Organic Farming | 2019 | Volume 5 | Issue 1 | Pages 3–13
DOI: 10.12924/of2019.05010003
ISSN: 2297–6485

Organic Farming

Research Article

Comparative Harvest Efficiency of Soybeans between Cropping Systems Affected by First Pod Height and Plant Length

Mareike Beikűfner[1,*], Bianka Hűsing[1], Dieter Trautz[1], Insa Kűhling[1,2]

[1] Osnabrück University of Applied Sciences, Osnabrück, Germany
[2] Martin Luther University Halle-Wittenberg, Halle (Saale), Germany

*Corresponding author: E-Mail: m.beikuefner@hs-osnabrueck.de, Tel.: +49 541 969-5236, Fax: +49 541 969-5170

Submitted: 21 March 2018 | In revised form: 18 December 2018 | Accepted: 21 January 2019 | Published: 10 April 2019

Abstract: Today, the demand for soybean for feed industry and food production in Germany is met by imports from South and North America. Soybean cultivation in Germany, although challenging, will be of interest in the future due to an increasing demand for non-genetically modified (NGM) soybeans. To meet this rising demand for NGM soybeans and to increase resource use efficiency there is a need to reduce soybean harvest losses arising from harvesting with combine harvester. The height of the first pod can be a major factor affecting harvest losses, especially when it is not possible to maintain a sufficiently low cutting height. From 2011 to 2013, six soybean varieties were cultivated using two cropping systems (conventional 'CON' and organic 'ORG') at the Osnabrück University of Applied Sciences in a randomized block design with four replications to investigate the effect of first pod height and plant length on harvest losses and the effect of the cropping system on these parameters. Before harvesting with an experimental harvester, 1.5 m^2 per plot were harvested manually as a reference. First pod height, number of pods per plant and plant length were determined on 10 plants per plot. Over the three years of the study, the first pod height (10.4 cm) and plant length (81.4 cm) were on average higher under conventional conditions compared to organic cultivation (7.3 cm; 60.9 cm). On average, lower harvest losses (25.6% vs. 39.2%) and higher grain yields (20.8 dt ha^{-1} vs. 16.9 dt ha^{-1}) were also observed under conventional cultivation. Varieties differed significantly in grain yield, first pod height and plant length. A high first pod height was related to a longer plant length and lower harvest losses at both sites. However, a high first pod height and a high plant length did not lead to higher grain yields on any of the plots. These results indicate that harvest efficiency can be improved by choosing varieties with long plant lengths if it is not possible to maintain a low cutting height when harvesting with a combine harvester.

Keywords: conventional agriculture; early maturity varieties; *Glycine max* (L.) Merr.; organic agriculture; pulses

1. Introduction

Soybean (*Glycine max* (L.) Merr.) is an important legume crop characterized for its protein quality and biological availability and highly valued in the international food industry for animal and human consumption [1]. The global demand for soybean is rising each year, particularly as the world population is shifting towards consuming more food products

librello

derived from livestock. In Germany, the demand for soybean for livestock feed is mainly met by imports from North and South American (3.6 Mio. t per year), while in contrast, only about 15800 ha were cultivated locally in 2016 [2]. The increasingly popular cultivation of genetically modified (GM) soybean in the Americas combined with stricter regulations for organically produced soybean for human nutrition will likely lead to an increasing demand for GM-free soybeans in the future [3,4]. In the context of climate change and sustainable land management, the importance of organically cultivated soybean is increasing [5]. Therefore, the cultivation of regional organic and conventional soybean will not only be interesting, but also a challenge for the future. Soybean varieties are known to respond differently to environmental and climate conditions, such as drought, low temperatures and nutrient availability as well as management system (e.g. seeding rate, row width, planting date) by changing their growth patterns and yield components such as number of pods per plant, and 1000-grain weight, but also their morphology, e.g. plant length and first pod height [6–8]. There are high-yielding soybean varieties with early maturity groups (00 and 000, respectively) available for the German climate conditions, with yields being highly correlated with temperature at flowering time [8]. Additionally, stable yields at a lower level were observed for very early maturing varieties (maturity group (MG) 000) with a high tolerance of cold conditions while early maturing varieties (MG 00) have achieved higher yields in years with higher temperatures [8]. Other aspects, besides climate adaptability and yield potential of soybean varieties, are growth traits influencing soybean harvest losses such as plant length, first pod height and pod stability [9,10]. Philbrook and Oplinger [9] observed soybean harvest losses ranging from 5.5 to 12% of the potential yield. They attributed these harvest losses to delayed harvest time, which led to increased plant lodging and increased pre-harvest shatter and stem losses. Shatter losses are influenced by grain moisture at harvest, with low grain moisture leading to high shatter losses [11] and by the gene expression for the thickening of the lignified fiber cap cell walls of the pod [12]. Soybean harvest losses derived from lodging were related to an increased plant length and plant population density [13,14]. Besides, Weber and Fehr [13] observed 12.2% stem losses due to a higher cutting height of 16.5 cm. Schnug and Beuerlein [15] mentioned that stem losses can be greater than 10% if proper combine adjustment is not possible (e.g. on stony soils). Therefore, first pod height can be a major factor affecting harvest losses, especially when pods form below the cutting height [9,10]. It has been frequently reported that crop yield under organic farming conditions is often reduced compared to conventional farming while this yield difference is highly dependent on crop species and site characteristics [16,17]. For soybean, lower yields as well as higher yields were demonstrated under organic compared to conventional cropping conditions [17,18]. There is a lack of information on the impact of different cropping systems (conventional vs. organic) in combination with different soybean varieties on yield and growth traits affecting harvest losses (e.g. plant length, first pod height) under German climate conditions.

