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Effects of early planting and cultivars on the yield and agronomic traits of soybeans grown in southwestern Japan

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ABSTRACT

Early planting contributed to increased soybean yields in the U.S. Because a double-cropping system dominates in southwestern Japan, early planting is not performed; it is thus unclear how much the yield potential could be increased by early planting. To address this question, we planted seven U.S. and five Japanese cultivars on around 20 May (early planting), measured the agronomic traits, including yield, yield components, and oil and protein contents, and compared these traits with those of the same cultivars planted on around 20 July (normal planting). In the early planting, the yields of the U.S. cultivars were 322–453 g m⁻², whereas the highest yield among the Japanese cultivars was only 315 g m⁻², which is significantly lower than those of the top five U.S. cultivars, indicating the adaptability of U.S. cultivars to early planting. The increases in yield obtained with early planting were 99–199 g m⁻² and –26–144 g m⁻² for the U.S. and Japanese cultivars, respectively. The yield obtained by early planting was positively correlated with the pods m⁻², seeds pod⁻¹, and oil contents, but negatively correlated with the sterile pod rate, 100 seed weight and protein content. In the early planting, the U.S. cultivars had greater pods m⁻², seeds pod⁻¹ and oil content and less sterile pod rate, 100-seed weight, and protein content than the Japanese cultivars. These results suggest that early planting can increase the yield in southwestern Japan, if cultivars with agronomic traits observed in the U.S. cultivars of this study are grown.

Abbreviations: ESPS: early soybean production system; MG: maturity group

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Introduction

Soybean (*Glycine max* L.) is one of the most important legume crops because of its abundant protein, oil and nutrients. In the U.S., soybean productivity is soaring. It was reported that the U.S. soybean yield increased from 2.0 to 3.0 t ha⁻¹ in the past 30 yr (USDA-NASS, 2013). In Japan, during the same period, the soybean yield stayed constant, and the 30-yr (1982–2012) average of the soybean yield is 1.65 t ha⁻¹ (MAFF, 2013b). The increased soybean yield in the U.S. might have been achieved by the use of early soybean production systems (ESPSs). The main reason for the introduction of an ESPS is to avoid late-season drought by planting early maturing cultivars. In the U.S. Midsouth, the planting date was shifted from the latter half of May through June to April to the first half of May. The ESPSs may contribute not only to avoid late-season drought, but also to increased seed yields due to the longer duration of vegetative and reproductive stages (Chen & Wiatrak, 2010).

In southwestern Japan, the double-cropping system is widely dominant. In the summer season, soybean or

rice is cultivated, and in the winter season, wheat or barley is grown. In general, the harvest of wheat or barley is completed by early June. The rainy season usually hits southwestern Japan from mid-June to mid- to late July. Rice seedlings are transplanted from mid- to late June, taking precedence over the planting of soybean seeds. If soybean seeds are sown during the rainy season, the seeds may be subjected to flooding stress. This will reduce the germination rate and the early plant growth, resulting in the reduction of seed yield.

For these reasons, the optimum planting date for soybeans in southwestern Japan has long been considered to be after the rainy season (i.e. early to late July). However, it is difficult to predict when rainy season will end and thus when the rainy season continues until late July, the seed yield is generally decreased because the vegetative growth period cannot be ensured by late planting (Fatichin et al., 2013; Uchikawa et al., 2009). Field experiments conducted by Fatichin et al. (2013) with 6–17 cultivars grown for 3 yr in southwestern Japan revealed that late planting (August 2–5) reduced the seed yield by on average >21%

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Table 1. Characteristics of the soil used in 2012 and 2013.

	2012	2013
Soil type	Light clay	Light clay
sand (%)	21.2	28.7
silt (%)	44.0	31.3
clay (%)	34.8	40.0
Soil pH (1:1)	6.6	6.4
Available P (mg kg ⁻¹)	83	138
Exchangeable K (mg kg ⁻¹)	203	345
Exchangeable Mg (mg kg ⁻¹)	526	417
Exchangeable Ca (mg kg ⁻¹)	4,361	4,215
CEC [†] (cmol kg ⁻¹)	30.6	32.2

[†]CEC, cation exchange capacity.

Table 2. Cultivars used with country, origin, maturity group (MG), growth habitat, and reference citation.

