Siegfried Schittenhelm[1], Dominik Reus[2], Sandra Kruse[3], Johannes Hufnagel[4]

Assessment of productivity and profitability of sole and double-cropping for agricultural biomass production

Bewertung der Produktivität und Wirtschaftlichkeit von Hauptfruchtanbau und Zweifruchtnutzung für die landwirtschaftliche Biomasseproduktion

Abstract

Double-crop (DC) systems are receiving serious consideration as cropping alternative for agricultural biomass production in Germany. In this study the productivity and economics of DC and sole-crop (SC) systems were compared from 2007 to 2009 at three climatically diverse sites of Germany. The warm season crops maize (*Zea mays* L.), forage sorghum [*Sorghum bicolor* (L.) Moench] and sorghum-sudangrass [*S. bicolor* (L.) Moench × *S. sudanense* (Piper) Stapf] were either grown as sole crops or as second crop following winter rye (*Secale cereale* L.). The winter rye first crop was harvested premature at early-to-mid May (early) or early June (late). While the winter rye was grown under rainfed conditions, maize, forage sorghum, and sorghum-sudangrass were grown with or without irrigation. Winter rye produced an aboveground dry matter yield (DMY) of 5.2 t ha^{-1} at early harvest and 9.0 t ha^{-1} at late harvest. The highest yielding DC system (rye-maize) out-yielded the most productive SC system (maize) by 3.6 t ha^{-1} (23%) under rainfed conditions and by 5.2 t ha^{-1} (24%) with irrigation. Irrigation increased DMY of sole crops by 5.3 t ha^{-1} (37%), of early sown second crops by 5.6 t ha^{-1} (43%), and of late sown second crops by 6.8 t ha^{-1} (77%). Under rainfed conditions, the higher DMY of the DC as compared with the SC systems did not compensate the higher production costs. With irrigation, however, the rye-maize DC achieved higher contribution margins than SC maize at two of the three experimental sites.

Key words: Maize, forage sorghum, sorghum-sudangrass, energy crops, cropping systems, economy

Zusammenfassung

Zweifruchtsysteme werden in Deutschland als alternative Anbausysteme für die landwirtschaftliche Biomasseproduktion erwogen. In dieser Untersuchung wurden die Produktivität und Wirtschaftlichkeit von Zweifruchtnutzung und Hauptfruchtanbau in den Jahren 2007 bis 2009 an drei klimatisch unterschiedlichen Standorten in Deutschland verglichen. Die wärmeliebenden Kulturen Mais (*Zea mays* L.), Futterhirse [*Sorghum bicolor* (L.) Moench] und Sudangras [*S. bicolor* (L.) Moench × *S. sudanense* (Piper) Stapf] wurden entweder allein als Hauptfrüchte oder als Zweitfrüchte nach Winterroggen (*Secale cereale* L.) angebaut. Bei Zweifruchtnutzung wurde der Winterroggen entweder zwischen Anfang und Mitte Mai (früh) oder Anfang Juni (spät) geerntet. Während der Winterroggen kein Zusatzwasser erhielt, wurden Mais, Futterhirse und Sudangras sowohl mit als auch ohne künstliche Bewässerung angebaut. Der Winterroggen lieferte einen oberirdischen Trockenmasseertrag von 5,2 t ha^{-1} bei früher Ernte und von 9,0 t ha^{-1} bei später Ernte. Die ertragreichste Zweifruchtnutzung (Roggen- Mais) war der produktivsten Hauptfrucht (Mais) ohne Zusatzbewässerung um 3,6 t ha^{-1} (23%) und mit Zusatzbewässerung um 5,2 t ha^{-1} (24%) überlegen. Durch die Zusatzbewässerung erhöht sich der Trockenmasseertrag bei den

Institute

Julius Kühn-Institute (JKI), Federal Institute for Cultivated Plants, Institute for Crop and Soil Science, Braunschweig, Germany[1]
Justus Liebig University Giessen, Institute of Agricultural and Food Systems Management, Giessen, Germany[2]
Centre for Agricultural Technology Augustenberg (LTZ), Rheinstetten-Forchheim, Germany[3]
Leibniz Centre for Agricultural Landscape Research (ZALF e.V.), Institute of Land Use Systems, Müncheberg, Germany[4]

Correspondence

Dr. Siegfried Schittenhelm, Julius Kühn-Institute (JKI), Federal Institute for Cultivated Plants, Institute for Crop and Soil Science, Bundesallee 50, 38116 Braunschweig, Germany, E-Mail: siegfried.schittenhelm@jki.bund.de

Accepted

20 September 2011

Hauptfrüchten um 5,3 t ha^{-1} (37%), bei den früh gesäten Zweitfrüchten um 5,6 t ha^{-1} (43%) und bei den spät gesäten Zweitfrüchten um 6,8 t ha^{-1} (77%). Ohne Zusatzbewässerung wurden die, im Vergleich zum Hauptfruchtanbau, höheren Produktionskosten bei der Zweifruchtnutzung nicht durch entsprechend höhere Trockenmasseerträge kompensiert. Mit Zusatzbewässerung hingegen erzielte das Zweifruchtsystem Roggen-Mais an zwei von drei Versuchsstandorten höhere Deckungsbeiträge als der Hauptfruchtanbau von Mais.

Stichwörter: Mais, Futterhirse, Sudangras, Energiepflanzen, Anbausysteme, Biomasse, Ökonomie

Introduction

The number of mostly farm-based biogas plants for energy production in Germany greatly increased from 1,043 in the year 2000 to approximately 5,800 in 2010 (FNR, 2010). The cultivation area of biogas maize, as the by far most important feedstock for biogas plants, also markedly increased to about 700,000 ha in 2011. Currently agronomists are seeking alternative crops and cropping systems in order to minimize problems associated with intensive maize production such as enhanced soil erosion and nutrient losses, increasing pest pressure, and monotonous landscapes.