Therefore, the aim of this study was to investigate the impact of variety choice in an organic and a conventional cropping system on yields and the growth traits of soybean varieties in relation to combine harvester losses.

2. Material and methods

Field trials took place at the experimental farms of Osnabrück University of Applied Sciences in close proximity (52.32°N; 8.04°E) with two different management systems (organic (ORG) at Waldhof and conventional (CON) at Nettehof/Langsenkamp) during three consecutive seasons (2011-2013). Waldhof is a certified organic farm according to European Union and Bioland regulations since more than 20 years. The sites are located in the temperate oceanic (Cfb) climate zone [19] with a mean annual air temperature of 9.5°C and a mean annual precipitation of 883 mm. Six early to very early maturing soybean varieties (Aligator: maturity group (MG) 000; Aveline: MG 000; ES Mentor: MG 00; Gallec: MG 000/00; Lissabon: MG 000; Sultana: MG 000) were grown in a randomized block design with four replications. For inoculation treatment the product HiStick (BASF) was used in 2011, while Force48 (BASF) was used in 2012 and 2013 (4 g kg^{-1} seeds with more than $2*10^9$ viable cells g^{-1}). Both products contain the *Bradyrhizobium japonicum* strain 532c. The seeds were inoculated directly before sowing according to the manufacturer's recommendations. Each year, the field plots were ploughed and the seedbed prepared for sowing. The plot width was 1.5 m with a plot length of 10 m and a total plot size of 15 m^2. The row spacing between the 4 rows of each plot was 37.5 cm. The seeding rate was increased from year to year (from 65 kernels m^{-2} to 77 kernels m^{-2}, see Table 1) to compensate low emergence, plant damages by birds and plant damages by mechanical weeding. Nets were used in 2013 under ORG to protect the plants from birds. The harvest time was adapted to the different maturity groups. The irrigation was performed as required. Detailed descriptions of the soil conditions and the timing of management operations at each field and year are given in Table 1.

Table 1. Description of the specific field trial management conducted within the two cropping systems organic (ORG) and conventional (CON) over the three experimental years and field specific soil conditions (n.a.: data not available).

		2011		2012		2013	
		ORG	**CONV**	**ORG**	**CONV**	**ORG**	**CONV**
Experimental set up							
Previous crops	Trial year - 1	potato	rye as cover crop	potato	wheat	potato	wheat
	Trial year - 2	wheat	wheat	spelt	wheat	triticale	wheat
Seeds m^{-2}		65	65	70	70	77	77
Sowing date (dd.mm)		27.04.	27.04.	29.04.	30.04.	05.05.	02.05.
Harvest date (dd.mm)		30.09.	30.09.	10.10.	11.10.	02.10.	02.10.
		(MG 000-000/00)	(MG 000-000/00)	(MG 000-000/00)	(MG 000-000/00)	(MG 000)	(MG 000)
		20.10.	20.10.	20.10.	21.10.	07.10.	07.10.
		(MG 00)	(MG 00)	(MG 00)	(MG 00)	(MG 000/00)	(MG 000/00)
						22.10.	22.10.
						(MG 00)	(MG 00)
Plant protection		mechanical and manual weeding	910 g ha^{-1} Pendimethalin	mechanical and manual weeding	910 g ha^{-1} Pendimethalin	mechanical and manual weeding	910 g ha^{-1} Pendimethalin
			480 g ha^{-1} Bentazon		480 g ha^{-1} Bentazon		480 g ha^{-1} Bentazon
			2.5 g ha^{-1} Thifensul-furon Methyl		2.5 g ha^{-1} Thifensul-furon Methyl		2.5 g ha^{-1} Thifensul-furon Methyl

Table 1. *Continued from previous page.*

	2011		2012		2013	
Soil conditions						
Soil pH	5.0	6.0	5.0	6.0	6.0	6.0
Soil mineral nitrogen 0-30cm (kg N ha^{-1})	52.2	55.2	58.8	74.4	50.6	62.4
Phosphorus (mg P 100 g^{-1} soil)	3–4	5–9	3–4	5–9	n.a.	5–9
Potassium (mg K 100 g^{-1} soil)	0–2	4–7	0–3	8–12	n.a.	8–12
Soil type	Planosol	plaggic Anthrosol	Planosol	Cambisol	Planosol	plaggic Anthrosol
Soil texture	loamy sand	sandy loam	sandy loam	loamy sand	sandy loam	loamy sand

The plant length and first pod height were measured on 10 randomly selected plants per plot in real field position after elongation growth was completed. Before harvesting with an experimental combine harvester, 1.5 m^2 per plot divided into two areas were harvested manually. Before the whole plants were cut directly above the soil surface, the plants were counted to determine the plant population density. In each year of the trial, the cutting height was set at 10 cm for both systems; this was the minimal necessary height due to a stony soil at ORG. For each plot, the number of pods per plant were counted on 10 randomly selected plants from the manual harvest. Two yield results were estimated: the combine harvested (CH) yield from an area of 13.5 m^2 and manual yield from an area of 1.5 m^2. The CH yield and manual yield were standardized to a grain moisture content of 86% while the measured grain moisture was taken into account. Losses were investigated by comparing the combine harvested yield with yield from the manual harvest.

