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Yield and dry matter productivity of Japanese and US soybean cultivars

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ABSTRACT

The difference in yields of cultivars may be causing difference in soybean yield between Japan and the USA. The objective of this study was to identify the effect of the cultivar on dry matter production and to reveal the key factors causing the differences in yield by focusing utilization of solar radiation in recent Japanese and US soybean cultivars. Field experiments were conducted during two seasons in Takatsuki, Japan (34°50'), and in a single season in Fayetteville (36°04'), AR, USA. Five Japanese and 10 US cultivars were observed under near-optimal conditions in order to achieve yields as close to their physiological potential as possible. The seed yield and total aboveground dry matter (TDM) were measured at maturity as long as radiation was intercepted by the canopy. The seed yield ranged from 3.10 t ha⁻¹ to 5.91 t ha⁻¹. Throughout the three environments, the seed yield of US cultivars was significantly higher than that of Japanese cultivars. The seed yield correlated with the TDM rather than the HI with correlation coefficients from .519 to .928 for the TDM vs. .175 to .800 for the HI, for each of the three environments. The higher TDM of US cultivars was caused by a higher radiation use efficiency rather than higher total intercepted radiation throughout the three environments. The seasonal change in the TDM observed in four cultivars indicated that dry matter productivity was different between cultivars, specifically during the seed-filling period.

Abbreviations: DAE: days after emergence; TDM: total dry matter; RUE: solar radiation use efficiency

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Soybeans (*Glycine max* (L.) Merrill) are an important crop for protein and oil. The future demand for soybeans will increase and the soybean yield must be improved to meet this demand (Ainsworth et al., 2012). The productivity of soybeans, soybean production per unit area in the USA has increased steadily over the last 50 years, and the average rate of yield increase was 31 kg ha⁻¹ year⁻¹ (Specht et al., 1999). On the other hand, soybean productivity in Japan is stagnating and the yield gap between Japan and the USA is increasing (Katsura et al., 2009). We focused on the limiting factor of soybean productivity in Japan.

Genetic improvement could be an important factor for the increasing productivity gap between Japan and the USA. Improvements in soybean yields are explained by greater total dry matter (TDM) accumulation or an increase in the harvest index (HI) (Jin et al., 2010; Kumudini, 2002; Morrison et al., 1999). Kumudini et al. (2001) compared new and old soybean cultivars in the MG00 and MG0 in Canada, and reported that the increased dry matter accumulation contributed 78% and increased HI contributed 22% towards the genetic gains in yield. De Bruin and

Pedersen (2009) compared new and old soybean cultivars in Iowa and reported that new cultivars produced higher yields as a result of improved TDM accumulation. Also in Japan, the dry matter productivity differs among cultivars (Shiraiwa et al., 2004), but improvement of seed yield has not been clearly demonstrated. In a study (Okabe et al., 2006), though the lodging resistance of recently released cultivars was significantly improved, no advantage in yield was recognized in recently released cultivars as compared with old cultivars.

The meteorological environment could also be an important factor for high yields. Total dry matter correlates with solar radiation (Monteith, 1977; Shibles & Weber, 1966). Katsura et al. (2008) compared rice productivity between Yunnan, China and Kyoto, Japan through a cross-location experiment and revealed that the high potential yield of irrigated rice in Yunnan is achieved mainly by the intense incident solar radiation. Katsura et al. (2013) compared the meteorologically possible yields of soybean at four locations between the USA and Japan, and reported that the potential yields of soybean in Illinois,

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Arkansas, Hokkaido, and Shiga were $7t\ ha^{-1}$, $8t\ ha^{-1}$, $5t\ ha^{-1}$, and $6t\ ha^{-1}$, respectively. High potential yields estimated in two locations in the USA are mainly due to higher solar radiation. Solar radiation in Illinois and Arkansas is over 30% higher than that in Hokkaido and Shiga. The amount of solar radiation intercepted during the seed-filling period is important for seed yield, especially in soybeans (Board, 2004; Shiraiwa et al., 2004). However, information on the direct comparison of yield and dry matter production during growing season between the USA and Japanese soybean cultivars is very limited.

The radiation use efficiency (RUE), the amount of dry matter produced per unit of solar radiation intercepted, is a good trait to express dry matter productivity (Loomis & Amthor, 1999; Shiraiwa et al., 1994; Sinclair & Horie, 1989; Sinclair & Muchow, 1999). The effects of the cultivar and the solar radiation environment can be distinguished by measuring the RUE. Shiraiwa et al. (1994) found a considerable variability of RUE among old and new Japanese cultivars. There is a possibility that differences in the RUE may exist between US and Japanese recent cultivars. As a trait related to photosynthesis, Tanaka et al. (2010) reported the diversity in the potential stomatal conductance of soybeans calculated from morphological traits of leaves. The morphologically determined potential of stomatal conductance is higher in US cultivars than in Japanese cultivars, and this result suggests that US soybean cultivars have a greater capacity for photosynthesis and dry matter production. Direct comparison of solar radiation use is lacking for recent commercial cultivars, regardless of the great need to understand the physiological potential of soybean productivity in Japan and the USA.