An alternative to producing maize in narrow rotation sequences consists of growing cool season first crops followed by warm season second crops. Growing of winter rye or winter triticale, which after premature harvest in May or June are followed by maize, forage sorghum or sorghum-sudangrass would best exploit the growing season at many sites in Germany. Such bioenergy double-cropping has recently been proposed as sustainable cultivation concept for annual energy crops (Karpenstein-Machan, 2001; Anex et al., 2007; Baker and Griffis, 2009; Goff et al., 2010). However, the idea of increasing area productivity through extending the photosynthetic duration is not new. After the first oil crisis in 1973, field experiments were conducted in the USA, which aimed at maximizing biomass yields through double-cropping (Lewis and Phillips, 1976; Crookston et al., 1978; Helsel and Wedin, 1981). Such double-crop (DC) systems are not only an option to increase biomass yields, but the almost whole-year soil cover associated with double-cropping also reduces the risk of soil erosion (Buxton et al., 1999) and nutrient losses (Heggenstaller et al., 2008). Nevertheless, the enhanced soil water consumption through nearly all year round soil cover with growing plants in DC systems may be critical at summer drought sites as prevailing in the north-eastern part of Germany. On arid sites, irrigation may be required for rapid germination and fast early growth of the warm season second crop, because there is only a short window of time to allow soil water recharge after harvest of the cool season first crop.

Late planting of summer crops as practiced in DC systems normally results in lower dry matter yield (DMY) due to a shorter growing season. This may not be relevant with sorghum crops. In Germany, the high warmth demand of sorghum (Neild, 1982; Anda and Pinter, 1994) is not met before the mid of May. However, the lower dry matter concentration associated with a shortened growing season may be relevant with regard to biomass transportation costs and high-quality silage production. Furthermore, the higher production costs of double-cropping caused by additional costs for seeds, fertilizers, and field operations, must be compensated by adequate biomass yield surpluses.

In the present study, six biomass DC systems and three sole-crop (SC) systems were compared in climatically diverse regions of Germany to (1) investigate whether double-cropping has either a yield or economic advantage over sole-cropping, (2) test whether forage sorghum or sorghum-sudangrass are alternatives for maize, and (3) examine the potential of irrigation to stabilize DC system yields.

Materials and methods

Experimental sites and weather conditions

The experiments were conducted from autumn 2007 to autumn 2009 at three sites in Germany: Braunschweig, Rheinstetten-Forchheim, and Müncheberg. The annual means for air temperature, precipitation, and growing period (> 10°C) are decreasing continuously from Rheinstetten-Forchheim in the south-west (10.6°C, 770 mm, 207 d), via Braunschweig in the north central (9.1°C, 627 mm, 177 d) to Müncheberg in the north-east (8.8°C, 562 mm, 170 d). The loamy sand soils prevailing at the three experimental sites are classified as Lamellic Luvisol (Braunschweig), Haplic Luvisol (Rheinstetten-Forchheim), and Eutric Cambisol (Müncheberg) (FAO, 1997). Because of groundwater tables below 8 m and soil water- holding capacities below 100 mm, irrigation is necessary at all sites in most of the years to attain satisfactory biomass yields.

Experimental treatments and field management

At each of the three sites, nine cropping systems comprising of six DC and three SC systems were studied during the 2007/2008 and 2008/2009 growing season. The experiments were conducted on different fields in both seasons. The first and second crops were managed according to local practice as described in Tab. 1. In the DC systems the winter rye cultivar 'Visello' was grown as a first crop without irrigation in eight 18 × 8 m plots in Braunschweig and Müncheberg and eight 27 × 10 m plots in Rheinstetten-Forchheim. Depending on site and year, winter rye early harvest (R_E) took place at the beginning to end of heading stage and late harvest (R_L) at the full flowering to late milk stage. The winter rye whole-plant biomass was taken from the centre of plots with a forage plot harvester. Basic fertilization to meet the needs of first and second crops was applied before planting the winter rye, except for the second growing season in Rhein-

Tab. 1. Management data for the winter rye first crop as well as the warm-season crops maize, forage sorghum, and sorghum-sudangrass grown as sole or second crop following early or late harvested winter rye in a double-crop system at Braunschweig, Rheinstetten-Forchheim, and Müncheberg in the 2007/2008 and 2008/2009 growing seasons

Anbaudaten für die Erstfrucht Winterroggen und für die als Hauptfrüchte oder als Zweitfrüchte nach früh oder spät geerntetem Winterroggen angebauten wärmeliebenden Kulturen Mais, Futterhirse und Sudangras in Braunschweig, Rheinstetten-Forchheim und Müncheberg für die Vegetationsperiode 2007/2008 und 2008/2009