Statistical analysis was performed with the SPSS software (version 24, SPSS, Inc, Chicago, IL, USA), by using the procedure 'Mixed' and followed by a LSD post-hoc test. The factors - year, variety and system - were considered to be fixed while the factor block within a year and system was considered to be random. Correlations according to Pearson (p = 0.01) among the parameters were computed on the basis of the data from three years for both cropping systems.

3. Results

In 2011, the warm and dry spring led to beneficial conditions for soybean emergence. In June and July, there was sufficient water for flowering and seeding (Figure 1).

In 2012, the spring season was cold, while July received above average rainfall. At the end of June at the R2 stage (full bloom), night temperatures were lower than 10°C resulting in flower losses. The spring season in 2013 was also cold while in June and July precipitation was below the long-term average. Thus, the plots were irrigated as required. Significant system and year effects were observed for all parameters as well as some interactions. The analysis of variance results for the varieties within the two growing systems over the three years studied are shown in Table 3.

Due to different weather conditions, separate post-hoc tests were conducted for system×variety for each year. CH yield was higher under conventional conditions on average by 3.8 dt ha^{-1}. Large differences between the years, systems and varieties were determined (Table 2).

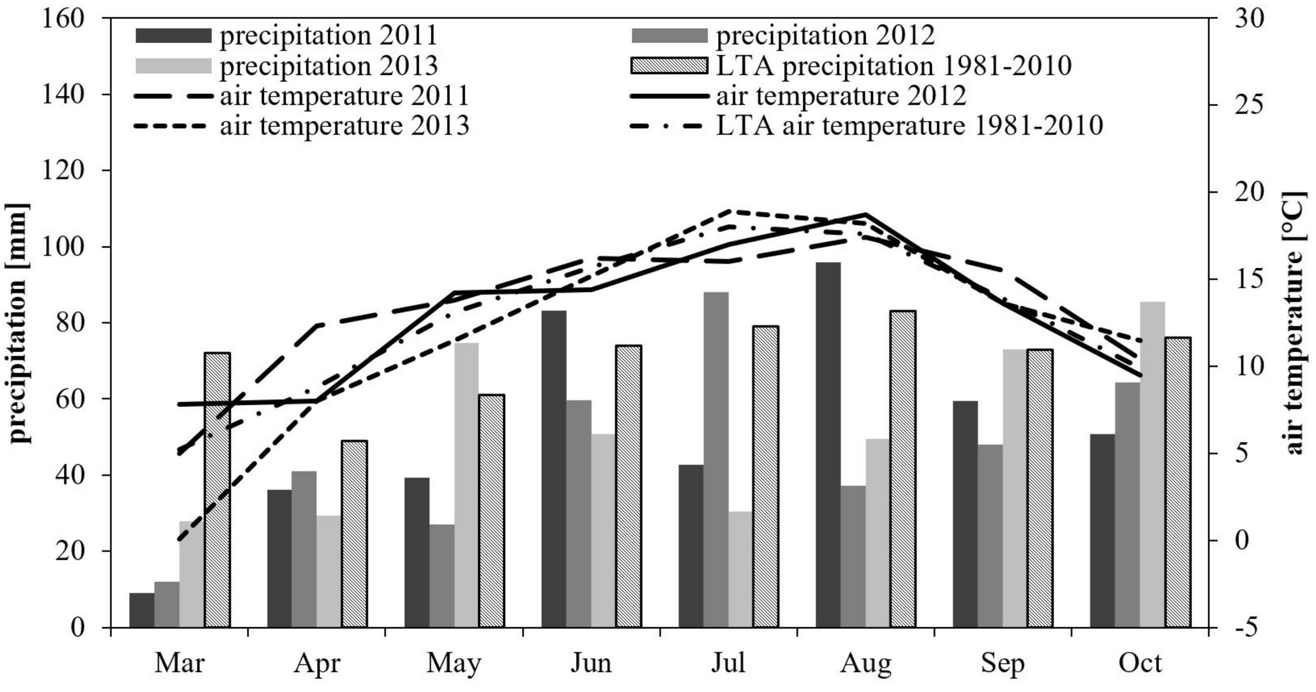

Figure 1. Monthly precipitation (bars) and air temperature (curves) during vegetation period March–October for 2011–2013 and for the long-term average (LTA) from 1981–2010. Data source: [20].

Table 2. Mean values (± standard error) for combine harvested (CH) yield, harvest losses, first pod height, plant length, plant population density, number of pods per plant and 1000-grain weight for the varieties tested over the three years studied with organic (ORG) and conventional (CON) cropping systems. Multiple comparisons were done with LSD-test (p = 0.05) for each parameter except for harvest losses and 1000-grain weight. There are no differences between the varieties with the same letters within each year and system (p = 0.05).