The objective of our study is to compare the potential productivity of soybean cultivars derived from the USA and Japan under optimum growing conditions in reference to yield and dry matter production. If they differed, we then tried to note the key factor related to the difference in the yield and dry matter productivity in reference to solar radiation utilization.

Material and methods

Location and environments

Field experiments were conducted at two locations in 2009: the Experimental Farm, Kyoto University, Takatsuki, Osaka, Japan ($34^{\circ} 50'N$) and the Experimental Farm, University of Arkansas, Fayetteville, AR, US ($36^{\circ} 04'N$). In 2010, the experiment was repeated only in Takatsuki. The experimental plots were managed under conventional conditions, with which soybean performance had been observed at the respective sites. Soybean seeds were sown in a converted paddy field (a clay loam soil, Eutric Fluvisols) after adding fertilizers (NH_4 ; P_2O_5 : $K_2O = 3:10:10\ g\ m^{-2}$) in Takatsuki in both years, and in an

Table 1. Cultivar entries, year of release, and stem growth habit type.

Cultivar	Year of release	Stem growth habit type	
Jpn cvs.	Enrei	1971	Determinate
	Suzukari	1985	Determinate
	Suzuyutaka	1982	Determinate
	Tachinagaha	1986	Determinate
	Tamahomare	1980	Determinate
US cvs.	Athow	1996	Indeterminate
	Omaha	1996	Indeterminate
	LD00-3309	2005	Indeterminate
	Manokin	1991	Determinate
	5002T	2002	Determinate
	UA4805	2005	Determinate
	Osage	2007	Determinate
	5601T	2001	Determinate
	Ozark	2004	Determinate
	Hutcheson	1987	Determinate

upland field (fine-silty, mixed, active, mesic Mollic Paleudalfs) after fertilization (Zn: P: K = 1.12: 4.9: $14.9\ g\ m^{-2}$) according to the soil test in Fayetteville. The planting density was .7 by .15 m in Takatsuki and .15 to .20 by .19 m in Fayetteville. There were three replications in Takatsuki and four in Fayetteville, which were arranged in a completely randomized block design. Furrow irrigation was used to avoid drought stress. Weeding and the spraying of agrochemicals were conducted to maintain optimal conditions.

Plant materials

The cultivars were chosen from recent major non-GM cultivars in both regions. The cultivar entries and year of release, stem growth habit type were shown in Table 1 (Buss et al., 1988; Chen et al., 2004; Chen et al., 2006; Chen et al., 2007; Diers et al., 2006; Kenworthy et al., 1996; Ministry of Agriculture, Forestry and Fisheries, 2015; Nickell et al., 1998; Pantalone et al., 2003, 2004; Rincker et al., 2015; Wilcox & Abney, 1997). In 2009, 5 Japanese cultivars (Suzukari, Suzuyutaka, Enrei, Tachinagaha, and Tamahomare) and 10 US cultivars (Athow, Omaha, LD00-3309, Manokin, 5002T, UA-4805, Osage, 5601T, Ozark and Hutcheson) were grown in Takatsuki. In Fayetteville, two Japanese cultivars (Tachinagaha and Tamahomare) and seven US cultivars (Manokin, 5002T, UA-4805, Osage, 5601T, Ozark and Hutcheson) were grown. The sowing date was 16 June in Takatsuki and 2 June in Fayetteville. In 2010, 5 Japanese cultivars (Suzukari, Suzuyutaka, Enrei, Tachinagaha, and Tamahomare) and the same 10 US cultivars were sown on 7 July in Takatsuki.

Measurements

Meteorological data (daily solar radiation and temperature) were recorded. In 2009, daily solar radiation and daily

temperature were measured by QMS101 and QMH101 (VAISALA, Tokyo), respectively. In 2010, solar radiation meter (LI200X Pyranometer, Li-COR, Lincoln, NE) was used to estimate daily solar radiation and daily temperature was measured by HMP45C (Campbell Scientific, INC., Logan, UT). Growth stages (R1, R5, R7 and R8) were recorded according to Fehr et al. (1971). Canopy coverage was measured following Purcell (2000) and Shiraiwa et al. (2011) to estimate the fraction of radiation intercepted. Canopy coverage was measured one or two times a week.

The seed yield (Yield), total above ground dry matter per unit area (TDM) and HI were measured at R8. Seed moisture content was measured and converted into 14%. 1.26 m² was harvested from one replication in Takatsuki and 4.35 m² was harvested from one replication in Fayetteville. If leaves and petioles were attached to the plant at R8, they were included in the TDM. The dry matter was measured after drying with the oven for 72 h at 80 °C.

The change in the TDM during growing season was measured in Takatsuki in 2009 and 2010. Two Japanese cultivars (Tachinagaha and Tamahomare) and two US cultivars (UA-4805 and 5601T) were harvested in 2009 as the representatives of each groups. Plant materials were harvested at R5, 20 days after R5 of the respective cultivars in 2009. In addition, simultaneous sampling of four cultivars was done 33, 52, and 75 days after emergence (DAE). At the 33DAE sampling, four plants per replication were harvested. After 33DAE sampling, six plants per replication were harvested. In 2010, only Tachinagaha and UA-4805 were harvested at 35, 47, 61, and 74 days after emergence. Twelve plants per replication were harvested in 2010.