Cultural practice	Crop or cropping system	Braunschweig		Rheinstetten-Forchheim		Müncheberg	
		2007/2008	2008/2009	2007/2008	2007/2008	2007/2008	2008/2009
First crop							
Sowing date		15.10.	25.9.	11.10.	14.10.	19.9.	19.9.
Sowing rate (kg ha^{-1})		112	70	108	150	94	72
N fertilisation (kg ha^{-1})		100	100	60	R_E:60; R_L:100	90	90
Harvest area (m^2)		12	R_E:12, R_L:6	12	12	11	11
Harvest date (R_E/R_L)		13.5./2.6.	5.5./2.6.	7.5./4.6.	5.5./5.6.	14.5./2.6.	7.5./2.6.
Sole and second crops							
Sowing/ harvest date	SC	M:28.4./18.9.	M:27.4./17.9.	M:28.4./25.8.	M:24.4./24.8.	M:25.4./4.9.	M:22.4./9.9.
		F:8.5./29.9.	F:7.5./14.10.	F:14.5./4.11.	F:20.5./13.10.	F:13.5./9.10.	F:11.5./13.10.
		S:8.5./26.8.	S:7.5./6.10.	S:14.5./11.9.	S:20.5./28.9.	S:13.5./2.9.	S:11.5./13.10.
	2ndC$_E$	M:15.5./26.9.	M:14.5./1.10.	M:8.5./25.8.	M:7.5./26.8.	M:19.5./13.10.	M:14.5./30.9.
		F:15.5./7.10.	F:15.5./19.10.	F:14.5./4.11.	F:20.5./13.10.	F:19.5./13.10.	F:18.5./13.10.
		S:15.5./27.8.	S:15.5./6.10.	S:14.5./11.9.	S:20.5./2.10.	S:19.5./8.10.	S:18.5./13.10.
	2ndC$_L$	M:9.6./8.10.	M:5.6./19.10.	M:9.6./3.11.	M:5.6./28.8.	M:6.6./13.10.	M,S:5.6./7.10.
		F:9.6./14.10.	F:5.6./21.10.	F:9.6./4.11.	F:5.6./13.10.	F:6.6./13.10.	F,S:5.6./13.10.
		S:9.6./24.9.	S:5.6./21.10.	S:9.6./10.10.	S:5.6./28.9.	S:6.6./8.10.	S:5.6./13.10.
Plot size (m^2)		48	48	90	90	48	48
Row width (cm)		M:75, F:50, S:25		M:75, F:50, S:25		M:75, F,S:50	
Plant density (plants m^{-2})		M:10, F:25; S:50		M:10, F:25, S:50		M:10, F:25, S:100	
Harvested area (m^2)		M:15.8, F:10.5, S:5.3 (manually)		12.0 (plot chopper)		12.0 (plot chopper)	
Herbicide[a] (l ha^{-1})	M	Artett (2.5) + Motivell (1.0)		Callisto (1.25) + Certrol B (0.3)		Gardo Gold (4.0)	
	F,S	Certrol B (1.5)		Gardo Gold (2.0)	Gardo Gold (2.5)	Gardo Gold (4.0)	
Irrigation (mm)	SC	S:169, M,F:204	M,F,S:231	M,F,S:125	M:125, F,S:165	F,S:144, M:164	M,F,S:110
	2ndC$_E$	S:162, M,F:197	M,F,S:231	M,F,S:125	M:125, F,S:165	F,S:113, M:123	M,F,S:110
	2ndC$_L$	S:146, M,F:166	M,S:231; F:211	M,F,S:105	M,F,S:145	F,S:113, M:123	M,F,S:100

R_E, R_L = early and late harvested winter rye; SC = sole-crop; 2ndC$_E$, 2ndC$_L$ = second crop following early and late harvested rye; M = maize; F = forage sorghum; S = sorghum-sudangrass

[a] Active ingredients (g l^{-1}). Artett: bentazone (150) and terbuthylazine (150); Callisto: mesotrione (100); Certrol B: bromoxynil (235); Dual Gold: S–metolachlor (960); Gardo Gold: S-metolachlor (312.5) and terbuthylazine (187.5); Motivell: nicosulfuron (40)

stetten-Forchheim were basic fertilizer was supplied before planting the warm season crops. The prospective SC plots were planted with white mustard (*Sinapis alba* L.) as freeze-off catch crop in Braunschweig and Rheinstetten-Forchheim. The winter rye used for soil cover in Müncheberg was destructed by burndown application with glyphosate at the beginning of the growing season. Thus, winter soil moisture at each site was preserved for the warm season SCs.

The plots of early and late harvested winter rye as well as the winter catch crop plots were ploughed and subdivided into three plots carrying the warm season crops maize (‘Atletico’), forage sorghum (‘Sucrosorgo 506’), and sorghum-sudangrass (‘Lussi’). The experimental design at each site was a randomized complete block in a split-plot arrangement with four replications. The main plots (i.e. former first crop and winter catch crops) carried the two water regimes (rainfed and irrigated). The subplots were the nine cropping systems consisting of maize, forage sorghum, or sorghum-sudangrass grown either as sole-crop or as second crop following early (2ndC$_E$) or late harvested winter rye (2ndC$_L$). Slow-release N–fertilizer was broadcast in a single application of Alzon 46 (Braunschweig, Rheinstetten-Forchheim) and Piasan 24-S (Müncheberg) at rates of 200 kg ha^{-1} for maize and 170 kg ha^{-1} for forage sorghum and sorghum-sudangrass. The irrigated plots were kept above 50% plant available soil water (PASW) using drip lines in Braunschweig and Müncheberg and a nozzle trailer in Rheinstetten-Forchheim. At harvest, plants were taken from the central rows of each plot. Duplicate samples of chopped plant material were oven-dried at 105 °C to a constant weight, and reweighed to determine subsample dry weight.

Economic comparisons

Because farmland is the limiting factor in most agricultural enterprises, the economic comparison of cropping systems is based on the contribution margin per unit of land defined as difference between variable revenues and variable costs. The price of maize silage sets the benchmark to calculate the revenues of different biogas feedstock. Based on a silage maize price of 35 € t^{-1} fresh matter (FM) and the maize silage characteristics shown in Tab. 2, a methane price of 0.33 € (m^3 CH$_4$)$^{-1}$ is ascertained. The revenues for the other crops were determined based on their DM content measured in the experiments. The production costs of biogas feedstock include costs depending on the achieved FM or DM yields and the constant costs per unit of land. The costs linked to land area are those for seeds, pesticides, and field operations (labour and machinery) except transportation costs. The costs for labour and machinery were obtained from KTBL (2011), assuming an average field size of 10 ha and an average 5 km farm-to-field distance. The capital costs were calculated at an interest rate of 5% and an assumed wage per person of 15 € h^{-1}. The yield-depending costs are those for fertilizers as well as transport of harvest and fermentation residues. It was assumed that the fermentation residues are completely applied on the field of biogas feedstock production. For the irrigation system, costs for depreciation and capital were considered as costs per unit of land, while costs for labour, maintenance, fuel, and water were considered per mm irrigation. The assumed equipment is a mobile irrigation system with a sprinkler gun, representing the most common technology in Europe. The costs per unit of land amount to 138.3 € ha^{-1} and the variable costs for irrigation to 1.5 € mm^{-1} (Sourell, 2011).