Variety	CH yield (dt ha^{-1})			Harvest losses (%)		First pod height (cm)			Plant length (cm)			Plant population density (plant m^{-2})			Number of pods per plant			1000-grain weight (g)	
Site: ORG																			
2011																			
Aligator	21.3	(± 1.1)	bc	33.0	(± 3.6)	8.7	(± 0.8)	ab	66.7	(± 9.3)	ab	30.0	(± 6.5)	ab	22.7	(± 2.5)	a	257.0	(± 2.4)
Aveline	17.2	(± 3.6)	a	41.9	(± 21.2)	8.2	(± 0.9)	ab	72.8	(± 4.7)	b	29.3	(± 1.3)	a	21.5	(± 4.3)	a	246.4	(± 17.8)
ES Mentor	28.7	(± 1.5)	d	26.5	(± 14.5)	7.5	(± 0.9)	a	66.9	(± 2.0)	ab	39.5	(± 3.2)	c	19.7	(± 1.3)	a	270.6	(± 3.7)
Gallec	18.7	(± 2.2)	ab	40.9	(± 7.2)	8.5	(± 0.8)	ab	63.9	(± 2.4)	a	30.8	(± 5.4)	ab	22.2	(± 2.0)	a	247.2	(± 6.9)
Lissabon	19.5	(± 3.2)	ab	41.7	(± 6.9)	9.4	(± 1.6)	b	65.0	(± 6.2)	a	35.0	(± 2.9)	abc	19.3	(± 4.1)	a	240.3	(± 3.8)
Sultana	23.6	(± 1.2)	c	30.1	(± 11.4)	7.1	(± 0.4)	a	63.2	(± 7.7)	a	35.8	(± 4.8)	bc	23.9	(± 2.2)	a	242.8	(± 9.7)
2012																			
Aligator	13.8	(± 3.1)	bc	54.5	(± 3.8)	6.7	(± 1.1)	a	63.3	(± 3.7)	b	23.5	(± 1.5)	a	31.8	(± 2.4)	a	241.7	(± 8.1)
Aveline	8.3	(± 3.6)	a	56.4	(± 25.0)	7.8	(± 0.8)	a	56.6	(± 4.5)	b	29.0	(± 5.2)	ab	32.0	(± 4.8)	a	198.2	(± 14.6)
ES Mentor	9.8	(± 4.7)	ab	56.9	(± 21.1)	6.8	(± 1.4)	a	48.1	(± 2.3)	a	23.3	(± 8.2)	a	27.6	(± 2.3)	a	230.2	(± 8.6)
Gallec	13.9	(± 1.9)	bc	40.5	(± 10.7)	6.3	(± 0.6)	a	45.2	(± 1.1)	a	33.0	(± 1.6)	b	29.0	(± 3.6)	a	197.8	(± 7.2)
Lissabon	18.1	(± 0.4)	c	29.7	(± 4.6)	8.2	(± 0.2)	a	74.0	(± 5.8)	c	38.0	(± 7.0)	b	26.8	(± 1.5)	a	199.5	(± 22.7)
Sultana	14.2	(± 2.5)	c	53.1	(± 12.8)	6.8	(± 1.0)	a	62.4	(± 3.4)	b	32.0	(± 1.0)	ab	32.8	(± 2.0)	a	227.1	(± 4.0)
2013																			
Aligator	13.7	(± 1.9)	ab	50.1	(± 2.9)	6.6	(± 0.8)	a	52.4	(± 6.4)	a	27.8	(± 6.3)	a	25.3	(± 5.8)	a	215.2	(± 5.6)
Aveline	16.1	(± 1.8)	bc	34.5	(± 6.2)	8.4	(± 0.9)	b	70.8	(± 5.3)	c	32.0	(± 4.1)	a	27.5	(± 5.1)	a	189.8	(± 6.7)
ES Mentor	14.8	(± 2.6)	abc	48.7	(± 9.8)	6.0	(± 0.8)	a	59.6	(± 5.5)	b	25.5	(± 3.4)	a	25.8	(± 2.6)	a	229.0	(± 6.6)
Gallec	17.7	(± 3.3)	c	38.1	(± 9.7)	5.7	(± 0.5)	a	60.4	(± 8.4)	b	30.0	(± 1.6)	a	27.0	(± 3.7)	a	217.2	(± 4.2)
Lissabon	12.6	(± 2.0)	a	52.3	(± 9.8)	5.6	(± 0.4)	a	56.0	(± 2.6)	ab	26.0	(± 2.5)	a	28.3	(± 5.4)	a	189.5	(± 3.4)
Sultana	16.5	(± 1.5)	bc	41.2	(± 7.4)	5.8	(± 0.5)	a	50.9	(± 2.4)	a	28.5	(± 1.5)	a	29.5	(± 0.5)	a	196.7	(± 5.0)