Cultivar name	Country	Origin	MG	Growth habitat	References
LS93-0375	U.S.	Illinois	4.2	Indeterminate	Schmidt and Klein (2002)
Stressland	U.S.	Ohio	4.3	Indeterminate	Cooper et al. (1999)
LD00-3309	U.S.	Illinois	4.5	Indeterminate	Diers et al. (2006)
Spry	U.S.	Illinois	4.8	Determinate	Bernard and Nickell (1992)
UA4805	U.S.	Arkansas	4.8	Determinate	Chen et al. (2006)
UA4910	U.S.	Arkansas	4.9	Indeterminate	Chen et al. (2011)
5002T	U.S.	Tennessee	5.1	Determinate	Pantalone et al. (2004)
Suzuyutaka	Japan	Tohoku	3	Determinate	Zhou et al. (2002)
Enrei	Japan	Nagano	4	Determinate	Ude et al. (2003)
Tachinagaha	Japan	Nagano	5	Determinate	Ude et al. (2003)
Sachiyutaka	Japan	Kyushu	5	Determinate	Matsuo et al. (2013)
Fukuyutaka	Japan	Kyushu	6	Determinate	Ude et al. (2003)

in two of three experiments, compared to the seed yields from normal planting (July 15–20).

Thus, the previous research in southwestern Japan has focused mainly on how to reduce the yield penalty in late planting cultures. Egli and Cornelius (2009) reported that in the southern part of the U.S. (the latitude of which is similar to that of southwestern Japan), the optimum planting date to maximize the seed yield was late May to early June. They also demonstrated that a yield decline began if the planting date was later than 30 May, 7 June, and 27 May in the Midwest, Upper South, and Deep South, respectively. The conventional planting date (early to late July) in southwestern Japan thus seems to be much later than the optimum planting date to maximize soybean yields (i.e. late May to early June).

Two types of soybean have been planted in southwestern Japan in the past: the summer type and the autumn type. Summer-type soybeans are photoperiod-insensitive and are planted in spring and harvested in summer [i.e. as an earlier maturity group (MG)]. The autumn-type soybeans are photoperiod-sensitive and are planted in summer and harvested in autumn (i.e. as a later MG). Because the double-cropping system has gradually dominated in this region, the summer-type soybean has not been cultivated in recent years. There are some old studies of the ecomorphological traits of summer- and autumn-type soybeans planted early (Nagata, 1949, 1950a, 1950b). However, those studies focused mainly on the differences

of ecomorphological traits between summer-type and autumn-type soybeans in response to the planting date and photoperiod. It has thus been unclear whether the early planting increased the seed yield.

Uchikawa et al. (2004) examined the effect of early planting on the autumn-type soybean yield in southwestern Japan. They planted soybean seeds (cv. Sachiyutaka; MG V) in mid-June (1 mo earlier than the conventional cultivation), and they reported that the seed yield tended to increase as the planting date was advanced from late July to mid-June. Matsuo et al. (2015) also studied the effect of mid-June planting on the soybean yield and reported that mid-June planting increased the seed yield by 9% in comparison to that in mid- to late July planting. Because they used only one cultivar and the planting date was only 1 mo earlier than that in the conventional culture, the merits of much earlier planting (e.g. May planting) and the effect of the planting date × cultivar interaction on soybean yield are unclear. Other than these reports, information about the effect of early planting on soybean production in southwestern Japan is still limited.

The objective of the present study was to clarify the effects of early (mid- to late May) planting on soybean phenology, yield, yield components, and seed components. Because the U.S. has succeeded in increasing the soybean yield using ESPs, we used not only Japanese cultivars but also U.S. cultivars and compared their responses to planting dates. The information obtained by this study will be

useful to improve the soybean yield potential in southwestern Japan.

Materials and methods

The field experiment was conducted at the National Agriculture and Food Research Organization (NARO), Kyushu Okinawa Agricultural Research Center (KARC) (33° 12' N lat., 130° 30' E long., 10 m a.s.l.), Chikugo, Fukuoka, Japan in 2012 and 2013. The soil was lowland paddy soil (Typic Endoaquept) in both years. Because the crop rotation trial was carried out at the KARC, the same field could not be used continuously. The detail of the soil properties are listed in Table 1. The previous crop for the experiment in 2012 was forage oat and that for the experiment in 2013 was wheat. Crop residues were plowed under the ground before the experiments.