Statistical analyses

The analyses of variance (ANOVAs) of the whole-crop DMY data for the winter rye first crop, the warm season sole and second crops, as well as the system totals were conducted with the PLABSTAT software (Utz, 2011). The ANOVAs were carried out for individual years and across years for each site. Because the winter rye was not irrigated, the prospective rainfed and irrigated plots were combined and analyzed according to a randomized complete block design with eight replications. The SC, 2ndC$_E$, and 2ndC$_L$ data were analyzed as split plot design with four replications. The total yields of the six DC systems were calculated by summing the first and second crop yields. Thereafter joint ANOVAs were performed for the nine cropping systems. When *F*-ratios were significant ($P < 0.05$), LSD values at that level were used to compare treatment means.

Tab. 2. Product characteristics, costs per land unit, and yield depending costs of four energy crops
Produkteigenschaften, Kosten pro Flächeneinheit und ertragsabhängige Kosten für vier Energiepflanzen

Crop	Product characteristics and average revenues		Overhead costs[2]	Yield depending costs[2]		
	Specific methane yield[1] [l$_N$ (kg oDM)$^{-1}$]	Organic DM content (%)	Seed, pesticides, and field operations (€ ha^{-1})	Nutrient costs [€ (t DM)$^{-1}$]	Harvesting costs [€ (t DM)$^{-1}$]	Fermentation residues application [€ (t DM)$^{-1}$]
Winter rye (first crop)	362	90	463.82	14.2	13.9	11.8
Maize (sole crop)	338	95	596.40	9.3	10.5	8.2
Forage sorghum (sole crop)	298	90	422.12	10.9	12.4	10.7
Sorghum-sudangrass (sole crop)	298	90	446.02	10.4	12.4	10.7
Maize (second crop)	338	95	560.91	9.6	11.6	9.0
Forage sorghum (second crop)	300	90	386.63	8.3	13.9	11.9
Sorghum-sudangrass (second crop)	300	90	410.53	10.4	13.9	11.9

[1] KTBL (2009) and Christiane Herrmann (2010, personal communication)
[2] KTBL (2011)

Results and discussion

Winter rye first crop

Averaged across years, the DMY of winter rye was lowest in Rheinstetten-Forchheim and highest in Müncheberg (Tab. 3). The unusual low DMY in Braunschweig in 2008 was attributable to excessive rains after sowing which required late resowing at mid October. Averaged over sites and years, winter rye produced 5.2 t DM ha^{-1} at the early-to-mid-May harvest and 9.0 t DM ha^{-1} at the early-June harvest. The average yields of double-cropped winter rye in the current study are comparable to the 3 to 5 t ha^{-1} obtained in Iowa at mid-May harvest (BUXTON et al., 1999) as well as the mid-June harvest of 9.6 t ha^{-1} in Minnesota (CROOKSTON et al., 1978), and 10.0 t ha^{-1} in Germany (TOEWS et al., 2008).

Sole and second crops

At each site, the combined ANOVA for DMY across the 2008 and 2009 season (not shown) exhibited highly significant differences ($P < 0.01$) among years, water regimes, and crops. Significant ($P < 0.01$) crop × year and significant ($P < 0.05$) crop × water regime interactions were also found at each site. This indicates a different performance of the warm season crops and a different response to irrigation in 2008 and 2009, respectively.

At each site and in each year, the overall DMY was significantly ($P < 0.05$) greater in the irrigated than in the rainfed treatment (Tab. 4). The yield response to irrigation averaged 5.9 t ha^{-1} (49%). The highest DMY increase through irrigation of 7.6 t ha^{-1} (64%) was observed in Braunschweig, followed by 5.6 t ha^{-1} (42%) in Rheinstetten-Forchheim and 4.7 t ha^{-1} (40%) in Müncheberg. The irrigation effects increased from 5.3 t ha^{-1} (37%) for SC, via 5.6 t ha^{-1} (43%) for $2ndC_E$, to 6.8 t ha^{-1} (77%) for $2ndC_L$. The increasing irrigation effect with later sowing ($2ndC_L > 2ndC_E >$ SC) results from an increasingly greater soil moisture depletion by the previous crop. The highest maize DMY of 24.9 t ha^{-1} was obtained with irrigated SC maize in Braunschweig in 2008. SC maize was also by far the highest yielding crop in Müncheberg. In Rheinstetten-Forchheim, the warmest of the three sites, forage sorghum within the same sowing date crop triplets produced higher DMY than irrigated $2ndC_E$ maize in 2008 and irrigated SC maize in 2009. Other maize and forage sorghum DMYs did not differ significantly at this site. The relative good performance of sorghum under rainfed conditions in the present study confirms earlier literature reports (MUCHOW, 1989; BERENGUER and FACI, 2001; MILLER and OTTMAN, 2010). This drought tolerance may be attributable to the ability of sorghum to root deeply and thus to draw water from great soil depths (SINGH and SINGH, 1995; FARRÉ and FACI, 2006).

Cropping systems

The total DMYs for the nine cropping systems are shown in Tab. 5. The system total DMY for double-cropping is the sum of the winter rye first crop plus the warm season second crop. The first crop contributed substantially to the total DMY. Across sites and years, the yield share of early-to-mid-May harvested winter rye averaged 28% for the rainfed and 20% for the irrigated water regimes. The respective figures for the early-June harvest were 49% under rainfed conditions and 34% with irrigation. At sites with low rainfall, light soil, or both, a considerable yield uncertainty exists for the warm season crops. Under such conditions, the cool season first crop significantly contributes to yield stability of the DC system because it can use winter precipitation and thus produce a relative foreseeable yield.