Analysis

The equation shown below was used to analyze the yield formation.

$$Y = HI \times TDM \\ = HI \times \overline{RUE} \times \bar{F} \times I$$

Y, HI, and TDM are the seed yield (g m⁻²), HI and total aboveground dry matter (g m⁻²) at R8, respectively. \overline{RUE} , \bar{F} and I are the mean solar RUE of the whole growth duration (from emergence to physiological maturity, R7) (g MJ⁻¹), the mean fraction of radiation intercepted during the whole growth duration, and the incident accumulated solar radiation (MJ). The mean fraction of radiation intercepted (\bar{F}) during whole growth duration was estimated by digital images taken above the canopy (Purcell, 2000; Shiraiwa et al., 2011) two times a week during growing season. Then the daily fraction of the solar radiation was estimated by interpolation and averaged. The incident accumulated solar radiation (I) was calculated from daily

meteorological data. The mean solar RUE (\overline{RUE}) of the whole growth duration was estimated by TDM, \bar{F} , I, and Y.

The effect of the cultivar group (two Japanese cvs. vs. seven US cvs.) and environment were analyzed for nine medium maturing cultivars in three environments, Takatsuki in 2009 and 2010 and Fayetteville in 2009 using ANOVA. In addition, the effect of the cultivar group (three Japanese cvs. vs. three US cvs.) and the environment were analyzed separately for six early maturing cultivars in Takatsuki in 2009 and 2010 using ANOVA. All these statistical analysis were conducted using Microsoft Excel (Microsoft, Redmond, WA, USA).

Results

Table 2 shows the daily average temperature and solar radiation. The average daily radiation of the whole growth duration was larger in Fayetteville (17.8 MJ m⁻²d⁻¹) relative to Takatsuki (17.0 and 17.0 MJ m⁻²d⁻¹ in 2009 and 2010, respectively). In the early growth stage, from June to July, the daily solar radiation in Takatsuki is lower than in Fayetteville over the two years because of the rainy season in Japan. The average daily temperature throughout the whole growth duration was 23.6 °C and 25.2 °C in Takatsuki in 2009 and 2010, respectively, and 21.9 °C in Fayetteville in 2009. These averages of whole growing season were similar between three environments, although

Table 2. Air temperature and solar radiation by month.

	2009		2010
	Takatsuki	Fayetteville	Takatsuki
Daily average radiation (MJ m ⁻² d ⁻¹)			
Jun	20.0	21.7	17.9
Jul	17.0	21.1	18.6
Aug	18.1	19.8	20.4
Sep	17.1	14.6	16.0
Oct	13.0	11.8	12.2
Whole	17.0	17.8	17.0
Daily average temperature (°C)			
Jun	23.3	25.9	23.7
Jul	26.6	25.5	27.6
Aug	27.3	24.7	29.8
Sep	23.3	20.3	25.7
Oct	17.7	13.1	18.9
Whole	23.6	21.9	25.2
Daily maximum temperature (°C)			
Jun	28.3	31.2	28.5
Jul	30.5	30.8	32.2
Aug	31.8	30.3	34.7
Sep	28.1	24.8	31.0
Oct	22.7	17.6	23.9
Whole	28.3	26.9	30.1
Daily minimum temperature (°C)			
Jun	18.7	20.6	19.4
Jul	23.4	20.2	23.7
Aug	23.4	19.2	25.6
Sep	18.7	15.7	21.0
Oct	13.3	8.6	14.7
Whole	19.5	16.8	20.9

Table 3. Growth stages of Japanese and US soybean cultivars measured at Takatsuki and Fayetteville.

Cultivar	Takatsuki (2009)				Fayetteville (2009)				Takatsuki (2010)				
	R1	R5	R7	R8	R1	R5	R7	R8	R1	R5	R7	R8	
Jpn cvs.	Enrei	19-Jul	11-Aug	23-Sep	8-Oct					9-Aug	25-Aug	13-Oct	19-Oct
	Suzukari	18-Jul	11-Aug	22-Sep	8-Oct					8-Aug	21-Aug	15-Oct	23-Oct
	Suzuyutaka	22-Jul	16-Aug	25-Sep	9-Oct					9-Aug	28-Aug	15-Oct	21-Oct
	Tachinagaha	18-Jul	11-Aug	9-Oct	22-Oct	22-Jul	21-Aug	28-Sep	–	8-Aug	26-Aug	17-Oct	4-Nov
	Tamahomare	25-Jul	20-Aug	17-Oct	28-Oct	1-Aug	1-Sep	8-Oct	–	12-Aug	5-Sep	28-Oct	9-Nov
US cvs.	Athow	16-Jul	11-Aug	23-Sep	4-Oct					6-Aug	26-Aug	15-Oct	20-Oct
	Omaha	17-Jul	13-Aug	29-Sep	10-Oct					6-Aug	26-Aug	17-Oct	23-Oct
	LD003309	18-Jul	13-Aug	25-Sep	18-Oct					6-Aug	27-Aug	15-Oct	23-Oct
	Manokin	25-Jul	23-Aug	9-Oct	18-Oct	26-Jul	21-Aug	1-Oct	–	14-Aug	2-Sep	20-Oct	27-Oct
	5002T	27-Jul	23-Aug	9-Oct	19-Oct	26-Jul	22-Aug	27-Sep	–	14-Aug	2-Sep	20-Oct	28-Oct
	UA-4805	1-Aug	22-Aug	9-Oct	20-Oct	27-Jul	24-Aug	29-Sep	–	15-Aug	28-Aug	20-Oct	2-Nov
	Osage	3-Aug	29-Aug	17-Oct	24-Oct	27-Jul	28-Aug	28-Sep	–	17-Aug	3-Sep	24-Oct	6-Nov
	5601T	27-Jul	23-Aug	17-Oct	27-Oct	–	28-Aug	2-Oct	–	14-Aug	2-Sep	27-Oct	10-Nov
	Ozark	30-Jul	27-Aug	17-Oct	27-Oct	30-Jul	28-Aug	28-Sep	–	14-Aug	5-Sep	24-Oct	6-Nov
	Hutcheson	3-Aug	27-Aug	19-Oct	29-Oct	30-Jul	26-Aug	29-Sep	–	15-Aug	1-Sep	27-Oct	9-Nov