Twelve cultivars were used in this experiment, consisting of seven U.S. and five Japanese cultivars (Table 2). The cultivation area of the five Japanese cultivars used in this study accounts for approx. 50% of the total soybean cultivation area in Japan (MAFF, 2013a). A split-plot design was used with the planting date as the main plot and the cultivars as a subplot. The experiment was replicated three times. Each subplot was 9.8 m². The row and hill spaces were 70 and 20 cm, respectively, and each plot consisted of five rows by 14 hills. Approximately 1 wk before planting, the fields received magnesium lime (150 g m⁻²), but other fertilizers such as phosphorus or potassium were not applied, in accord with the conventional farming practices in this area.

Soybean seeds were treated with insecticide with fungicides that contained 22.6% thiamethoxam, 1.7% mefenoxam, and 1.1% fludioxonil (Cruiser MAXX, Syngenta, Tokyo) at a rate of 8 ml per 1 kg seed before planting. Three seeds of each cultivar in early planting and normal planting were sown by hand on 22 May 2012 and 23 July 2012 and 2013, respectively. Just after this planting, a pre-emergence herbicide that contained 8% benthio-carb, .8% pendimethalin, and 1.2% linuron was applied at a rate of 5 g m⁻² to inhibit weed emergence. After seedling establishment, plants were thinned to one plant per hill (i.e. 7.1 plants per m⁻²). Approximately 1 mo after planting, intertillage and ridging were performed to control weeds and lodging. Thereafter, insecticide and pesticide were applied as necessary to maximize the yield.

The rainfall, air temperature, and solar radiation were measured at the meteorological station of the KARC with an Agricultural Meteorological Acquisition System (Yokogawa Denshikiki, Tokyo), located approx. 100 m away from the experimental field. For both early and normal planting, the number of days to R1 [i.e. one flower at any node: Fehr et al. (1971)] and the number of days to R8 [i.e. 95% of pods brown: Fehr et al. (1971)] were recorded for

each cultivar. At physiological maturity, plants from 4.2 m² from each plot were harvested manually, and we measured the main stem length, the number of main stem nodes, the yield, the yield components, and the sterile pod rate (defined as the number of sterile pods / the number of total pods × 100). The seed moisture was adjusted at 14%.

The crude protein and oil content of the seeds were determined by a near-infrared spectroscopic analysis (Infratec™ 1,241 Seed Analyser, Foss Tecator, Höganäs, Sweden). The conversion factor for the calculation of the protein content was 6.25.

We analyzed the data from 2012 to 2013 together using a linear mixed model of SPSS ADVANCED software ver. 20 (SPSS, Chicago, IL). The statistical model was a split-plot treatment structure. We analyzed the effects of planting date, cultivar, and their interaction on parameters measured by performing an analysis of variance (ANOVA). The planting date, cultivar, and their interaction were each considered fix effects. The year and replication (nested within the year) were considered random effects. This statistical model was similar to that used by Parvej et al. (2015), in which the year and replication were considered random effects. When the *F*-test result of the ANOVA exceeded the .05 probability level, significance ($p < .05$) was explored by Fisher's protected least significant difference (LSD). Simple linear regression analyses were computed to evaluate the relationships between seed yield and the agronomical traits measured.

Results

Weather

There were some differences in weather conditions between the 2012 and 2013 crop seasons (Table 3). In the 2012 crop season, the rainfall was concentrated during June to July, when southwestern Japan was in the rainy season. In the 2013 crop season, the amount of rainfall during the rainy season (June to July) was much less than the 30-yr average, whereas the amount of rainfall in August was much larger than the 30-yr average. Two typhoons which came close to (but did not hit) the experimental field in late August brought about a large amount of rainfall in the 2013 crop season. In the 2012 and 2013 crop seasons, the mean temperatures were basically similar to or higher than that of the 30-yr average. The mean temperature in the 2013 crop season was higher than that in the 2012 crop season throughout the season, especially in October. The trend in the solar radiation was similar to that in the mean temperature: the solar radiations were greater in the 2012 and 2013 crop seasons than that in the 30-yr average, and the solar radiation in the 2013 crop season was greater than that in the 2012 crop season.

