given values were the total amounts of methane produced over the whole CR. Biomass-specific methane yields of whole crops grown in EVA CRs under different edaphic conditions were analyzed according to VDI 4630 under uniform conditions in batch anaerobic digestion tests [12]. The analysis contained samples from all eight sites of all five standard CRs and four regionally adopted CRs within all four replications. Based on these result datasets, the biomass-specific methane yields per ha were determined according to crop type, dry matter content of the silage, position in the CR, phenological development scale of the crop (German BBCH scale), and – for perennial crops – first cut or subsequent cuts [13]. To calculate the methane yield per ha, biomass losses on field and losses during storage in the silo must be calculated first; this study follows standard default values for DM losses of ensiled biomass based on Jeroch et al. [14].

2.2.2 Energy Efficiency

Energy efficiency, or energy return on investment (EROI), is the ratio between the sum of produced energy (output in MJ methane yield) and the cumulative energy demand (CED, input in MJ) to produce this yield. If the ratio (output/input) is less than one, more energy was required than the amount of energy produced, but if the ratio is greater than one, the product is an energy source. The amount of energy input (CED) comprised all primary energy required during production of the crop based on VDI 4600 guidelines [15]. The system boundaries were set from cradle to farm gate, starting with the production of all inputs and ending with the harvest of the crop and storage or ensilage of the biomass. For the calculation, a field size of 10 ha and a field-to-farm distance of 5 km was assumed. The project used datasets from the Ecoinvent database v.3.1 [16] to calculate CED related to the production (including raw material exploration, transportation, and production process ending with transportation to the regional storehouse) of the farming material (seeds, fertilizer, pesticides, agricultural machinery, fuel) by using datasets representative for Germany, or if not available, for Europe. The diesel amount for each field operation was taken from an online database, the "Feldarbeitsrechner", developed by KTBL [17]. Diesel consumption was dependent on the following parameters: machinery type used for field operations (including operating width and performance of the machinery), soil type, amount of seeds, fertilizer and pesticides applied, and crop yield harvested. The diesel demand for tillage operations was related to soil texture (fine, medium, and coarse), whereas harvest operations were related to the quantity of material harvested. Lower heating values were used as a characterization factor for the primary energy amount from different inputs, e.g., for diesel combustion, the value was provided by the Renewable Energy Sources Act [1]. The CED was then summed over the whole CR.

2.2.3 Economic Efficiency

Economic efficiency was calculated as methane yield per Euro per ha by taking into account the costs of all variables and the fixed costs of machinery and labor [18]. Labor requirements and diesel consumption were also taken from the KTBL [17] database, considering typical regional production methods. The methane yield per € production cost per ha was calculated by dividing the methane yield per ha by the total costs of all crops in the CR.