Source. Based on Fehr et al. (1971).

the monthly averages somewhat differed with higher temperature in June at Fayetteville in 2009 and July and August at Takatsuki in 2010. However, the temperature in Fayetteville decreased rapidly from September to October compared to Takatsuki.

Table 3 shows the growth stage measured in Takatsuki in 2009 and 2010, and Fayetteville in 2009 based on Fehr et al. (1971). The beginning of the flowering (R1) stage ranged from 16 July (Athow) to 3 August (Osage and Hutcheson) at Takatsuki, from 22 July (Tachinagaha) to 1 August (Tamahomare) in Fayetteville in 2009, and from 8 August (Suzukari and Tachinagaha) to 17 August (Osage) at Takatsuki in 2010. The physiological maturity (R7) stage ranged from 22 September (Suzukari) to 19 October (Hutcheson) in Takatsuki, from 27 September (5002T) to 8 October (Tamahomare) in Fayetteville, and from 13 October (Enrei) to 28 October (Tamahomare) at Takatsuki in 2010. The growth stage in 2010 is later than in 2009 in Takatsuki because of delayed sowing due to continuous heavy rain. However, the order was quite consistent among the three environments.

Table 4 shows the yield and its components for the medium maturing cultivars observed in 2009 in Takatsuki and Fayetteville and in 2010 in Takatsuki. The seed yield ranged from 3.10t ha⁻¹ (Tachinagaha) to 5.50t ha⁻¹ (5601T) in Takatsuki in 2009 and from 3.44t ha⁻¹ (Tachinagaha) to 5.73t ha⁻¹ (5002T) in Fayetteville in 2009. It ranged from 3.77t ha⁻¹ (Tachinagaha) to 4.97t ha⁻¹ (5601T) in Takatsuki in 2010. While the effect of the cultivar group on the seed yield was significant throughout the three environments, the effect of the environment was not significant. The total dry matter at maturity ranged from 6.73t ha⁻¹ to 9.66t ha⁻¹ and 6.22t ha⁻¹ to 7.40t ha⁻¹ in Takatsuki in 2009 and 2010, and from 6.34t ha⁻¹ to 9.62t ha⁻¹ in Fayetteville in 2009. A significant difference was observed in the environment,

cultivar group, and interaction. HI ranged from .40 to .51 and from .52 to .58 in Takatsuki in 2009 and 2010, respectively, and from .42 to .52 in Fayetteville in 2009. A significant difference was observed in the environment and cultivars; however, no significant interaction was observed. The total intercepted solar radiation ranged from 1,402 to 1,556 MJ and from 1,225 to 1,331 MJ in Takatsuki in 2009 and 2010, respectively, and from 1,439 to 1,616 MJ in Fayetteville. The RUE ranged from .47 to .63 g MJ⁻¹ and .50 to .58 g MJ⁻¹ in Takatsuki in 2009 and 2010, respectively, and from .41 to .63 g MJ⁻¹ in Fayetteville.

Table 5 shows the result of the comparison between early maturing US and Japanese cultivars in Takatsuki in 2009 and 2010. The seed yield ranged from 3.64 to 5.91t ha⁻¹ in 2009 and from 3.69 to 4.88t ha⁻¹ in 2010. While the difference in year was not significant, the difference in cultivar was significant. The total dry matter ranged from 5.96 to 9.89t ha⁻¹ in 2009 and from 5.92 to 7.34t ha⁻¹ in 2010. The HI ranged from .50 to .58 in 2009 and from .54 to .61 in 2010. The total intercepted solar radiation ranged from 1,206 to 1,313 MJ in 2009 and from 1,168 to 1,203 MJ in 2010. The RUE ranged from .48 to .75 g MJ⁻¹ in 2009 and from .50 to .61 g MJ⁻¹ in 2010. The difference in cultivar group was significant and a significant interaction was observed.