Table 3. Precipitation, mean temperature, mean maximum temperature, and solar radiation at the NARO Kyushu Okinawa Agricultural Research Center, Chikugo Fukuoka, Japan, during the 2012 and 2013 crop seasons.

Month	Rainfall			Mean temperature			Solar radiation		
	2012	2013	30-yr	2012	2013	30-yr	2012	2013	30-yr
May	47	89	190	20.1	20.5	19.5	18.6	21.4	17.2
June	397	251	352	23.2	24.3	23.4	13.5	14.0	15.3
July	733	143	340	27.6	28.5	27.1	17.0	20.7	17.7
August	149	576	200	28.8	29.2	27.9	19.0	19.7	18.2
September	105	145	157	24.4	25.0	23.9	16.0	17.2	15.2
October	106	124	70	18.5	20.4	18.5	14.6	13.2	12.7
November	105	74	76	11.2	12.1	12.7	9.0	9.7	9.2

Table 4. Number of days from planting to R1, R1 to R8 and planting to R8 in early and normal planting averaged across the 2012 and 2013 growing seasons.

Cultivar	Planting to R1†		R1 to R8†		Planting to R8†		
	Planting date		Planting date		Planting date		
	Early	Normal	Early	Normal	Early	Normal	
	days after planting						
LS93-0375	31	25	93	72	124	97	
Stressland	34	26	91	70	125	96	
LD00-3309	35	27	93	73	128	100	
Spry	44	32	94	70	137	102	
UA4805	49	35	86	70	135	104	
UA4910	36	29	111	79	147	107	
5002T	48	33	101	74	148	107	
Suzuyutaka	43	29	86	61	129	90	
Enrei	37	29	84	56	121	85	
Tachinagaha	40	29	99	66	139	95	
Sachiyutaka	47	32	98	66	145	97	
Fukuyutaka	58	36	98	75	156	110	
Average	42	30	95	69	136	99	

†R1:one flower at any node, R8:95% of pods brown (Fehr et al., 1971).

Table 5. Planting date and cultivar influences on the treatment means and the significance of F values for fixed sources of variation from the statistical analyses of plant height, main stem node number (Node No.) plant⁻¹, sterile pod rate, yield components, seed yield, protein and oil content, and germination rate averaged across the 2012 and 2013 growing seasons.

Fixed source of variation	Plant height	Nod plant ⁻¹	Pods m ⁻²	Sterile pod rate	Seeds pod ⁻¹	100-seed weight	Yield	Protein	Oil
Sowing date (A)	<.001	<.001	<.001	<.001	<.001	.003	<.001	<.001	.174
Cultivar (B)	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
A × B	.034	<.001	<.001	<.001	<.001	.003	<.001	.032	.002

Phenology

In the present study, the duration from planting to R1 in the early planting ranged from 31 to 58 d (Table 4), and the durations in the normal planting ranged from 25 to 36 d. The duration from planting to R1 was extended by early planting by 6–22 d, compared to normal planting (on average 12 d). The durations from R1 to R8 in the early planting ranged from 84 to 111 d (Table 4), and those in the normal planting ranged from 56 to 79 d. Early planting expanded the duration from R1 to R8 by 27–48 d, compared to normal planting (on average 26 d). The duration from planting to R8 ranged from 121 to 156 d in early planting, and those in normal planting ranged from 85 to 110 d. Early planting extended the duration from planting to R8 by 27 to 48 d, compared to normal planting (on average 37 d).

For all cultivars, the reproductive stage (from R1 to R8) was more extended by the early planting than the vegetative stage (from planting to R1): early planting extended the reproductive stage by 25 d on average in comparison to the normal planting, whereas it extended the vegetative stage by 12 d on average.

Plant height and the number of main stem nodes plant⁻¹

There was a planting date × cultivar interaction on plant height (Table 5). For the Fukuyutaka (determinate) and UA4910 (indeterminate) cultivars, the early plantings reached a > 17 cm greater plant height compared to the normal plantings, but for the other cultivars, the planting date had little effect on the plant height (Table 6).

Table 6. Effect of planting date × cultivar interaction on the plant height, main stem node number (Node No.) plant⁻¹, sterile pod rate, yield components, seed yield, protein and oil content averaged across the 2012 and 2013 growing seasons.