2.3 Statistical Data Analysis

Resource efficiency indicators were calculated for each single plot, i.e., each CR within each replication. Results for single crops, including cover crops, were summarized over the four-year CR. Statistical analyses were performed by using SPSS 19.0 [19]. Prior to analyses, variables were tested for normal distribution by using the Kolmogorov-Smirnov test. Data showed normal distribution; therefore, transformation was not required. The CR effects and variability of the efficiency indicators were analyzed by using generalized linear mixed models (GLMMs) [20], which accounted for nonindependent errors that might occur due to the hierarchically nested sampling design (here: regional sampling and site differences between experimental sites within the investigational regions). We tested the effects of CR and region as fixed categorical factors, with variability within fertilization (nitrogen (N) application rate), soil tillage (total tillage depth per CR), and labor requirements (the sum of working hours required for CR cultivation) as co-variates, influencing variability of the target variables at the micro level. The production and use of mineral N fertilizer was associated with high environmental burdens and costs. Consequently, N fertilization was one of the key factors that influenced the environmental impact and economic efficiency of CRs [7]. Within the same region, the N fertilization rate could vary widely between CRs; in particular, a high share of cereals in the CR could lead to a high N fertilization rate [7]. This also applied to the analyzed CR (Tab. 4); CR 01 and CR 02, including cereals and maize, required more N-fertilizer than CR 03 and CR 04 at all sites. CR 04, including perennial field forages with legumes, required very little N-fertilizer; however, this varied from site to site. Soil characteristics and CR design could influence the frequency and intensity of soil tillage during a CR. According to Nemecek et al. [7], some crops (e.g., pea and rapeseed) integrated in the CR improved the soil structure and, as a result, reduced the need for soil tillage. In the analyzed four CRs, CR 01 and CR 02, comprising six annual crops, required the most soil tillage and CR 04, comprising two annual and one perennial crop, the least (Tab. 4). Labor requirement was a key factor that influenced the economic efficiency, since it was related to cost-intensive machinery use and employment of labor. CR 03, comprising four annual crops, had the lowest labor requirement at all sites. The other CRs comprised more crops, resulting consequently in a higher labor requirement, since each crop needed to be planted and harvested. CR 04 comprised perennial field forage crop, which was harvested 3–4 times a year, resulting in an intensive labor requirement. From the output values, the significance of the model, coefficient of determination R^2, the significance of each single variable and their combinations, the estimated marginal means, and the means for construction of the homogenous subgroups, calculated by the Bonferroni test, were used for interpretation. In the second step, the variance explanation of the particular fixed factors and their interaction was analyzed by using covariance analysis and the Wald Z-test. Finally, variance explanation of the covariates was partitioned by applying "empty" GLMM runs without fixed factors by using the single covariates as random factors and subtracting their variance explanation from the overall variance explanation of the model with only regions and CR as underlying grouping variables (subjects) [21].

3 Results

3.1 Area Use Efficiency

The soil values of the experimental sites varied between 29 and 90 (German agricultural classification system for soil fertility, the best value is 120). The methane yields per ha showed a standard deviation of 38 % within the dataset under investigation; methane yields were strongly related to regional soil fertility values (R^2 = 0.794). The choice of CR among the four investigated types always accounted for a high standard deviation at the investigated sites (average 34.1 %), while the regional differences for a specific CR varied much less (average standard deviation = 26.1 %). Our results (Fig. 2) showed generic trends across sites: the superiority of CR 01 and 02 over CR 03 and 04, but also regional differences in the relative performance between CR 01 and 02 and between CR 03 and 04. On less fertile soils, CR 02 reached methane yields of at least the same lev-

Table 4. Overview of the three co-variates N-Fertilizer application rate, soil tillage, labor requirement of CR 01–04 by sites (average values, sum for four-year CR, marginal means over four rotations 2005–2013), and the number of field trial observations were the statistical analysis was based on.

		Location name							
Co-variates	**CR**	Ascha (BV)	Bernburg (SA)	Dornburg (TH)	Efftlingen (BW)	Gülzow (MW)	Güterfelde (BB)	Trossin (SN)	Werlte (LS)
N-Fertilizer application rate [kg N ha^{-1}]	01	823	864	614	704	726	545	553	662
	02	850	839	643	730	744	540	636	819
	03	609	632	507	536	652	396	418	542
	04	631	287	277	299	437	254	428	914
soil tillage [cm tillage depth]	01	120	158	196	251	160	158	113	193
	02	122	150	213	271	180	158	123	206
	03	100	118	187	215	132	152	96	141
	04	46	66	97	148	67	82	77	81
labor requirement [working hours ha^{-1}]	01	27	31	27	29	27	23	24	25
	02	30	31	28	31	30	24	24	32
	03	18	21	22	21	21	18	17	17
	04	25	25	29	30	24	22	22	37
number of observations	01	16	16	48	16	64	64	16	40
	01	16	8	16	16	16	16	16	16
	03	16	8	16	16	16	16	16	16
	04	16	8	16	16	16	16	20	16