Discussion

In Japan, record yields, as high as 5t ha⁻¹ or more, have been reported in converted paddy fields (Nakaseko et al., 1984; Shimada et al., 1990). The average seed yield in our study was 4.67t ha⁻¹ and 4.58t ha⁻¹ in Takatsuki in 2009 and 2010, respectively, and the conditions were thought to be close to optimal. In Fayetteville in 2009, the average seed yield was 4.46t ha⁻¹ and twice as large as the average seed

Table 4. Yield and yield components of Japanese and US soybean cultivars for medium maturing cultivars.

		Seed yield (t ha ⁻¹) ^a	TDM (t ha ⁻¹) ^b	HI ^b	Mean F (%) ^c	Total solar radiation intercepted (MJ) ^d	Incident solar radiation (MJ) ^d	RUE (g MJ ⁻¹) ^e	
2009									
Takatsuki	(Emergence: 21st June)								
	Jpn cvs.	Tachinagaha	3.10	6.73	.40	78.2	1446	1850	.47
		Tamahomare	3.44	6.97	.43	79.0	1560	1976	.45
	US cvs.	Manokin	5.23	8.87	.51	75.7	1404	1855	.63
		5002T	4.69	8.76	.46	75.9	1402	1847	.63
		UA-4805	5.15	8.70	.51	76.5	1416	1850	.61
		Osage	5.19	9.60	.47	78.1	1535	1965	.63
		5601T	5.50	9.66	.49	79.0	1552	1965	.62
		Ozark	5.19	9.75	.46	79.1	1554	1965	.63
		Hutcheson	5.03	9.15	.47	78.0	1556	1995	.59
	Average	Whole	4.72	8.69	.47	77.7	1492	1918	.58
		Jpn cvs.	3.27	6.85	.41	78.6	1503		.46
		US cvs.	5.14	9.21	.48	77.5	1488		.62
	Fayetteville	(Emergence: 12th June)							
Jpn cvs.		Tachinagaha	3.44	6.34	.47	76.5	1528	1997	.41
		Tamahomare	3.48	7.23	.42	79.9	1636	2049	.44
US cvs.		Manokin	4.70	8.69	.47	78.3	1557	1989	.56
		5002T	5.73	9.62	.52	78.6	1616	2057	.60
		UA-4805	4.44	8.38	.46	72.1	1439	1994	.58
		Osage	4.72	8.58	.48	74.5	1540	2067	.56
		5601T	5.42	9.91	.46	77.4	1562	2018	.63
		Ozark	4.23	7.81	.47	75.8	1511	1994	.52
		Hutcheson	4.85	8.99	.47	75.6	1506	1993	.60
Average		Whole	4.56	8.40	.47	76.5	1544	2018	.54
		Jpn cvs.	3.46	6.79	.45	78.2	1582		.43
		US cvs.	4.87	8.85	.48	76.0	1533		.58
2010									
Takatsuki	(Emergence: 12th July)								
	Jpn cvs.	Tachinagaha	3.77	6.22	.52	72.9	1233	1690	.50
		Tamahomare	4.37	7.01	.54	75.4	1331	1765	.53
	US cvs.	Manokin	4.39	6.62	.57	72.4	1240	1712	.53
		5002T	4.76	7.05	.58	72.5	1241	1712	.57
		UA-4805	4.84	7.12	.58	71.7	1225	1708	.58
		Osage	4.90	7.36	.57	73.0	1264	1732	.58
		5601T	4.97	7.40	.58	73.8	1296	1756	.57
		Ozark	4.95	7.30	.58	73.5	1275	1735	.57
		Hutcheson	4.70	7.06	.57	74.5	1313	1763	.54
	Average	Whole	4.63	7.02	.57	73.3	1269	1730	.55
		Jpn cvs.	4.07	6.61	.53	74.2	1282		.52
		US cvs.	4.79	7.13	.58	73.0	1265		.56
	Analysis of variance ^f								
	Environment	.53NS	27.34***	60.31***	17.09***	52.42***		6.27**	
	Cultivar group	68.79***	48.36***	32.37***	3.59NS	.93NS		113.82***	
	Environment × Cultivar group	4.36*	5.80**	1.57NS	.20NS	.15NS		10.23***	

^aSeed weight with a 14% moisture content.

^bIncluding leaves and petiole attached at R8.

^cMean F: Fraction of light intercepted in the average of the whole growth duration (from emergence to R7).

^dAssessed for the period from emergence to R7.

^eRadiation use efficiency is the value of the total above ground dry matter at R7 divided by cumulative solar radiation intercepted.

^f*, **, *** *F* values significance at .05, .01 and .001 probability levels, respectively. NS means non-significant at *P* = .05 level.

yield in Arkansas (Katsura et al., 2009). Compared to the field experiment conducted in Arkansas by related authors, however, the value was in the range of the previous observations under favorable conditions (Purcell et al., 2002). A significant difference in yield was not found among the three environments. On the other hand, differences in seed yield among cultivars were evident. The seed yield of Japanese cultivars, Tachinagaha and Tamahomare, were

lower than the US cultivars. The comparison of early maturing cultivars in Takatsuki in 2009 and 2010 also coincided with the comparison of mid maturing cultivars. Combining these results with meteorological records suggests that, although this study provides only limited information, the difference in climate factors between Takatsuki and Fayetteville is not large to cause considerable differences in soybean productivity under well-managed conditions

Table 5. Yield and yield components of Japanese and US soybean cultivars for early maturing cultivars.