The biomass DMY superiority of the best DC system over the top SC system under rainfed conditions averaged 6.2 t ha^{-1} in Müncheberg, 5.3 t ha^{-1} in Braunschweig, and 3.8 t ha^{-1} in Rheinstetten-Forchheim. Thus, the relative excellence of double-cropping increased with decreasing growth temperature and length of growing season. This agrees with the finding of a comparatively better performance of double-cropping compared with sole-cropping at sites with low maize yields (TOEWS et al., 2008). To understand this finding it is worthwhile recalling the concept underlying double-cropping for biogas production. Essentially, the idea is to avoid unproductive or less productive periods as they regularly occur with early sowing of high warmth demanding C4 crops, and instead to better grow C3 crops during times with cool weather. In Müncheberg with a relatively short growing season (37 d less than in Rheinstetten-Forchheim), double-

Tab. 3. Biomass yield (t DM ha^{-1}) of early and late-harvested winter rye first crop at Braunschweig, Rheinstetten-Forchheim, and Müncheberg in the years 2008 and 2009

Biomasseertrag (t TM ha^{-1}) von früh und spät geerntetem Winterroggen in Braunschweig, Rheinstetten-Forchheim und Müncheberg in den Jahren 2008 und 2009

First crop[1]	Braunschweig			Rheinstetten-Forchheim			Müncheberg		
	2008	2009	Mean	2008	2009	Mean	2008	2009	Mean
R_E	3.4	6.3	4.9	4.4	4.7	4.5	6.3	5.9	6.1
R_L	5.7	11.9	8.8	8.1	6.9	7.5	10.3	10.9	10.6
LSD ($P < 0.05$)[2]	0.5	0.2	0.4	0.5	0.2	0.3	0.6	0.6	0.4

[1] R_E, R_L = early rye harvest (early-to-mid-May) and late rye harvest (early-June)
[2] Least significant difference to compare harvest dates

Tab. 4. Biomass yield (t DM ha^{-1}) of maize, forage sorghum, and sorghum-sudangrass grown either as sole-crop or as second crop following early or late-harvested winter rye first crop in a double-crop system at Braunschweig, Rheinstetten-Forchheim, and Müncheberg in the years 2008 and 2009

Biomasseertrag (t TM ha^{-1}) von Mais, Futterhirse und Sudangras als Hauptfrüchte oder als Zweitfrüchte nach früh oder spät geerntetem Winterroggen in einem Zweifruchtsystem in Braunschweig, Rheinstetten-Forchheim und Müncheberg in den Jahren 2008 und 2009

Water regime	Sole or second crop	Braunschweig			Rheinstetten-Forchheim			Müncheberg		
		2008	2009	Mean	2008	2009	Mean	2008	2009	Mean
Rainfed mean		12.9	10.6	11.7	14.5	12.0	13.2	10.0	13.5	11.7
Irrigated mean		19.4	19.1	19.3	20.2	17.4	18.8	14.4	18.4	16.4
LSD (*P* < 0,05)[1]		1.2	1.9	0.9	1.7	0.9	0.7	1.7	0.7	0.7
Irrigation effect	SC	7.8 (54)[4]	7.0 (51)	7.4 (53)	6.0 (39)	4.0 (27)	5.0 (33)	3.3 (25)	3.9 (25)	3.6 (25)
	2ndC$_E$	6.4 (45)	7.2 (56)	6.8 (50)	5.9 (38)	5.1 (39)	5.5 (39)	3.7 (39)	5.4 (41)	4.5 (40)
	2ndC$_L$	5.5 (55)	11.4 (223)	8.5 (111)	5.1 (41)	7.3 (86)	6.2 (59)	6.3 (87)	5.4 (46)	5.9 (61)
	Mean	6.6 (51)	8.5 (81)	7.6 (64)	5.7 (39)	5.4 (45)	5.6 (42)	4.4 (44)	4.9 (37)	4.7 (40)
Rainfed	M	16.3	13.8	15.1	15.8	14.5	15.1	15.7	18.5	17.1
	F	15.5	12.9	14.2	17.4	14.8	16.1	12.9	13.9	13.4
	S	11.7	14.0	12.9	13.2	14.4	13.8	11.6	14.0	12.8
	M_E	16.7	14.8	15.7	15.0	11.9	13.5	10.6	15.0	12.8
	F_E	14.5	12.3	13.4	17.5	13.4	15.4	8.3	12.2	10.3
	S_E	11.1	11.8	11.4	13.7	13.6	13.6	9.5	11.8	10.7
	M_L	10.4	5.7	8.1	12.7	7.5	10.1	7.1	14.3	10.7
	F_L	10.7	5.0	7.8	13.7	9.0	11.4	6.4	10.6	8.5
	S_L	9.1	4.6	6.9	11.5	8.8	10.2	8.0	10.8	9.4
LSD (*P* < 0,05)[2]		1.9	2.3	1.4	2.7	1.6	1.6	2.1	1.6	1.3
Irrigated	M	24.9	22.0	23.5	22.6	17.0	19.8	20.6	22.6	21.6
	F	24.0	20.4	22.2	23.1	21.1	22.1	17.6	19.0	18.3
	S	18.1	19.2	18.6	18.7	17.7	18.2	12.0	16.7	14.4
	M_E	24.8	22.7	23.8	24.2	17.7	21.0	16.1	21.5	18.8
	F_E	20.7	19.7	20.2	21.7	17.9	19.8	11.5	18.6	15.0
	S_E	15.9	18.2	17.0	18.0	18.4	18.2	11.8	15.2	13.5
	M_L	17.4	17.4	17.4	18.3	17.1	17.7	15.4	20.7	18.1
	F_L	15.3	16.9	16.1	18.4	15.7	17.1	12.0	16.2	14.1
	S_L	14.0	15.4	14.7	16.6	14.2	15.4	12.9	15.1	14.0
LSD (*P* < 0,05)[2]		2.0	2.7	1.7	1.8	2.6	1.6	1.9	2.0	1.3
LSD (*P* < 0,05)[3]		1.9	2.4	1.5	-	2.1	1.5	2.0	1.8	1.3

SC = sole crops; E, L = early and late sowing; 2ndC = second crop; M = maize; F = forage sorghum; S = sorghum-sudangrass
[1] Least significant difference to compare water regime means
[2] Least significant difference to compare crops within water regimes
[3] Least significant difference to compare crops between water regimes
[4] Percentage biomass yield increase

cropping with late sowing of the second crop was the cropping system of choice. In Rheinstetten-Forchheim on the other hand, early sowing of the C4 crop with its higher yield potential was more advantageous.