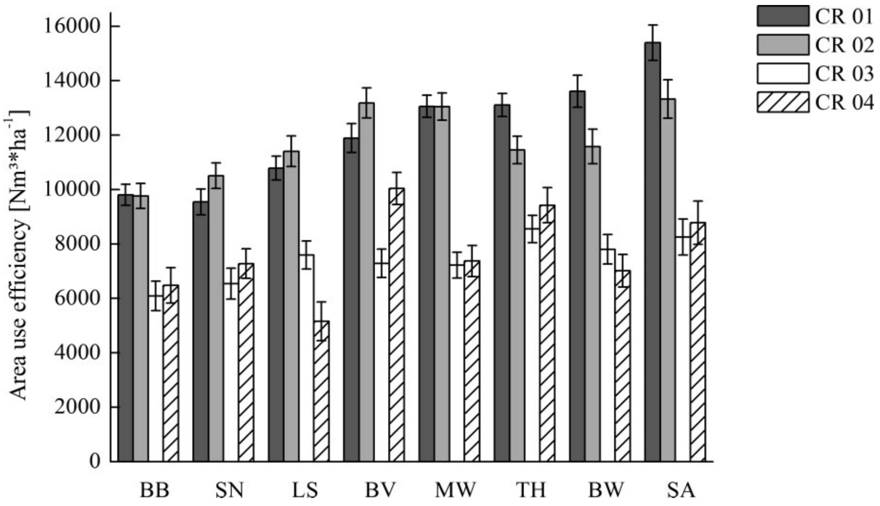

Figure 2. Comparison of area-related methane yields of CR 01–04 by site (sites ranked according to their soil fertility values from low (left) to high (right), average methane yield per ha, sum for four-year CR, marginal means over four rotations 2005–2013; the vertical bars represent standard error; the number of observations are described in Tab. 4).

el as that of CR 01; on highly fertile soils, CR 01 performed significantly better than CR 02. In general, CR 04 showed higher methane yields than those of CR 03, except for sites LS and BW. The relationship between soil value and methane yield differed among the CRs. For CR 01 and 03, a high dependence on soil fertility (R^2 = 0.599*** for CR 01; R^2 = 0.451*** for CR 03) was detected, but it was much lower for CR 02 (R^2 = 0.272***) and CR 04 (R^2 = 0.217***). The high impact of CR management can also be deduced from the standard deviation among CRs at each site, which ranged from 23.5 to 40.8 % of average methane yield, depending on the specific site.

3.2 Energy Efficiency

Despite the fact that the differences among the tested CRs showed similar trends for the EROI values as that for the methane yields, energy efficiency was less dependent on soil fertility. This was true both for the differences between CR 01/02 and CR 03/04, as well as between CR 01 and 02, and between CR 03 and 04 (Fig. 3). The standard deviation of the EROI values was 29.1 % of the average within the dataset under investigation. The coefficient of determination between EROI and soil value explained only 58 % of the variation among