Planting date	Cultivar	Plant height cm	Main stem nodes plant ⁻¹	Yield g m ⁻²	Pods m ⁻² No. m ⁻²	Seeds pod ⁻¹ No. pod ⁻¹	100 seed weight g	Protein content %	Oil content	
			No. plant ⁻¹							
Early	LS93-0375	53.0	16.9	322	1,494	1.49	15.8	41.5	22.2	
	Stressland	59.3	19.7	387	1,384	2.07	13.6	41.8	22.2	
	LD00-3309	55.0	21.0	365	1,457	1.91	13.2	41.7	21.0	
	Spry	50.3	11.6	402	1,132	1.75	20.2	41.7	22.5	
	UA4805	42.8	13.9	427	1,563	1.94	14.1	43.7	20.2	
	UA4910	65.0	21.9	452	1,366	2.11	15.8	41.3	22.0	
	5002T	42.5	12.4	453	1,273	1.93	18.4	40.5	23.3	
	Enrei	36.1	11.1	182	588	1.34	23.0	46.7	19.5	
	Tachinagaha	39.2	12.3	157	430	1.35	26.9	47.2	20.7	
	Suzuyutaka	35.1	12.0	315	1,089	1.84	15.9	43.3	20.5	
	Sachiyutaka	38.4	12.5	308	663	1.61	29.1	46.3	19.8	
	Fukuyutaka	62.8	16.9	262	690	1.43	26.3	44.5	21.2	
	Normal	LS93-0375	52.4	16.4	223	666	1.96	16.6	40.1	22.1
		Stressland	59.4	18.5	224	697	2.15	14.5	40.8	22.1
LD00-3309		47.9	17.2	198	647	2.09	14.3	39.8	21.8	
Spry		46.5	11.0	256	701	1.92	18.5	40.4	21.9	
UA4805		36.9	12.2	280	822	1.98	16.7	42.9	20.8	
UA4910		47.8	16.5	253	652	2.28	16.4	38.4	22.6	
5002T		38.9	12.2	294	870	1.85	17.9	40.9	21.9	
Enrei		34.1	10.4	161	406	1.62	23.8	45.6	18.4	
Tachinagaha		33.9	10.9	183	352	1.93	26.8	42.2	21.3	
Suzuyutaka		28.0	10.1	171	476	1.84	19.3	41.0	20.5	
Sachiyutaka		33.2	11.3	202	438	1.63	28.4	46.7	19.0	
Fukuyutaka		45.2	12.8	267	665	1.56	27.9	44.6	20.5	
LSD _{0.05}		8.0	1.4	63	238	.17	1.7	2.1	.9	

Regardless of the planting dates, the plant heights of the indeterminate cultivars tended to be greater than those of the determinate cultivars, except for Fukuyutaka. Averaged across cultivars, the early planting resulted in 15% taller plants than the normal planting (48.3 cm vs. 42.0 cm).

There was a planting date × cultivar interaction on the number of main stem nodes plant⁻¹ (Table 5). The early planting produced a greater number of main stem nodes plant⁻¹ compared to the normal planting for cultivars LD00-3309, UA4805, UA4910, Suzuyutaka and Fukuyutaka, although the planting dates had little influence on this number for the other cultivars (Table 6). Averaged across cultivars, the early planting resulted in a 14% greater number of main stem nodes plant⁻¹ (15.2 vs. 13.3). Regardless of the planting dates, the numbers of main stem nodes plant⁻¹ of the indeterminate cultivars were larger than those of the determinate cultivars (Table 6).

Yield and yield components

A significant planting date × cultivar interaction on seed yield was observed (Table 5). Early planting produced greater yields than normal planting for all of the U.S. cultivars, and the amount of increase ranged from 99 g m⁻² for LS93-0375 to 199 g m⁻² for UA4910. Although the seed yields of UA4910 and 5002T were not significantly different from those of Spry and UA4805 in the early planting, UA4910 and 5002T had the highest seed yields at approx.

450 g m⁻². Among the five Japanese cultivars, an increase in the seed yield with the early planting was observed only for Suzuyutaka and Sachiyutaka. The increased amounts of seed yield for these two cultivars were 144 g m⁻² for Suzuyutaka and 106 g m⁻² for Sachiyutaka. However, the absolute values of seed yield in Suzuyutaka and Sachiyutaka in early planting (315 and 308 g m⁻², respectively) were less than those of the top five U.S. cultivars. The seed yield of the rest of the Japanese cultivars did not differ significantly between the planting dates. Regardless of the planting dates, the seed yields of Spry, UA4805, UA4910, and 5002T tended to be greater than those of the other cultivars (Table 6).