		Seed yield (t ha ⁻¹) ^a	TDM (t ha ⁻¹) ^b	HI ^b	Mean F (%) ^c	Total solar radiation intercepted (MJ) ^d	Incident solar radiation (MJ) ^d	RUE (g MJ ⁻¹) ^e
2009								
Takatsuki		(Emergence: 21st June)						
Jpn cvs.	Suzukari	3.64	5.96	.52	74.0	1244	1681	.48
	Suzuyutaka	4.13	6.78	.52	74.2	1286	1732	.53
US cvs.	Enrei	3.93	6.65	.51	74.2	1254	1690	.53
	Athow	5.07	7.57	.58	71.1	1206	1695	.63
	Omaha	5.91	9.89	.51	74.0	1313	1774	.75
	LD003309	5.06	8.69	.50	69.4	1207	1741	.72
Average	Whole	4.62	7.59	.53	72.8	1252	1719	.61
	Jpn cvs.	3.89	6.46	.52	74.2	1261		.51
	US cvs.	5.35	8.72	.53	71.5	1242		.70
2010								
Takatsuki		(Emergence: 12th July)						
Jpn cvs.	Enrei	4.41	6.33	.60	72.2	1178	1631	.54
	Suzuyutaka	4.23	6.00	.61	71.3	1181	1656	.51
US cvs.	Suzukari	3.69	5.92	.54	71.8	1189	1656	.50
	Athow	4.61	6.92	.57	70.8	1168	1650	.59
	Omaha	4.88	7.34	.57	71.7	1203	1678	.61
	LD00-3309	4.60	6.80	.58	69.0	1141	1652	.60
Average	Whole	4.40	6.55	.58	71.2	1177	1654	.56
	Jpn cvs.	4.11	6.09	.58	71.8	1183		.52
	US cvs.	4.70	7.02	.58	70.5	1171		.60
Analysis of variance ^f								
Year		1.22NS	7.72*	10.42*	4.48NS	12.97**		5.17NS
Cultivar group		26.63***	18.16**	.03NS	6.21*	.58NS		39.71***
Year × Cultivar group		4.78NS	3.12NS	.20NS	.79NS	.03NS		5.68*

^aSeed weight with a 14% moisture content.

^bIncluding leaves and petiole attached at R8.

^cMean F: Fraction of light intercepted in the average of the whole growth duration (from emergence to R7).

^dAssessed for the period from emergence to R7.

^eRadiation use efficiency is the value of the total above ground dry matter at R7 divided by cumulative solar radiation intercepted.

^f*, **, *** F values significance at .05, .01 and .001 probability levels, respectively. NS means non-significant at $P = .05$ level.

(Table 2). Therefore, at least for the cultivars commercially cultivated in recent years, US cultivars are better yielding than Japanese cultivars. This is the first direct comparison between US and Japanese soybean cultivars. In this experiment, tested US cultivars are relatively new (released from 1987 to 2005) as compared with Japanese cultivars (released from 1971 to 1986). Rincker et al. (2015) examined genetic yield gain per year in US soybean cultivars during past 80 yr and reported acceleration of improvement in yield released after 1960s. Considering the recent yield difference, our result may contain the difference of release years. Therefore, it may be worth trying to compare US cultivars with Japanese cultivars developed very recently. In this study, the only cultivars dominant in commercial production in Japan were studied.

The TDM (including the attached leaves and petiole) at maturity was higher in US cultivars. The seed yield correlated with the TDM rather than the HI with correlation coefficients from .519 to .928 for the TDM vs. .175 to .800 for the HI, for each of the three environments. The relationship between the seed yield and TDM was quite significant

throughout the three environments with the R^2 of linear regression for every environment ranging from .81 to .93 (data not shown). This means that the contribution to yield variation of the other component, HI, was limited. As the result, the contribution to yield was thought to be large from the TDM compared to that of HI (Figure 1(a) and (b)).

The mean F differed significantly among environments in medium maturing cultivars, while not significant in cultivar group and no interaction was observed (Table 4). In this analysis, mean F was assessed from emergence to R7 and the difference in mean F among environments caused by planting density or planting date became relatively smaller. Though the planting density was higher in Fayetteville, the mean F was lower than Takatsuki in 2009. There is a possibility that rainy season in Takatsuki provided more favorable soil moisture condition as compared with Fayetteville in early growth stage. On the other hand, significant difference in cultivar group was observed in early maturing cultivars (Table 5). The stem growth habit of early maturing US cultivars was indeterminate and different from Japanese cultivars (Table 1). The difference in