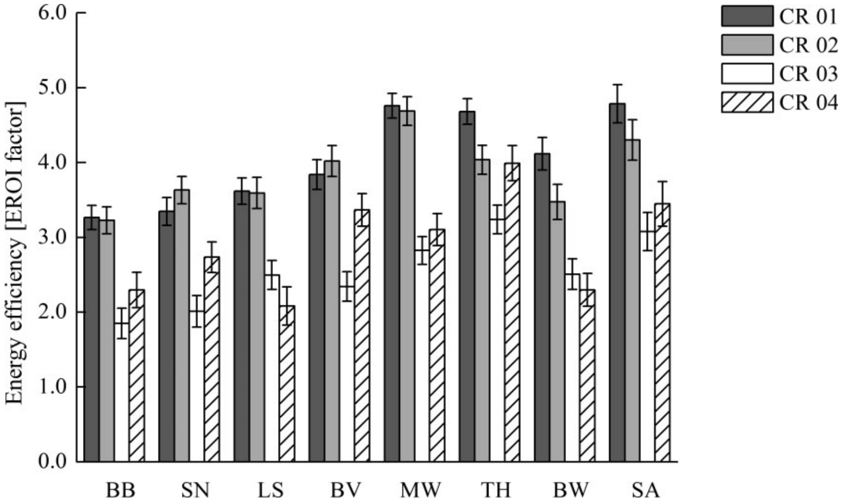

Figure 3. Comparison of energy efficiency of CR 01–04 by site (sites ranked according to their soil fertility values from low (left) to high (right), totals for the four-year CR, marginal means over four rotations 2005–2013; the vertical bars represent standard error; the number of observations are described in Tab. 4).

the sites (R^2 = 0.579). Energy efficiency revealed a relatively stronger dependence on soil fertility for CR 01 (R^2 = 0.383***), CR 03 (R^2 = 0.260***), and CR 04 (R^2 = 0.286***). CR 02 (R^2 = 0.110***) demonstrated a lower coefficient of determination. Fig. 3 indicates that the relationship between soil fertility and EROI more or less follows a saturation curve with polynomial curve fittings. Among the CRs tested, energy efficiency varied least among the different regions at CR 02 (standard deviation = 15 %), but the standard deviations of CR01 (22 %), CR 03 (29 %), and 04 (27 %) were almost twice as high.

3.3 Economic Efficiency

Economic efficiency showed a very different picture from that of the previously presented efficiency indicators (Fig. 4). In general, the performances of CR 01 and 02 are noticeably better than those of the other two CRs, but the differences are not significant for all sites (e.g., SN, BV, BW). The economic efficiency of CR 02 showed no significant relationship to soil fertility gradients (R^2 = 0.05, n. sign.). Differences in the economic efficiency of CR 01 and 02 differed only slightly between the sites, but the trend was significant for CR 01 (coefficient of determination with soil value R^2 = 0.301***). However, the economic efficiency of the mixed CR 03 varied greatly among sites and showed a trend to greater differences in sites with low soil fertility. Consequently, the standard deviation of CR 03 was the highest among the tested CRs, at 36 %. CR 04 tended to reach comparable economic efficiency with CR 01 and 02 on several sites (SN, BV, BW). This trend was not related to soil fertility.

3.4 Variance Explanation by Impact Factors

Analyzing the region and CR effects on the efficiency indicators, by taking variations caused by different management options into account, revealed a variance explanation between 70 and 87 % by the interaction of the two main factors: region and CR (Tab. 5). When broken down into individual factors, the choice of CR accounted for the higher part of the variance explanation. Regional impacts were particularly high for energy efficiency and low for economic efficiency. CR choice played an important role in area use efficiency.

Among the management covariates, the labor requirement fundamentally influenced the efficiency result. Soil tillage intensity had no direct impact on the efficiency indicators. Fertilization inputs strongly affected the energy efficiency, but only partly affected economic efficiency.

3.5 Integrative Efficiency Analysis

When analyzing the relationship between the efficiency indicators, a strong correlation emerged (Fig. 5). The EROI increased with higher methane yield per ha. This relationship was approximately linear, but with saturation tendency. The best fit could be achieved with potential approximation. The methane yield per € production cost increased with higher methane