A significant planting date × cultivar interaction on pods m⁻² was found (Table 5). All U.S. cultivars planted early produced significantly greater pods m⁻² than those planted normally (Table 6). The increase amount ranged from 403 pods m⁻² for 5002T to 828 pods m⁻² for LS93-0375. Among the five Japanese cultivars used, early planting significantly increased the pods m⁻² only for Suzuyutaka (1,089 vs. 476 pods m⁻²). Suzuyutaka had an intermediate pods m⁻² value between those of the Japanese and U.S. cultivars in early planting. Regardless of the planting dates, the U.S. cultivars had greater pods m⁻² than the Japanese cultivars (Table 6).

There was a significant planting date × cultivar interaction on the sterile pod rate (Table 5). The effect of the planting date on the sterile pod rate differed greatly between the Japanese and U.S. cultivars (Table 6). Early

planting significantly increased the sterile pod rates for the Japanese cultivars other than Suzuyutaka, whereas no significant difference in the sterile pod rates between planting dates were observed any of the U.S. cultivars other than UA4910. Averaged across U.S. cultivars, the sterile pod rates were 8.1% and 6.1% for early and normal planting, respectively, whereas averaged across the Japanese cultivars, the sterile pod rates were 22.4% and 9.6% for early and normal planting, respectively.

Seeds pod^{-1} was significantly influenced by the planting date \times cultivar interaction (Table 5). For four of the U.S. cultivars (LS93-0375, LD00-3309, Spry, and UA4805) and two of the Japanese cultivars (Enrei and Tachinagaha), the early planting produced lower seeds pod^{-1} compared to the normal planting (Table 6). Regardless of the planting dates, the seeds pod^{-1} value of UA4910 exceeded 2.00 and was significantly larger than those of the other cultivars, except for Stressland. The main effect of planting date on seeds pod^{-1} was significant ($p < .0001$, Table 5) and the seeds pod^{-1} in the early planting (1.73) was significantly smaller than that in the normal planting (1.90).

There was a significant planting date \times cultivar interaction on the 100-seed weight (Table 5). The cultivar Spry planted early had a greater 100-seed weight than that planted normally, whereas the 100-seed weights of 5002T and Suzuyutaka were lower in early planting than in normal planting. The planting date had little effect on the 100-seed weight for the other cultivars (Table 6). Regardless of planting dates, the Japanese cultivars, except for Suzuyutaka, had significantly greater 100-seed weights than the U.S. cultivars. Suzuyutaka had a 100-seed weight that was intermediate between those of the Japanese and U.S. cultivars in both the early and normal plantings. The main effects of the planting date ($p = .003$) and the cultivar ($p < .001$) on 100-seed weight were significant (Table 5). Averaged across the cultivars, the 100-seed weight of the early planting was smaller than that of the normal planting (19.4 vs 20.1 g), but the difference was only .7 g. Averaged across the planting dates, the 100-seed weight ranged from 13.7 g (LD00-3309) to 28.7 g (Sachiyutaka), and the difference was 15.0 g.

Protein and oil contents

The protein and oil contents were significantly influenced by planting date \times cultivar interactions (Table 5). A significant increase in the protein content by early planting was found for cultivars UA4910, Tachinagaha, and Suzuyutaka, whereas the planting date had little effect on the protein content for the other cultivars (Table 6). Regardless of the planting dates, the protein contents of Enrei and Sachiyutaka were higher than those of the other cultivars, and the protein contents of the U.S. cultivars tended to be lower than those of the Japanese cultivars.

A significant increase in the oil content by early planting was found for 5002T and Enrei, but the planting date had little effect on the oil content for the other cultivars (Table 6). Regardless of the planting dates, the U.S. cultivars tended to have higher oil contents than those of the Japanese cultivars.