Most productive under irrigated conditions were DC systems with maize as the follow-up crop. The overall highest total system yield of 31.7 t ha^{-1} was attained in Müncheberg 2009 by double-cropping late harvested rye and irrigated maize. The top yielders under rainfed conditions on the contrary were split equally between DC systems with maize as the second crop component on the one hand and forage sorghum or sorghum-sudangrass on the other.

In each of the six year-site combinations, the most productive DC system significantly ($P < 0.05$) outperformed the highest yielding SC system. The average DMY advantage of DC over SC systems amounted to 3.6 t ha^{-1} (23%) under rainfed conditions and 5.2 t ha^{-1} (24%) with irri-

Tab. 5. Dry matter yield (t ha^{-1}) of nine cropping systems at Braunschweig, Rheinstetten-Forchheim, and Müncheberg in the years 2008 and 2009

Trockenmasseertrag (t ha^{-1}) von neun Anbausystemen in Braunschweig, Rheinstetten-Forchheim und Müncheberg in den Jahren 2008 und 2009

Water regime	Cropping system	Braunschweig			Rheinstetten-Forchheim			Müncheberg		
		2008	2009	Mean	2008	2009	Mean	2008	2009	Mean
Rainfed mean		15.9	16.8	16.4	18.7	15.9	17.3	15.6	19.1	17.4
Irrigated mean		22.4	25.0	23.7	24.3	21.3	22.8	19.9	24.0	21.9
LSD (P < 0,05)[1]		2.0	1.9	0.8	1.8	1.0	0.8	2.1	1.0	2.4
Rainfed	M-SC	16.3	13.8	15.1	15.8	14.5	15.1	15.7	18.5	17.1
	F-SC	15.5	12.9	14.2	17.4	15.0	16.2	12.9	13.9	13.4
	S-SC	11.7	14.0	12.9	13.2	14.4	13.8	11.6	14.0	12.8
	R-M-DC_E	20.2	21.2	20.7	19.4	16.5	18.0	17.6	21.2	19.4
	R-F-DC_E	17.9	18.7	18.3	22.0	18.2	20.2	14.7	18.0	16.3
	R-S-DC_E	14.6	18.5	16.6	18.1	18.3	18.2	15.5	17.6	16.6
	R-M-DC_L	16.2	17.8	17.0	20.6	14.4	17.5	17.5	26.4	22.0
	R-F-DC_L	16.3	17.5	17.0	22.1	15.9	19.0	16.6	20.9	18.7
	R-S-DC_L	14.8	16.4	15.6	19.8	15.8	17.8	18.4	21.7	20.0
LSD (P < 0,05)[2]		2.0	2.6	1.6	2.8	1.7	1.6	2.3	2.2	1.5
Irrigated	M-SC	24.9	22.0	23.5	22.6	17.0	19.8	20.6	22.6	21.6
	F-SC	24.0	20.4	22.2	23.1	21.1	22.1	17.6	19.0	18.3
	S-SC	18.1	19.2	18.6	18.7	17.7	18.2	12.0	16.7	14.3
	R-M-DC_E	28.1	28.7	28.4	28.6	22.5	25.6	22.3	27.7	25.1
	R-F-DC_E	23.9	25.9	24.9	26.1	22.4	24.2	17.9	24.3	21.1
	R-S-DC_E	19.2	24.4	21.8	22.3	23.0	22.6	17.9	20.9	19.4
	R-M-DC_L	23.0	29.1	26.0	26.7	24.0	25.3	26.4	31.7	29.1
	R-F-DC_L	21.0	28.9	25.0	26.2	22.8	24.5	21.3	26.9	24.1
	R-S-DC_L	19.7	26.7	23.2	24.6	20.9	22.7	23.1	25.7	24.4
LSD (P < 0,05)[2]		2.2	2.6	1.7	2.0	2.8	2.4	2.1	1.7	1.4
LSD (P < 0,05)[3]		2.0	2.5	1.6	–	2.3	1.6	2.2	–	–

SC = sole-crop; DC_E, DC_L = double-crop system with early or late switch from 1st to 2nd crop; M = maize; F = forage sorghum; S = sorghum-sudangrass

[1] Least significant difference to compare water regime means

[2] Least significant difference to compare cropping systems within water regimes

[3] Least significant difference to compare cropping systems between water regimes

gation. Comparable DMY surpluses of DC systems over warm-season SC systems of 26% (Murdock and Wells, 1978), 25% (Heggenstaller et al., 2008; Heggenstaller et al., 2009), and 20% (Toews et al., 2008) were reported in literature. Other studies found yield surplus for DC systems of maximal 10% (Buxton et al., 1999) or no DMY superiority at all (Crookston et al., 1978).

From a practical point of view, it is important to know, whether switching from the first to the second crop between early-May and mid-June is possible without system yield sacrifices. Only moderate differences were found for biomass productivity between double-cropping with early and late rye harvest. For the rye-maize DC systems for instance, the DMY difference between early and late harvest average 0.05 t ha^{-1} only. However, a somewhat different picture emerges when examining the sites separately. The total DC system productivity difference ranged from 3.1 t ha^{-1} in favour of an early changeover to the warm season crop in Braunschweig to 3.3 t ha^{-1} in favour of a late changeover in Müncheberg.