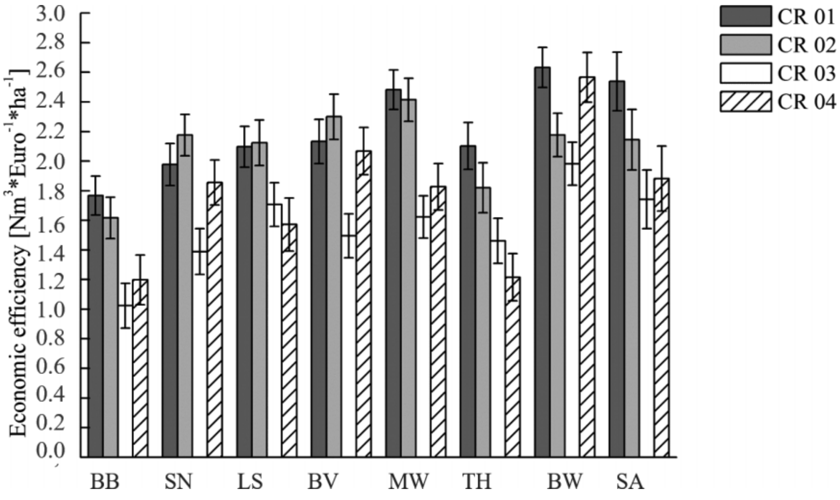

Figure 4. Comparison of economic efficiency of CR 01–04 by sites (sites ranked according to their soil fertility values from low (left) to high (right), sum for the four-year CR, marginal means over four rotations 2005–2013; the vertical bars represent standard error; the number of observations are described in Tab. 4).

Table 5. Details on the variance explanation, as provided by the particular model factors (upper part for fixed factors, lower part for co-variates; calculation based on covariance analysis performed by using GLMM).

Factor	Area use efficiency			Energy use efficiency			Economic efficiency		
	F value	Sign.	Variance explanation[a)]	*F* value	Sign.	Variance explanation[a)]	*F* value	Sign.	Variance explanation[a)]
CR	106.1	***	65.5	104.0	***	50.0	30.61	***	50.1
region	7.81	***	26.1	9.22	***	36.0	4.59	**	18.4
CR* region	12.83	***	86.8	10.41	***	77.0	8.84	***	66.1
CR × Region as co-variated by									
fertilization	0.54	n. sign.	17.1	26.0	***	32.9	8.94	***	5.2
soil tillage	0.01	n. sign.	13.1	0.37	n. sign.	4.6	0.00	n. sign.	0.6
labor requirement	134.29	***	57.8	47.95	***	36.9	55.46	***	50.2

[a)] Covariance tests after WALD; n. sign. = not significant; sign. = significance level, * = 0.05, ** = 0.01, *** = 0.001.