Table 2. *Continued from previous page.*

Variety	CH yield (dt ha^{-1})			Harvest losses (%)		First pod height (cm)			Plant length (cm)			Plant population density (plant m^{-2})			Number of pods per plant			1000-grain weight (g)	
Site: CONV																			
2011																			
Aligator	22.0	(± 2.4)	a	17.6	(± 10.8)	12.8	(± 0.9)	b	79.2	(± 5.4)	bc	31.5	(± 2.5)	a	15.1	(± 1.5)	a	259.2	(± 3.0)
Aveline	22.8	(± 2.2)	a	10.3	(± 11.8)	12.2	(± 1.3)	ab	79.4	(± 3.5)	bc	30.5	(± 4.2)	a	16.4	(± 1.7)	a	263.5	(± 2.1)
ES Mentor	31.9	(± 3.4)	c	12.8	(± 21.8)	10.7	(± 0.8)	a	73.5	(± 1.3)	ab	39.3	(± 5.4)	b	16.7	(± 2.2)	a	275.3	(± 6.8)
Gallec	27.3	(± 1.3)	b	18.5	(± 10.3)	11.0	(± 2.0)	ab	82.6	(± 3.3)	c	33.8	(± 5.8)	ab	20.2	(± 3.1)	a	252.7	(± 5.8)
Lissabon	31.6	(± 1.7)	c	19.9	(± 6.4)	10.6	(± 2.0)	a	72.0	(± 2.5)	a	31.3	(± 5.6)	a	17.4	(± 2.2)	a	271.4	(± 6.8)
Sultana	26.9	(± 2.0)	b	23.6	(± 6.0)	11.5	(± 1.8)	ab	73.3	(± 2.9)	ab	31.8	(± 4.5)	ab	19.9	(± 2.9)	a	251.7	(± 1.1)
2012																			
Aligator	14.4	(± 1.6)	ab	31.9	(± 11.8)	11.6	(± 0.5)	b	97.9	(± 3.6)	c	36.0	(± 2.3)	a	22.5	(± 2.2)	ab	194.4	(± 5.8)
Aveline	13.3	(± 1.6)	ab	29.8	(± 5.6)	11.2	(± 0.8)	b	100.3	(± 3.4)	c	49.8	(± 10.1)	c	17.6	(± 2.5)	a	206.8	(± 7.6)
ES Mentor	18.0	(± 1.5)	c	25.6	(± 4.7)	8.9	(± 1.2)	a	88.2	(± 1.7)	b	45.0	(± 1.9)	bc	19.0	(± 2.0)	a	216.7	(± 10.7)
Gallec	17.2	(± 1.0)	bc	22.9	(± 14.3)	11.0	(± 1.5)	b	96.2	(± 4.1)	c	48.8	(± 5.3)	c	21.0	(± 2.7)	ab	188.9	(± 15.8)
Lissabon	18.5	(± 2.0)	c	28.0	(± 12.4)	10.5	(± 1.3)	ab	83.9	(± 4.5)	ab	39.0	(± 2.5)	ab	25.9	(± 3.7)	b	181.3	(± 2.8)
Sultana	15.0	(± 0.8)	abc	34.1	(± 12.9)	10.9	(± 1.2)	b	79.8	(± 2.5)	a	48.0	(± 3.7)	c	25.5	(± 2.5)	b	162.1	(± 6.6)
2013																			
Aligator	19.1	(± 1.9)	a	39.1	(± 5.9)	7.9	(± 1.4)	ab	66.2	(± 3.9)	b	33.0	(± 6.0)	abc	29.0	(± 3.8)	ab	229.8	(± 8.6)
Aveline	19.9	(± 1.2)	a	27.8	(± 5.2)	9.3	(± 0.5)	b	78.1	(± 4.1)	c	36.5	(± 6.8)	abc	28.4	(± 4.5)	ab	211.0	(± 5.4)
ES Mentor	24.0	(± 1.5)	bc	33.4	(± 4.9)	9.3	(± 1.1)	b	76.4	(± 3.0)	c	40.3	(± 4.5)	c	28.3	(± 1.8)	ab	239.1	(± 11.1)
Gallec	24.1	(± 1.4)	c	23.8	(± 5.9)	8.9	(± 0.4)	b	72.2	(± 2.4)	bc	38.0	(± 3.0)	bc	27.2	(± 3.7)	a	210.9	(± 5.2)
Lissabon	20.5	(±1.4)	ab	34.9	(± 4.6)	8.9	(± 1.0)	b	72.0	(± 1.9)	bc	31.8	(± 4.1)	ab	30.0	(± 3.4)	ab	201.6	(± 11.1)
Sultana	17.5	(±1.7)	a	38.3	(± 6.1)	6.9	(± 1.0)	a	54.1	(± 1.5)	a	29.3	(± 4.3)	a	33.6	(± 8.2)	b	194.2	(± 4.9)

Table 3. P-values from the mixed model for combine harvested (CH) yield, harvest losses, first pod height, plant length, plant population density, and number of pods per plant (bold numbers indicate level of significance $p < 0.05$).

Factor	CH yield (dt ha^{-1})	Harvest losses (%)	First pod height (cm)	Plant length (cm)	Plant population density (plant m^{-2})	Number of pods per plant
Variety (V)	<**0.001**	0.496	<**0.001**	<**0.001**	<**0.001**	**0.005**
System/Site* (S)	<**0.001**	<**0.001**	<**0.001**	<**0.001**	**0.022**	**0.001**
Year (Y)	<**0.001**	**0.001**	<**0.001**	<**0.001**	**0.001**	<**0.001**
V×S	**0.001**	0.663	0.920	<**0.001**	**0.020**	0.244
V×Y	<**0.001**	0.109	0.162	<**0.001**	**0.002**	0.766
S×Y	0.102	0.283	0.324	<**0.001**	<**0.001**	<**0.001**
V×S×Y	**0.004**	0.686	**0.045**	<**0.001**	0.319	0.565

* The organic system was performed on the site Waldhof, the conventional system on the site Nettehof/Langsenkamp

The highest CH yields were observed in 2011 ranging between 17.2 to 28.7 dt ha^{-1} at ORG and 22.0 to 31.9 dt ha^{-1} at CON with best results for ES Mentor in both systems. In 2012 the lowest CH yields were observed with Aveline at 8.3 dt ha^{-1} (ORG) and 13.3 dt ha^{-1} (CON). CH yields in 2013 were slightly higher compared to 2012. There were significant effects of year and system on harvest losses, but no interactions and no influence of variety were determined (Table 3). Average harvest losses in 2011 (24.3%) were consistently lower than in 2012 (38.7%) and 2013 (34.4%) (Table 2). No significant differences between the harvest losses in 2012 and 2013 were detected. Organic growing conditions resulted in higher average harvest losses (39.2%) compared to conventional growing conditions (25.6%).