Economic considerations

The worth of irrigation depends on whether the biomass yield increase covers the extra costs for irrigation plus the associated yield depending costs. Irrigation may also affect DM concentration, which, in turn, strongly influences transportation costs of the biogas feedstock. It is therefore not possible to specify a constant minimum increase for DMY necessary to achieve a positive contribution margin.

In the irrigated treatment, PASW of the sole and second crops was maintained above 50% during almost the entire growing period. This irrigation strategy proved to be economically reasonable in maize, but not in forage sorghum and particularly not in sorghum-sudangrass (Tab. 6). As for the DMY, the effect of irrigation on the contribution margin of maize also increased with later sowing from -21 € ha^{-1} for SC, via 57 € ha^{-1} for $2ndC_E$, to 164 € ha^{-1} for $2ndC_L$.

Under rainfed conditions, SC maize at each site gave the highest average contribution margins. Thus, the consistently higher DMY of double-cropping (Tab. 5) did not offset the higher costs associated with this cropping system. In Rheinstetten-Forchheim, double-cropping was economically most disadvantageous in comparison to sole-crop maize among all sites. At that site, the contribution margin of the best DC system (R-M-DC_L) was 255 € ha^{-1} lower than for SC maize. In Müncheberg, on the contrary the disadvantage of the best DC system (also R-M-DC_L) was only 135 € ha^{-1}. The competitiveness of sorghum versus maize differed greatly between the experimental sites. The contribution margin for SC forage sorghum was only slightly lower than for SC maize in Rheinstetten-Forchheim (–47 € ha^{-1}) but substantially lower in Müncheberg (–362 € ha^{-1}). Sorghum-sudangrass was especially worth cultivating when grown as second crop following late-harvested rye in Müncheberg. Although SC maize under rainfed conditions achieved the highest contribution margin at each site, differences existed among the sites with respect to the second-best cropping system option. SC forage sorghum was the best alternative in Rheinstetten-Forchheim and DC maize in Braunschweig and Müncheberg.

With irrigation, the disadvantage of forage sorghum and sorghum-sudangrass compared to maize increased in both, SC and DC systems. Forage sorghum mostly out-

Tab. 6. Contribution margin (€ ha^{-1}) of maize, forage sorghum, and sorghum-sudangrass grown either as sole-crop or as second crop following an early or late harvested winter rye first crop at Braunschweig, Rheinstetten-Forchheim, and Müncheberg in the years 2008 and 2009

Deckungsbeiträge (€ ha^{-1}) für Mais, Futterhirse und Sudangras als Hauptfrucht oder als Zweitfrucht nach früh oder spät geerntetem Winterroggen in Braunschweig, Rheinstetten-Forchheim und Müncheberg in den Jahren 2008 und 2009

Water regime	Crop/ Cropping system	Braunschweig			Rheinstetten-Forchheim			Müncheberg		
		2008	2009	Mean	2008	2009	Mean	2008	2009	Mean
Rainfed	All	83	118	100	259	91	175	80	281	181
Irrigated	All	−8	40	16	214	−20	97	10	245	128
Irrigation effect	M	36	80	58	91	53	72	94	44	69
(all systems)	F	−151	−100	−126	−120	−156	−138	−120	0	−60
	S	−156	−215	−186	−108	−231	−170	−183	−152	−168
Rainfed	M-SC	509	291	400	418	389	403	432	595	513
	F-SC	252	106	179	338	373	356	127	174	151
	S-SC	121	181	151	186	276	231	105	170	138
	R-M-DC_E	214	254	234	111	−219	−54	−41	285	122
	R-F-DC_E	−31	−28	−29	227	−9	109	−186	10	−88
	R-S-DC_E	−134	−41	−88	100	55	78	−69	−26	−48
	R-M-DC_L	−60	72	6	362	−67	148	71	686	378
	R-F-DC_L	−52	158	53	320	−1	159	63	302	183
	R-S-DC_L	−74	70	−2	274	25	149	219	334	276
Irrigated	M-SC	606	324	465	551	119	335	400	505	453
	F-SC	187	−56	66	273	139	206	22	117	70
	S-SC	24	−137	−57	46	0	23	−216	−13	−114
	R-M-DC_E	236	229	233	122	−61	31	−7	424	208
	R-F-DC_E	−180	−205	−193	53	−203	−75	−340	40	−150
	R-S-DC_E	−375	−330	−353	−69	−159	−114	−249	−180	−214
	R-M-DC_L	−70	304	117	489	204	347	351	770	560
	R-F-DC_L	−292	197	−48	200	−42	79	−37	330	146
	R-S-DC_L	−204	31	−86	258	−178	40	170	215	192

SC = sole-crop; DC_E, DC_L = double-crop system with early or late switch from first to second crop; R = rye; M = maize; F = forage sorghum; S = sorghum-sudangrass performed sorghum-sudangrass. The contribution margin disadvantage of SC forage sorghum compared to SC maize averaged -399 € ha^{-1} in Braunschweig but only -129 € ha^{-1} in Rheinstetten-Forchheim. The highest contribution margins at two of three sites were achieved with a DC system. Double-cropping of late harvested rye plus maize yielded 12 and 107 € ha^{-1} higher contribution margins than SC maize in Rheinstetten-Forchheim and Müncheberg, respectively. Only in Braunschweig did the contribution margin of SC maize exceeded that of the best DC system (R-M-DC_E) by 232 € ha^{-1}. An economic advantage of double-cropping might result from shorter transportation distances because of lower agricultural area requirement to produce biogas feedstock. However, this aspect was not addressed in the present study.