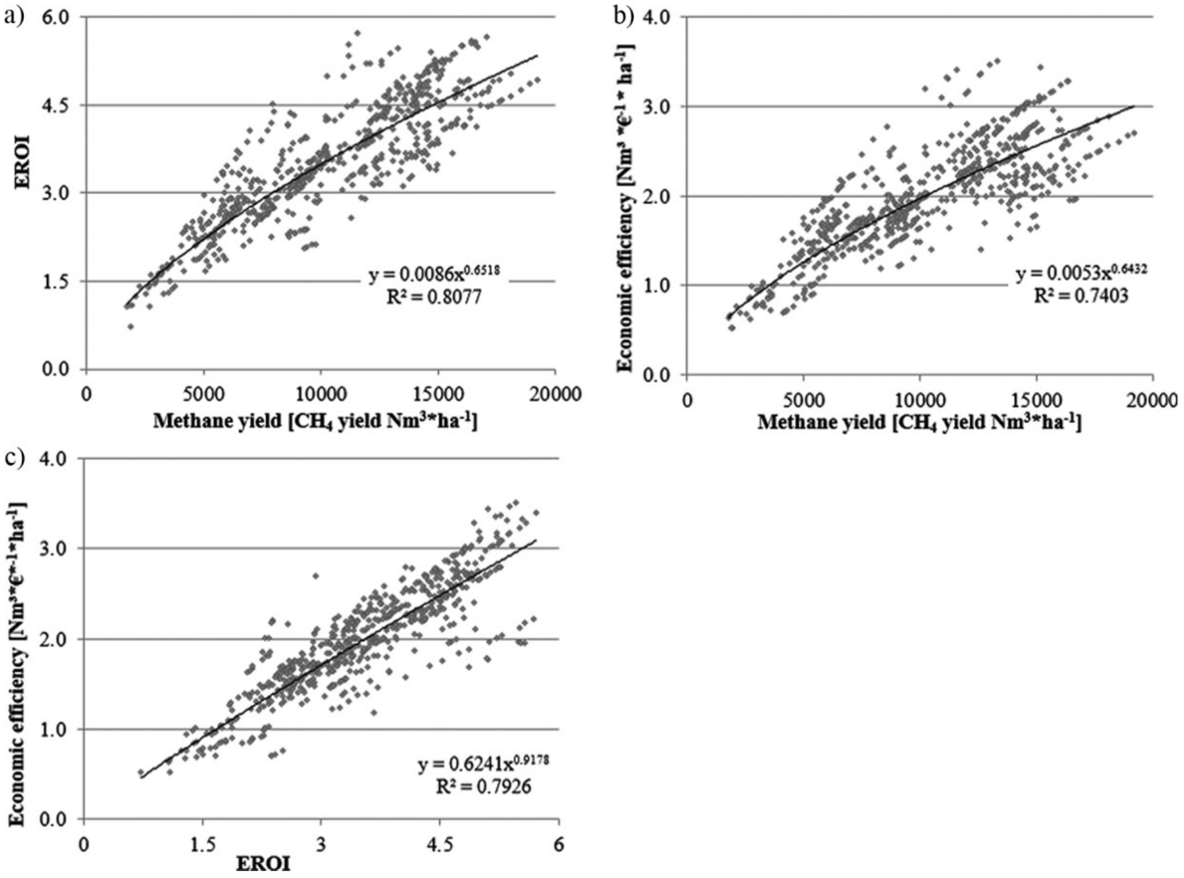

Figure 5. Internal relationships of the three efficiency indicators under review (correlation coefficient over all experimental sites and replications).

yields per ha and EROI factor. Both relationships could be best described with potential approximation. High methane yields served as prerequisites for high economic efficiency. From the graphs, it can be considered that this is not a single factorial relationship. Variation in economic efficiency increases considerably where yields exceed 10 000 $\mathrm{Nm^3}$ methane yield per ha over four years. On the other hand, cropping systems that guarantee a high energy efficiency (EROI) showed a strong relationship with high economic efficiency. Here, the relationship was approximately linear with a high gradient of the curve. Increasing EROI by 1.5 elevated the economic efficiency by 1 $\mathrm{Nm^3€^{-1}ha^{-1}}$.

4 Discussion

Various cropping systems, including ECs, are feasible, but their sustainability depends on site-specific criteria and farm management [6]. In the USA, 35 million ha of maize were harvested in 2007 alone for bioethanol production with an upward trend [2]. In Germany, 73 % of total biomass used as feedstock for biogas production is maize [3]. To reduce the potential negative impact of this specification and increase biomass yield, several crops have been investigated as alternatives to maize, as well as cropping systems involving maize production (catch crops, double-cropping systems) [22–24]. In accordance with our results, these studies revealed that management intensities and regional site potentials were also of major importance for improving the sustainability of EC systems [23]. In addition to existing comparisons of ECs reported by other authors [25, 26], we would like to draw attention to the design of CRs as a suitable tool to balance economic and ecological effects of different crops.

4.1 Validity of the Results in the Context of Other Publications

4.1.1 Area Use Efficiency

The reasons why farmers opt for maize are apparent: the crop is characterized by a high biomass and energy yield, as well as high water and nutrient efficiency [27]; consequently, the widespread cultivation knowledge among farmers results in high profitability. Consistent with our results, Gissén et al. [25] found varying performance of ECs regarding methane yield per ha in Sweden. Maize provided higher methane yields than forage grasses and hemp (environmentally friendly crops), but sugar beets produced the highest methane yield. For single ECs under similar site conditions, the dry matter yield of EC might be strongly affected by the nutrient supply through fertilization [28], but our results questioned the validity of this relationship in a multiannual perspective, for CRs, and across a variety of site conditions. We determined that not only did the crop type have a major impact on the methane yield per ha, but so did the design of the CR (e.g., cover crops, double-cropping systems), the position of the crop within the CR (harvest date), the site characteristics, and the type of management related to the crops. Good farming practice applies an optimal fertilization plan, including mineral and organic fertilizer, crop residues, and cover crops to maintain soil fertility. The interactions between previous and assessed crops (CR effects), such as nutrient shifts, reductions of cultivation operations, and workload peaks and different timing of farming activities not only have a large impact on the achievable methane yield per ha, but also on production efficiency [29].