Relationship between yield and agronomic traits

The results of simple linear regression analyses with respect to each planting date are listed in Table 7. In the early planting, the pods m^{-2} , seeds pod^{-1} and oil content were significantly and positively correlated with the seed yield, but the sterile pod rate, the 100-seed weight and the protein content were significantly and negatively correlated with the seed yield. The seed yield increased by 20.4 g m^{-2} for every 100 pods m^{-2} increase, 31.2 g m^{-2} for every .1 seeds pod^{-1} increase and 50.2 g m^{-2} for every 1% increase in the oil content. On the other hand, the seed yield decreased by 7 g m^{-2} for every 1% increase in the sterile pod rate, 11.4 g m^{-2} for every 1 g increase in the 100-seed weight and 35.5 g m^{-2} for every 1% increase in the protein content.

In the normal planting, the number of days from R1 to R8, that from planting to R8, and pods m^{-2} were significantly and positively correlated with the seed yield. The seed yield increased by 5.6 g m^{-2} for every 1 d increase from R1 to R8, 5.1 g m^{-2} for every 1 d increase from planting to R8 and 23.8 g m^{-2} for every 100 pods m^{-2} increase.

Discussion

The effects of the planting date on soybean phenology, growth, yield, and seed quality have been discussed for many years and were reviewed by Hu and Wiatrak (2012). A combined analysis of planting date examinations from April to July revealed that the optimum planting dates in the southern U.S. were at late May to early June (Egli & Cornelius, 2009). Therefore, conventional planting dates (early to late July) in southwestern Japan seem to be late to obtain a high yield. Matsuo et al. (2015) and Uchikawa et al. (2004) reported that early to mid-June planting increased soybean yields. However, the planting dates in their studies were only 1 mo earlier than that in conventional cultivations, and the numbers of cultivar were small in their studies. Consequently, we studied the effect of much earlier (mid- to late May) planting on the agronomic traits of 12 soybean cultivars, consisting of seven U.S. and five Japanese cultivars.

The results indicate that soybean phenology is influenced by the planting date (Table 4). As the MG was delayed, the duration of the vegetative stage, reproductive stage, and total growing period were extended by

Table 7. Regression equation and correlation coefficients between the seed yield and the number of days from planting to R1, the days from R1 to R8, the days to planting to R8, plant height, main stem node number (Node No.) plant⁻¹, sterile pod rate, yield components, protein content, and oil content averaged across the 2012 and 2013 growing seasons (n = 12).

Planting date	Valuable	$y = ax + b$		<i>r</i>	<i>P</i> value	
		<i>a</i>	<i>b</i>			
Early	Planting to R1	-.69	364.85	-.055	.866 ns	
	R1 to R8	7.04	-328.78	.543	.068 ns	
	Planting to R8	2.77	-40.67	.312	.324 ns	
	Plant height	3.66	159.34	.397	.201 ns	
	Nodes No. plant ⁻¹	9.69	188.92	.386	.215 ns	
	Pods m ⁻²	.20	113.18	.828	<.001***	
	Sterile pod rate	-7.0	435	-.663	.019*	
	Seeds pod ⁻¹	312.88	-250.54	.885	<.001***	
	100 seed weight	-11.39	556.41	-.656	.021*	
	Protein content	-35.47	1873.81	-.841	<.001***	
	Oil content	50.21	-731.41	.609	.036*	
	Normal	Planting to R1	5.80	51.05	.457	.136 ns
		R1 to R8	5.56	-159.57	.799	.002**
		Planting to R8	5.10	-278.60	.880	>.001***
Plant height		1.64	157.30	.347	.269 ns	
Nodes No. plant ⁻¹		2.53	192.32	.175	.586 ns	
Pods m ⁻²		.24	79.41	.882	>.001***	
Sterile pod rate		-6.2	273	-.333	.290 ns	
Seeds pod ⁻¹		35.14	159.20	.180	.586 ns	
100 seed weight		-2.21	270.44	-.264	.408 ns	
Protein content		-4.21	402.46	-.246	.441 ns	
Oil content	16.37	-118.92	.490	.106 ns		

Note. ns: not significant.

p* < .05; *p* < .1; ****p* < .001.

early planting, compared with those in normal planting. Early planting extended the duration of the reproductive stage more than that of vegetative stage (26 d vs. 12 d on average). This result agrees with the report by Chen and Wiatrak (2010), who examined the effect of planting date from late April to mid-July on phenology for MG IV to VIII soybean cultivars and reported that earlier planting generally extended the duration of the reproductive stage more than the vegetative stage, regardless of the MGs.