Conclusions

This study confirmed the dominant role of maize as biogas substrate. Under rainfed conditions, sole crop maize yielded the highest average contribution margin on each site. Irrigation is generally necessary to produce the high biomass yields necessary to compensate for the additional costs associated with double-cropping. Nevertheless, other aspects than economy must also be considered when judging biomass cropping systems such as nutrient leaching, soil erosion, production risks, and agrobiodiversity. In this context double-cropping systems and alternative crops are ecologically important options. On warm and dry sites, double-cropping can be practiced profitably if irrigation is available. Likewise, on warm sites forage sorghum can be grown with moderate additional costs as an alternative for maize either as sole-crop or as crop companion in DC systems. Appropriate adjustment of the biogas bonus system could help to support farmers in adopting ecologically beneficial farming systems and reduce the dominance of maize as a biogas substrate.

Acknowledgements

Funding for this research was provided by the Federal Ministry of Food, Agriculture, and Consumer Protection via the Agency for Renewable Resources under grant number 22013408. The authors thank Sabine Peickert, Torsten Neumann, Gunhild Rosner, Andreas Krieger, and Kristin Mahler for their help in executing the field experiments.

References

Anda, A., L. Pinter, 1994: Sorghum germination and development as influenced by soil temperature and water content. Agronomy Journal **86** (4), 621-624.

Anex, R.P., L.R. Lynd, M.S. Laser, A.H. Heggenstaller, M. Liebman, 2007: Potential for enhanced nutrient cycling through coupling of agricultural and bioenergy systems. Crop Science **47** (4), 1327-1355.

Baker, J.M., T.J. Griffis, 2009: Evaluating the potential use of winter cover crops in corn-soybean systems for sustainable co-production of food and fuel. Agricultural and Forest Meteorology **149** (12), 2120-2132.

Berenguer, M.J., J.M. Faci, 2001: Sorghum (*Sorghum bicolor* L. Moench) yield compensation processes under different plant densities and variable water supply. European Journal of Agronomy **15** (1), 43-55.

Buxton, D.R., I.C. Anderson, A. Hallam, 1999: Performance of sweet and forage sorghum grown continuously, double-cropped with winter rye, or in rotation with soybean and maize. Agronomy Journal **91** (1), 93-101.

Crookston, R.K., C.A. Fox, D.S. Hill, D.N. Moss, 1978: Agronomic cropping for maximum biomass production. Agronomy Journal **70** (6), 899-902.

FAO, 1997: Soil Map of the World. Revised legend, with corrections and updates. World Soil Resources Report 60, Rome, FAO. Reprinted with updates as Technical Paper 20, Wageningen, ISRIC.

Farré, I., J.M. Faci, 2006: Comparative response of maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) to deficit irrigation in a Mediterranean environment. Agricultural Water Management **83** (1-2), 135-143.

FNR, 2010: Biogas Basisdaten Deutschland. Gülzow, Fachagentur Nachwachsende Rohstoffe e.V. (FNR) [in German].

Goff, B.M., K.J. Moore, S.L. Fales, E.A. Heaton, 2010: Double-cropping sorghum for biomass. Agronomy Journal **102** (6), 1586-1592.

Heggenstaller, A.H., R.P. Anex, M. Liebman, D.N. Sundberg, L.R. Gibson, 2008: Productivity and nutrient dynamics in bioenergy double-cropping systems. Agronomy Journal **100** (6), 1740-1748.

Heggenstaller, A.H., M. Liebman, R.P. Anex, 2009: Growth analysis of biomass production in sole-crop and double-crop corn systems. Crop Science **49** (6), 2215-2224.

Helsel, Z.R., W.F. Wedin, 1981: Harvested dry matter from single and double-cropping systems. Agronomy Journal **73** (5), 895-900.

Karpenstein-Machan, M., 2001: Sustainable cultivation concepts for domestic energy production from biomass. Critical Reviews in Plant Sciences **20** (1), 1-14.

KTBL, 2009: Faustzahlen Biogas. 2nd ed. Darmstadt, Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL), 236 p. [in German].

KTBL, 2011: Feldarbeitsrechner. Darmstadt, Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL). Available from: http://daten.ktbl.de/feldarbeit/entry.html [in German; accessed 10 August 2011].

Lewis, W.M., J.A. Phillips, 1976: Double cropping in the eastern United States. In: Papendick R.I. (Ed.), Multiple cropping, Madison, ASA, CSSA, and SSSA, ASA Spec. Publ. 27. p. 41-50.

Miller, A.N., M.J. Ottman, 2010: Irrigation frequency effects on growth and ethanol yield in sweet sorghum. Agronomy Journal **102** (1), 60-70.

Muchow, R.C., 1989: Comparative productivity of maize, sorghum and pearl millet in a semi-arid tropical environment. II. Effect of water deficits. Field Crops Research **20** (3), 207-219.

Murdock, W.L., K.L. Wells, 1978: Yields, nutrient removal, and nutrient concentrations of double-cropped corn and small grain silage. Agronomy Journal **70** (4), 573-576.

Neild, R.E., 1982: Temperature and rainfall influences on the phenology and yield of grain sorghum and maize: a comparison. Agricultural and Forest Meteorology **27** (1-2), 79-88.

Singh, B.R., D.P. Singh, 1995: Agronomic and physiological responses of sorghum maize and pearl millet to irrigation. Field Crops Research **42**, 57-67.

Sourell, H., 2011: Die Kosten der Bewässerung im Umfeld steigender Agrar- und Energiepreise. Available from: http://media.manila.at/oekl/gems/Koll08ReferatSourell.pdf [in German; accessed 10 August 2011].

Toews, T., R. Stülpnagel, C. von Buttlar, 2008: Erhöhung der Flächenerträge durch das Zweikultur-Nutzungssystem. Top Agrar **6/2008**, 58-60 [in German].

Utz, H.F., 2011: PLABSTAT. A computer program for statistical analysis of plant breeding experiments, Version 3A. Available from: https://www.uni-hohenheim.de/plantbree-ding/software/index [accessed 10 August 2011].