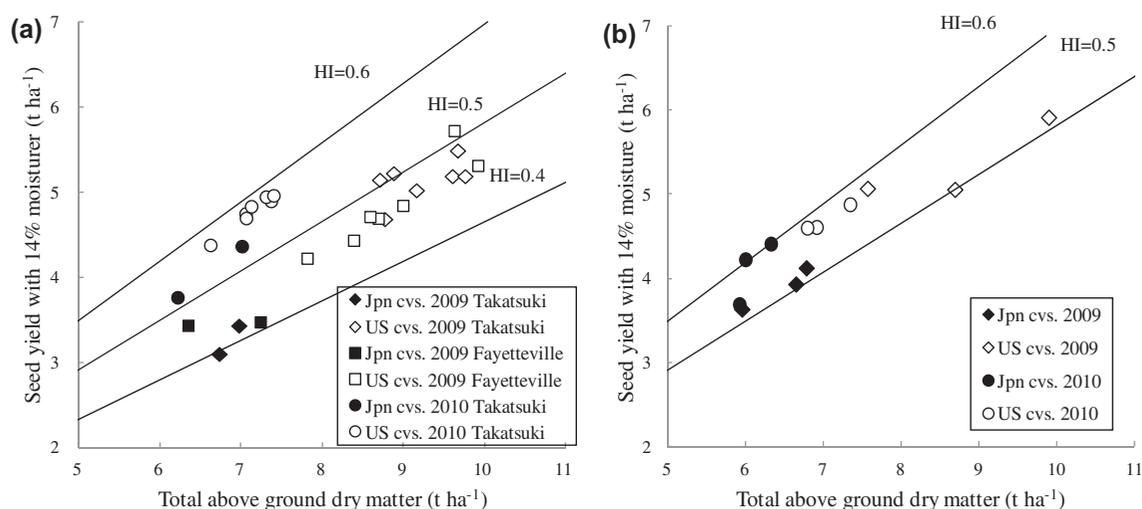


Figure 1. (a) Relationship between total above ground dry matter and seed yield of medium maturing two Japanese and seven US cultivars at three environments and (b) Relationship between total above ground dry matter and seed yield of early maturing three Japanese and three US cultivars at Takatsuki in 2009 and 2010.

stem growth habit may cause the difference in canopy coverage. However, the difference in mean F between cultivar groups was not large.

The total solar radiation intercepted differed significantly among environments, while the total solar radiation intercepted did not differ significantly in cultivar groups, and no significant interaction was observed. The response to temperature and day length of the early growth stage is related to the differentiated duration between sowing and flowering and hence, the total intercepted solar radiation. This difference of the total solar radiation among environments is thought to be caused by the difference in location, the sowing date.

The results of the RUE were consistent between Takatsuki and Fayetteville (Figure 2). Purcell et al. (2002) reported that planting density does not affect the RUE in Fayetteville. US cultivars showed significantly higher values compared to Japanese cultivars (Tables 3 and 4). The observed range of the RUE in this study was .41–.72 g MJ⁻¹ and quite low compared to prior reports (Sinclair & Horie, 1989; Shiraiwa et al., 1994). One possible reason is the difference in solar radiation environment. Sinclair and Muchow (1999) reported that RUE increased when incident radiation was low and high-diffuse component condition as compared with high radiation and low-diffuse component condition. Nakaseko and Gotoh (1983) reported that RUE decreased curvilinearly with increase in light intensity. Takatsuki and Fayetteville are higher solar radiation environment, 19–24 MJ per day, compared to that in the measurement of Shiraiwa et al. (1994), 13 to 15 MJ per day. Actually, Ries et al. (2012) measured RUE at Fayetteville in the same way using digital image analysis and reported .85–1.60 g MJ⁻¹ based on PAR during vegetative growth.

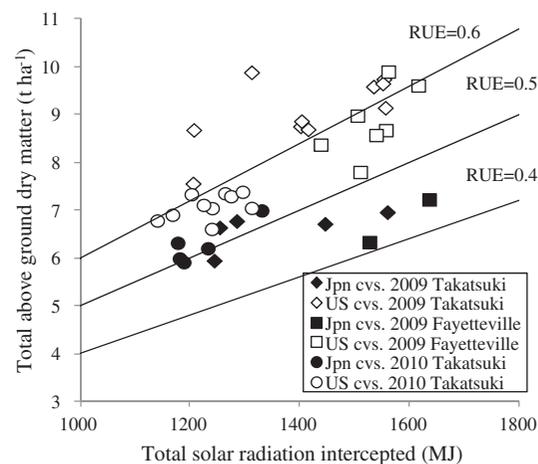


Figure 2. Relationship between total radiation intercepted and total above ground dry matter at three environments.

The calculation of the RUE is divided into two types, based on the photosynthetic active radiation and solar radiation (Bonhomme, 2000; Hatfield, 2014). Ries et al. (2012) estimated PAR as 50% of total incident solar radiation and the range of RUE based on total solar radiation was similar to our result. In addition, the duration of the measurement also can be a reason. Unlike previous studies, we assessed the intercepted solar radiation for the entire duration of growth, from emergence to physiological maturity. This measurement included the period from the late seed-filling period to maturity when a decrease in the photosynthetic rate occurs. In addition, the abscission of the leaves and petioles was not included to the total dry matter at maturity. In the late seed-filling period, the abscission of leaves and petioles occurred and the above ground dry weight of the canopy began to decrease. These factors may