First pod height and plant length were significantly influenced by year, system and variety. Additionally, a significant year×system×variety interaction was observed (Table 3). First pod heights were consistently lower at ORG compared to CON (on average 3.1 cm) (Table 2). The highest first pod heights were observed in 2011 at 9.4 cm (Lissabon) at ORG and at 12.8 cm (Aligator) at CON. In 2013, the lowest heights of the first pod were measured at ORG at 5.6 cm (Lissabon) and at CON at 7.9 cm (Aligator). The average difference in plant length between the two cropping systems amounted to 20.4 cm. Plant lengths under conventional growing conditions were longer in each year, especially in 2012. The longest plant length was observed for Aveline: in 2011 at 72.8 cm at ORG and in 2012 at 100.3 cm at CON. At ORG, the plant length was shortest in 2012 at 45.2 cm (Gallec), while at CON plant length was shortest in 2013 at 54.1 cm (Sultana) (Table 2).

For plant population densities and number of pods per plant, significant effects of year, system, variety, and the interaction between year×system were observed. Additionally, the interaction system×variety had a significant effect on plant population density (Table 3). On average, plant population density was higher under conventional conditions (+ 8.2 plants m^{-2}), especially in 2012, while the number of pods per plant was slightly higher at ORG (+ 2.9 pods per plant) with variation between the years and varieties.

The highest plant population density at ORG was registered in 2011 with 39.5 plants m^{-2} (ES Mentor) and at CON in 2012 with 48.8 plants m^{-2} (Aveline). In 2012 at ORG, damages caused by birds reduced plant population density at some plots resulting in the lowest plant population density of 23.3 plants m^{-2} (ES Mentor). The lowest plant population density at CON was observed in 2013 with 29.3 plants m^{-2} (Lissabon). Under organic conditions, the number of pods per plant ranged between 19.3 (Lissabon, 2011) and 32.8 (Sultana, 2012), while at CON the number of pods per plant ranged between 15.1 (Aligator, 2011) and 33.6 (Sultana, 2013) (Table 2).

Since there were no differences between the correlation coefficients when they were calculated separately for each cropping system, results are presented together for both systems. The analyses of correlations (Table 4) showed significant negative relations between harvest losses and CH yield.

First pod height was positively correlated with plant length and negatively with harvest losses. Furthermore, the results reveal significant positive correlations for plant population density with plant length and first pod height as well as a significant negative correlation with harvest losses.

Table 4. Correlation coefficients of agronomic characteristics for the mean of six soybean varieties of both cropping systems (n = 136).

	CH yield (dt ha^{-1})	harvest losses (%)	first pod height (cm)	plant length (cm)	number of pods per plant
Harvest losses (%)	−0.704*				
First pod height (cm)	0.409*	−0.522*			
Plant length (cm)	0.236	−0.449*	0.666*		
Number of pods per plant	−0.151	0.061	−0.113	0.076	
Plant population density (plant m^{-2})	0.198	−0.321*	0.412*	0.577*	0.090

* Correlation significant at p = 0.01.

4. Discussion

Climate effect

All recorded variables responded to the different weather conditions in each year. In 2011, beneficial temperatures during emergence (April/May) and harvest (September/October) as well as sufficient water during flowering and low precipitation during harvest resulted in the highest CH yields of all years with differences between the varieties and cropping systems. Plant population density at harvest and the number of pods per plant were lower than in 2013. Presumably, the high CH yields in 2011 were achieved due to high 1000-grain weights (Table 2). Several authors [21–25] also observed higher 1000-grain weights when the number of pods per plant was lower. The first pod height was higher in 2011 compared to 2012 and 2013. Beneficial weather conditions at harvest and higher first pod heights may have led to low harvest losses in 2011. In 2012, low temperature during flowering caused flower losses which resulted in the lowest CH yields. Balko et al. [8] and Kurosaki et al. [23] also determined flower losses and reduced pod setting when air temperatures were lower than 10°C during the flowering stage. Additionally, plant population density was reduced at some plots in our field trials due to damages from birds. In these plots with a low plant population density, a higher number of pods per plant, lower first pod heights and shorter plant lengths were observed. Leithold et al. [26], Lueschen and Hicks [23] and Stock et al. [27] also observed a higher number of pods per plant with low plant population densities. In our study, reduced yields due to lower plant population densities were not prevented by a higher number of pods per plant which was probably attributed to low 1000-grain weights in 2012. Although the seeding rate was increased in each trial year, CH yields and plant population density at harvest were not significantly higher in the third year. Low spring temperature may have led to low emergence. Additionally, weather conditions at harvest time were wet compared to the long-term average which could also have been a reason why CH yields in 2013 were lower than in 2011. Philbrook and Oplinger [9] also observed lower yields with precipitation at harvest time. The results of our study indicate that soybean plants are able to change their growth patterns and yield components in respect to environmental and climatic conditions. This had already been confirmed by other researchers [6,7,25].