4.1.2 Energy Efficiency

In accordance with our findings, Alluvione et al. [30] concluded that, due to large differences in energy conversion efficiency among the crops (e.g., C_4 vs. C_3 crops), the CR design seemed to be at least as important as adaption of crop management practices to energy efficiency. Alonso and Guzmán [31] found that organic farming management in Spain reduced energy input during crop cultivation and thereby enhanced energy efficiency. Poor management practice, however, can lead to increased energy input during crop cultivation and decreased energy yield, which is likely to reduce energy efficiency. Börjesson and Tufvesson [23] investigated different biofuel production systems and revealed that a 35 % higher biomass harvest led to an improved energy efficiency of 10 % (on average). These figures are in accordance with our findings: with an increased yield of 30 %, energy efficiency could be improved by 10 %. Börjesson et al. [26] analyzed six ECs used for vehicle gas production and detected a variation in energy efficiency ranging from 35 to 44 % per energy unit. Triticale had the highest energy efficiency, followed by maize, wheat, sugar beet, ley crops, and hemp. This is consistent with our findings, where the triticale-/maize-/sorghum-based CRs (CR 01 and 02) performed best across all sites. Nemecek et al. [7] determined nitrogen management to be the key driver for CED of arable CRs (in France), but our results revealed the labor requirement to be equally important. According to Alluvione et al. [30], energy efficiency was a suitable indicator to be integrated into life cycle assessments or multicriteria analyses; CR design and management could be included in the evaluation of their environmental impacts.

4.1.3 Economic Efficiency

In contrast to our results, in Sweden, cereal-based biogas systems proved to be more favorable than EC systems based on maize [23]. In the study by Gissén et al. [25], triticale showed the lowest feedstock costs per GJ of methane followed by beet tops, maize, and first- and second-year ley. A study in Italy also found triticale to have the best economic performance per product unit, followed by maize (grown as a first crop) and grasses [32]. As demonstrated by our results, the combined implementation of triticale and maize in one CR is highly efficient. The pronounced economic efficiency of maize was caused by high yields; the attractiveness of triticale and grasses resulted from low production costs. The high variation of the yield for forage grasses among sites and cultivation years implies a high risk for economic efficiency or deficient cultivation management. When focusing on the cost per unit of greenhouse gas reduction, forage-based biogas cropping systems perform best [26]. In addition, current biogas prices can have a major influence on the relative economic attractiveness of particular feedstocks compared with food crops [25, 32].

4.2 Evaluation of the Design and Impact Factor of CRs

Most sustainability assessments conducted for annual and perennial crop cultivation typically take into account only one vegetation period, from seedbed preparation to harvesting. The influence of the previous crop on the assessed crop is often outside the system boundary [29]. We overcome this problem by expanding the system boundaries and taking the entire CR into account. A comparison of the four CRs showed that CRs including a C_4 crop were the most efficient ones at all sites and across the efficiency indicators, but the design of the CR was also relevant. CR 01 and 02 had exactly the same portions of maize and other C_4 crops, but varied with respect to the effects considered. In particular, at sites with lower soil values, CR 01 was more efficient in terms of energy and area use than CR 02, and vice versa for sites with higher soil values. The variation between the four CRs at each site was higher than the variation between the sites. In accordance with the results of Mayer et al. [33], we found strong interdependencies between the cropping environment (soil fertility) and achievable methane yields per ha. Perennial forage grasses demonstrated many advantages, such as low production costs (economic and energy related), environmental friendliness due to low nitrogen and tillage demand, and growth under unfavorable conditions. However, CR 04 was not the most efficient CR because the methane yield varied greatly among the sites and years, and under most cultivation conditions it was lower than that of CRs with maize (CR 01 and 02). Combining energy and cash crops (CR 03) within one CR may be a reliable alternative for improving diversification of the EC system, soil organic matter (if chopped straw is left on the field) and resource efficiency. However, the functional unit chosen for our assessment (methane yield) made it difficult to integrate cash crops into the efficiency assessment, causing an underestimation of the CR output and consequently interfering with the resource efficiency results for CR 03. This CR would have performed better if the alternative cash crop (oilseed rape) could have been included in the indicators.