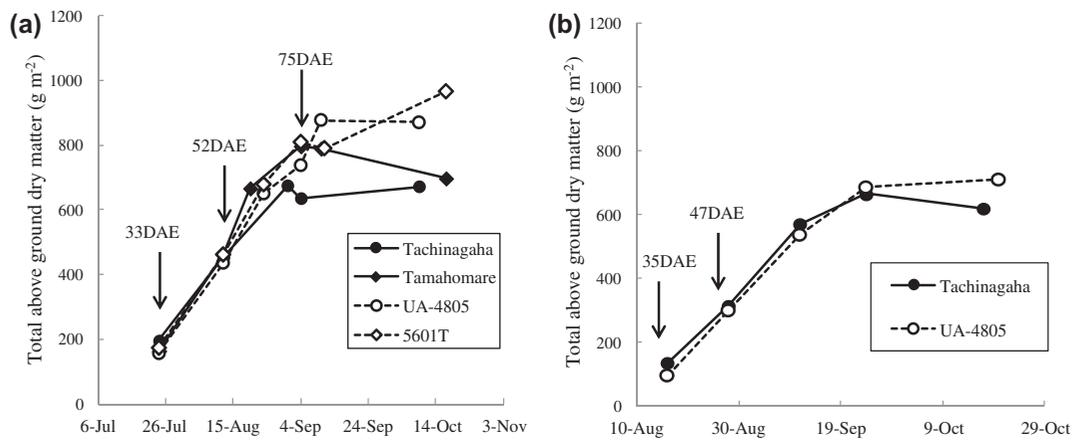


Figure 3. (a) Seasonal change in total above ground dry matter measured at Takatsuki in 2009 and (b) Seasonal change in total above ground dry matter measured at Takatsuki in 2010.

explain the incomparable values of RUE observed in this experiment.

To look for key factors in the differences in TDM at maturity and the dry matter productivity, the change in the total dry weight of representative cultivars (Tachinagaha, Tamahomare, UA-4805 and 5601T) was measured in Takatsuki in 2009. The result was shown in Figure 3(a). The change in TDM of Tachinagaha and UA-4805 in Takatsuki in 2010 was shown in Figure 3(b). Before R5, the dry matter production did not differ between US cultivars (UA-4805, 5601T) and Japanese cultivars (Tachinagaha and Tamahomare). However, after R5, US cultivars tended to show higher dry matter production compared to Japanese cultivars. The amount of intercepted solar radiation during the seed-filling period is said to be important in yield formation (Board, 2004). The seed-filling period is important because there are reports that the canopy photosynthesis rate during the seed-filling period correlates with seed yield (Ashley & Boerma, 1989; Wells et al., 1982), and dry matter production during the seed-filling period correlates with seed yield (Shiraiwa & Hashikawa, 1995; Specht et al., 1999; Kumudini et al., 2001; Shiraiwa et al., 2004). There is a high probability that the higher total above ground dry matter of US cultivars at R8 is explained by higher dry matter production during seed filling.

Tanaka et al. (2008) compared leaf photosynthetic rate of the top leaflet of US soybean cultivar 'Stressland' and Japanese soybean cultivar 'Tachinagaha' during seed-filling period and reported that Stressland showed higher photosynthetic rate than that of Tachinagaha after R5. The high photosynthetic rate of Stressland was mainly explained by higher stomatal conductance. In addition, Tanaka et al. (2010) reported that the diversity in stomatal density measured at seed-filling stage and the estimated potential stomatal conductance in US cultivars are higher than Japanese cultivars. The difference in potential

stomatal conductance also suggested that the photosynthetic rate in US cultivars is higher than in Japanese cultivars. There is a possibility that the differences in the stem growth habit can be attributed to dry matter production in early maturing cultivars (Tanaka & Shiraiwa, 2009).

The analysis of dry matter production of the cross-location experiment between Takatsuki and Fayetteville was done at the R8 stage and the relationship between the total above ground dry matter and the seed yield in this experiment was 'apparent' HI. Apparent HI is calculated as the ratio of seed dry matter to above ground dry matter at harvest (Kumudini, 2002). In this analysis, the final above ground dry matter does not take into consideration dry matter lost as senescent leaves abscise prior to harvest. In general, it is difficult to detect the dry matter production during seed-filling period because of the abscission of the leaves and petioles observed during this period. However, a high correlation was found in a previous study between an apparent HI and the true HI, which include abscised leaves and petioles (Schapaugh & Wilcox, 1980). In addition, there were several reports that the improvement in the apparent total dry matter at R8 contributed more than the improvement in the apparent HI (Cregan & Yaklich, 1986; Specht et al., 1999; Kumudini et al., 2001; De Bruin & Pedersen, 2009) and our results coincide with those reports. To survey the key trait that can improve the yield of Japanese soybean cultivars, more attention must be paid to the seed-filling period and focused on the traits related to dry matter dynamics.

Conclusions

The seed yield of US cultivars was higher than Japanese cultivars. When the fields were managed to optimal conditions as much as possible, the environmental factor did not cause a difference in the seed yield. The difference in

yield was closely associated with the difference in the TDM rather than a difference in HI. The apparent dry matter production per unit of intercepted solar radiation was higher in US cultivars. These results suggest that a difference in yield exists between US and Japanese soybean cultivars that can be attributed to crop biomass productivity. Traits related to canopy photosynthesis or information about the contribution of abscised leaves to dry matter production is needed to further understand the difference in true dry matter productivity.

Disclosure statement

No potential conflict of interest was reported by the authors.

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