Varieties

The varieties tested in our study responded differently to the weather conditions in each year and to the cropping systems. In 2011, the early maturing variety ES Mentor (MG 00) benefited from air temperature above the long-term average, which led to the highest CH yields. But the difference between maximum and minimum yield of ES Mentor amounted to 25.3 dt ha^{-1}. In contrast, Aligator (MG 000) achieved moderate CH yields in all years but the difference between maximum and minimum yield was much lower (13.8 dt ha^{-1}) compared to ES Mentor. These results are in line with Balko et al. [8], who determined stable but moderate yielding varieties with high tolerance to cold conditions and very early maturity. Furthermore, the varieties tested in our study showed significantly different plant lengths and first pod heights. The positive correlation observed between first pod height and plant length was also obtained in other experiments [10,28]. However, Cober et al. [29] found no correlation between first pod height and plant length, but a higher first pod height correlated with additional nodes without pods at the bottom of the main stem. In several studies, longer plant lengths led to increased lodging which is considered as a factor influencing harvest losses [9,10,13]. Since in our study, lodged plants occurred rarely, we suggest that harvest losses did not result from lodging. Furthermore, higher first pod heights were associated with decreased harvest losses in our study. Although Philbrook and Oplinger [9] determined that harvest losses resulted primarily from threshing and shatter losses, the results of our research suggest that harvest losses also result from low first pod heights. The cutting height was kept at 10 cm due to a stony soil at ORG as well as at CON, so that pods below the cutting height remained on the stem after harvesting with the combine harvester. Ramteke et al. [10] also observed higher harvest losses when first pod heights were below the cutting height. However, where it is possible to maintain a low cutting height, very few pods remain on the stem [9]. Furthermore, high CH yields were not attributed to higher first pod heights in our study and also in other field trials [10]. CH yields are directly influenced by variety, cropping system and weather conditions. These results confirm our observation that ES Mentor had the highest yield potential but showed short plant lengths and low first pod heights, while Aveline had the lowest yield potential and showed long plant lengths and high first pod heights.

Cropping system

CH yield, first pod height and plant length were consistently higher under conventional compared to organic cropping conditions whereas harvest losses were higher at ORG than at CON. De Ponti et al. [16] pointed out that yield limiting conditions like water and nutrient availability, pest activities, diseases and weeds are more easily to control under conventional than under organic conditions. Global meta-analyses demonstrate that the yields of organic soybean achieved on average 90% of conventional yields, with large differences between regions [16,17]. The authors indicated that the gap between soybean yield under organic and conventional growing conditions were smaller than the yield gap between non-legumes due to a high N supply through biological nitrogen fixation (BNF). In a single site study, Mäder et al. [18] even observed a slightly higher soybean yield (+ 5%) under organic growing conditions which they also attributed to BNF. In our study, yield gap between the organic and conventional cropping system was 18.4%. At the ORG plots examined in this research, the soil content of mineral nitrogen, phosphorus and potassium was lower than at CON plots. Compared to the CON plots, the lower availability of potassium and phosphorus have caused presumably, among other factors, an impaired vegetative and generative growth which led to lower grain yield, lower first pod heights and shorter plant lengths. Although the impact of the cropping system on soybean yield and some growth traits was investigated in our study, further detailed research is needed to clarify the yield limiting and growth affecting factors (e.g. soil fertility) under organic cropping conditions. Furthermore, there are no soybean varieties available which have been bred specifically for organic cropping systems. Therefore, further research should focus additionally on breeding organic soybean varieties with respect to stabilized yields, as well as growth traits influencing harvest efficiency.

5. Conclusion

In the three years of the study, we observed lower CH yields, first pod heights and shorter plant lengths, and higher harvest losses under organic growing conditions. The varieties with longer plant lengths and higher first pod heights did not necessarily lead to higher CH yields but to lower harvest losses at ORG and CON. Improving the harvest efficiency of organic soybeans is of importance to serve increasing demands. This study indicates that yield performance and harvest efficiency can be improved specifically for ORG conditions by choosing varieties with moderate but stable yields and long plant lengths. This can lead to reduced harvest losses, especially at sites where a low cutting height is not feasible (e.g. stony soil) or yield potential is low.

Acknowledgements

The trials took place within the project ‘Expansion of soybean cultivation in Germany through adaptation by breeding as well as optimization of crop production and processing technology’ funded by the German Government, Federal Ministry of Food and Agriculture within their BÖLN framework (funding reference 11NA002). We thank M. Kohlbrecher, M. Vergara and T. Zurheide for help with field data collection and H.-G. Schön for assistance with data analysis. Finally, we are grateful for the valuable anonymous reviewer comments that substantially improved the manuscript.

References and Notes

[1] Recknagel J. Soja-Anbaupotentiale und Absatzmöglichkeiten in Deutschland. Schriftenreihe der Bayerischen Landesanstalt für Landwirtschaft. 2015;6:14–20. Available from: https://www.lfl.bayern.de/mam/cms07/publikationen/daten/schriftenreihe/soja-tagung-2015_lfl-schriftenreihe.pdf.

[2] DESTATIS. Anbaufläche von Sojabohnen. Available from: https://www.destatis.de/DE/ZahlenFakten/Wirtschaftsbereiche/LandForstwirtschaftFischerei/FeldfruechteGruenland/Tabellen/AckerlandHauptfruchtgruppenFruchtarten.html.

[3] Nik AM, Tosh SM, Poysa V, Woodrow L, Corredig M. Protein Recovery in Soymilk and Various Soluble Fractions as a Function of Genotype Differences, Changes during Heating, and Homogenization. Journal of Agricultural and Food Chemistry. 2008;56(22):10893–10900. doi:10.1021/jf800897s.

[4] Hartman G, Pawlowski M, Herman T, Eastburn D. Organically Grown Soybean Production in the USA: Constraints and Management of Pathogens and Insect Pests. Agronomy. 2016;6(1):16. doi:10.3390/agronomy6010016.

[5] Wilbois KP, Spiegel AK, Asam L, Balko C, Becker H, Berset E, et al. Ausweitung des Sojaanbaus in Deutschland durch züchterische Anpassung sowie pflanzenbauliche und verarbeitungstechnische Optimierung. Frankfurt, Germany: Forschungsinstitut für biologischen Landbau (FiBL); 2014.

[6] Frederick JR, Bauer PJ, Busscher WJ, McCutcheon GS. Tillage Management for Doublecropped Soybean Grown in Narrow and Wide Row Width Culture. Crop Science. 1998;38(3):755. doi:10.2135/cropsci1998.0011183x003800030023x.