Our results clearly demonstrate that there is no ideal CR for all sites, since regional conditions and the corresponding crop management have a significant impact on CR performance. The indicators discussed are strongly correlated; therefore, by improving one of the indicators, the other two benefit as well. This indicates that economic efficiency does not necessarily conflict with other efficiency goals. The improvement is limited, however, by the potential relationship of the efficiency indicators. Nevertheless, the design of CR adapted to regional site conditions can be a useful tool for steering and optimizing resource efficiency.

4.3 Drawbacks and Advantages of a Multiple Efficiency Indicator Set

Börjesson and Tufvesson [23] stated that a broad system analysis approach was needed when different crop production systems were compared. The most important results of such studies may be the identification of parameters with the highest impact on the energy and environmental performance of ECs. Therefore, analyses have to consider local conditions and apply multiple indicators; otherwise, assessment results contain a high level of uncertainty and a low quality of their predictions. However, it can be difficult to interpret the results of multiple indicators to derive recommendations for action. Often aggregation or normalization are used to overcome this problem, but both approaches show methodological weak points and can cause a loss of information [34]. In our approach, we initially analyzed and interpreted the indicators separately to identify the management, CR, and site-specific parameters that influenced each indicator; only afterward did we perform an integrative efficiency analysis to test the relationship between these indicators. This method offers a way to analyze a large number of CRs cultivated under different local conditions. It provides experts with the possibility to compare resource efficiency from agronomic, energy, and economic points of view, and based on these results allows potential improvements to be determined by selecting the optimal CR and management for the specific region.

For farmers and policymakers, resource efficiency is the focal indicator for biogas production pathways to identify efficient and high-yielding production lines to secure the global energy supply. However, to determine sustainable EC systems, it will be indispensable to extend our analysis to include social and environmental indicators to cover all indicators of sustainability assessment.

5 Conclusion

There is a critical lack of knowledge among farmers, policymakers, and scientists regarding the impact of new EC systems and their resource efficiency; this knowledge gap prevents the introduction of newly designed CRs. To close this gap, we evaluated four CRs in eight sites in terms of different aspects of their resource efficiency (area use, energy, and economic efficiency) to derive options for sustainable EC management. Our results revealed that the efficiency of each CR was dependent on the regional conditions and related management, and that the three indicators were strongly correlated. Consequently, by improving one of the efficiency indicators, the other two also benefitted. The approach presented above can contribute to the further improvement of indicators and models used for assessing the regional impacts of EC systems. Moreover, it was demonstrated that the design of CRs and regionally adopted management practices could be an appropriate steering option in land use management. By applying our approach to other regional datasets, more resource-efficient cropping systems could be identified and thereby help to improve the diversification of EC systems.

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Abbreviations

BB	Brandenburg
BW	Baden-Wuerttemberg
BV	Bavaria

CED	cumulative energy demand
CR	crop rotation
EC	energy crop
EROI	energy return on investment
EVA	Site-Adapted Cropping Systems for Energy Crops (project name)
FAO	Food and Agriculture Organization of the United Nations
MW	Mecklenburg-Western Pomerania
n. sign.	Not significant
LS	Lower Saxony
SN	Saxony
SA	Saxony-Anhalt
TH	Thuringia

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