[7] Pedersen P, Lauer JG. Response of Soybean Yield Components to Management System and Planting Date. Agronomy Journal. 2004;96(5):1372. doi:10.2134/agronj2004.1372.

[8] Balko C, Hahn V, Ordon F. Kühletoleranz bei der Sojabohne (Glycine max (L.) Merr.)—Voraussetzung für die Ausweitung des Sojaanbaus in Deutschland. Journal für Kulturpflanzen. 2014;66(11):378–388.
[9] Philbrook BD, Oplinger ES. Soybean Field Losses as Influenced by Harvest Delays. Agronomy Journal. 1989;81(2):251. doi:10.2134/agronj1989.00021962008100020023x.
[10] Ramteke R, Singh D, Murlidharan P. Selecting soybean (Glycine max) genotypes for insertion height of the lowest pod, the useful trait for combine harvester. 2012.
[11] Tiwari S. Characters of Pod Anatomy Associated with Resistance to Pod-Shattering in Soybean. Annals of Botany. 1995;76(5):483–485. doi:10.1006/anbo.1995.1123.
[12] Dong Y, Yang X, Liu J, Wang BH, Liu BL, Wang YZ. Pod shattering resistance associated with domestication is mediated by a NAC gene in soybean. Nature Communications. 2014;5(1). doi:10.1038/ncomms4352.
[13] Weber CR, Fehr WR. Seed Yield Losses from Lodging and Combine Harvesting in Soybeans1. Agronomy Journal. 1966;58(3):287. doi:10.2134/agronj1966.00021962005800030012x.
[14] Wilcox JR, Sediyama T. Interrelationships among height, lodging and yield in determinate and indeterminate soybeans. Euphytica. 1981;30(2):323–326. doi:10.1007/bf00033993.
[15] Schnug B, Beuerlein J. Harvesting, drying, handling, and storage. The soybean in Ohio Ohio Coop Ext Serv The Ohio State Univ Ext Bull. 1987;741:96–100.
[16] de Ponti T, Rijk B, van Ittersum MK. The crop yield gap between organic and conventional agriculture. Agricultural Systems. 2012;108:1–9. doi:10.1016/j.agsy.2011.12.004.
[17] Seufert V, Ramankutty N, Foley JA. Comparing the yields of organic and conventional agriculture. Nature. 2012;485(7397):229–232. doi:10.1038/nature11069.
[18] Mäder P, Fliessbach A, Niggli U, Gunst L, Mayer J. Ertrag von Mais und Sojabohnen im biologischen und konventionellen Anbausystem des DOK-Versuchs. 2013.
[19] Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-Geiger climate classification. Hydrology and Earth System Sciences. 2007;11(5):1633–1644. doi:10.5194/hess-11-1633-2007.
[20] Deutscher Wetterdienst: climate dataset—Archive monthly data Osnabrück. Available from: http://www.dwd.de.
[21] Begonia GB, Aldrich RJ, Salisbury CD. Soybean yield and yield components as influenced by canopy heights and duration of competition of velvetleaf (*Abutilon theophrasti* Medik.). Weed Research. 1991;31(3):117–124. doi:10.1111/j.1365-3180.1991.tb01750.x.
[22] Eaton B, Russ O, Feltner K. Competition of velvetleaf, prickly sida, and Venice mallow in soybeans. Weed Science. 1976;24(2):224–228.
[23] Lueschen WE, Hicks DR. Influence of Plant Population on Field Performance of Three Soybean Cultivars1. Agronomy Journal. 1977;69(3):390. doi:10.2134/agronj1977.00021962006900030015x.
[24] Uchino H, Iwama K, Jitsuyama Y, Yudate T, Nakamura S. Yield losses of soybean and maize by competition with interseeded cover crops and weeds in organic-based cropping systems. Field Crops Research. 2009;113(3):342–351. doi:10.1016/j.fcr.2009.06.013.
[25] Van Acker RC, Swanton CJ, Weise SF. The critical period of weed control in soybean [Glycine max (L.) Merr.]. Weed Science. 1993;41(2):194–200. doi:10.1017/S0043174500076050.
[26] Leithold G, Schulz F, Franz K. Eignung von Sojabohnensorten mit kurzer Vegetationszeit für einen Anbau auf einem ökologisch bewirtschafteten Grenzstandort unter Berücksichtigung unterschiedlicher Reihenabstände. Pflanzenbauwissenschaften. 2003;7:21–28.
[27] Stock H, Kazmi KWM. Analyse der Ertragsstruktur von Sojabohnen (Glycine max [L.] Merr.) aufeinem Standort im mitteldeutschen Trockengebiet. Die Bodenkultur. 1996;23(47):1.
[28] Grabau LJ, Pfeiffer TW. Management Effects on Harvest Losses and Yield of Double-Crop Soybean. Agronomy Journal. 1990;82(4):715. doi:10.2134/agronj1990.00021962008200040014x.
[29] Cober ER, Madill J, Voldeng HD. Early tall determinate soybean genotype E1E1e3e3e4e4dt1dt1 sets high bottom pods. Canadian Journal of Plant Science. 2000;80(3):527–531. doi:10.4141/p99-146.
[30] Kurosaki H, Yumoto S, Matsukawa I. Pod Setting Pattern during and after Low Temperature and the Mechanism of Cold-Weather Tolerance at the Flowering Stage in Soybeans. Plant Production Science. 2003;6(4):247–254. doi:10.1626/pps.6.247.