In the present study, there was a significant correlation between seed yield and the duration of reproductive stage or the total growing period only in normal planting (Table 7), indicating that later MG varieties produced greater seed yield in mid- to late July planting, regardless of their countries of origin. Fatichin et al. (2013) also found that days from planting to R7 [physiological maturity: Fehr et al. (1971)] was significantly and positively correlated with seed yield in this region under mid- to late July planting conditions, regardless of countries of origin they used. Therefore, this finding seems to be common in southwestern Japan. On the other hand, there were no significant correlations between seed yield and the duration of the vegetative stage, the reproductive stage or the total growing period in early planting (Table 7), probably because the early planting had different effects on the seed yield among the cultivars rather than the MGs. The cultivar difference in adaptability to early planting may not be related to their MGs. As for the U.S. cultivars, however, the seed yield tended to increase as the maturity group was delayed in the early planting (Tables 2

and 6). Because Japanese cultivars used in this study might not have been improved to adapt early planting, the yield potentials of these cultivars in the early planting were smaller than those of the U.S. cultivars.

The plant heights of UA4910 and Fukuyutaka were significantly increased by early planting, and those of the other cultivars also tended to be increased (Table 6). Averaged across cultivars, the early planting resulted in 15% taller plant heights. However, there was no significant relationship between the plant height and the seed yield for either planting date (Table 7). Steele and Grabau (1997) reported that the seed yield was significantly correlated with the plant height in late May to early June planting and mid-July planting for MG II cultivars (the growth habitat was not mentioned). Because the latitude of their experimental site (38°7' N lat.) was further north than our experimental site and the MG used in their study differed from that used in the present study, our results might not be consistent with their findings. Our results indicated that plant height might not be an important trait associated with seed yield in the environment studied here. Although severe lodging which led to yield reduction was not observed during 2 yr of the experiment (data not shown), plant height may affect the seed yield under the conditions where lodging occurs.

We observed that the effect of the planting date on the number of main stem nodes plant⁻¹ was also cultivar-specific rather than specific to the growth habitat. In addition, the seed yield was not significantly correlated with the

number of main stem nodes plant⁻¹. This result was consistent with that of Weaver et al. (1991), who conducted a field experiment with determinate and indeterminate cultivars in the southern part of the U.S. Several researchers have pointed out that the superiority of yield of a determinate or indeterminate growth habit depended on the location and the genetic background of the cultivars used (Boerma & Ashley, 1982; Cober & Tanner, 1995; McBroom et al., 1981; Ouattara & Weaver, 1995; Wilcox & Frankenberger, 1987). In the present environment, the number of main stem nodes plant⁻¹ or growth habit might not be an important factor to obtain high yields in early planting.

Fatichin et al. (2013) conducted a field experiment with cultivars from several countries of origin, focusing on the cultivar difference in the adaptability to late planting (early August) in southwestern Japan. They reported that some foreign cultivars showed adaptability to late planting. However, there are few reports on the cultivar difference in adaptability to early planting in this region. In the present study, the seed yields of all of the U.S. cultivars were significantly increased by early planting (Table 6). In southwestern Japan, a conventional cultivation method is planting Fukuyutaka in mid- to late July (267 g m⁻², Table 6). Compared to this conventional cultivation method, planting UA4910 or 5002T early produced an approx. 70% greater seed yield. Among the Japanese cultivars, a yield increase by early planting was observed only for Suzuyutaka and Sachiutaka (Table 6), but the absolute values of the seed yields of these two cultivars in early planting was significantly lower than those of the top five U.S. cultivars.

Among the yield components, the pods m⁻² of all of the U.S. cultivars were significantly increased by early planting (increase amount = 659 pods m⁻² on average), whereas a significant increase in pods m⁻² was observed only for Suzuyutaka (increase amount = 612 pods m⁻²) among the Japanese cultivars. Although the pods m⁻² values of Sachiutaka in the early planting were not significantly different from those in the normal planting (663 vs. 438 pods m⁻²), these values showed greater increases among the Japanese cultivars. The effect of the planting date on the seeds pod⁻¹ and 100-seed weight was cultivar-specific, but averaged across cultivars, early planting significantly decreased the seeds pod⁻¹ and 100-seed weight. It could thus be concluded that early planting resulted in the increase in seed yield, mainly due to an increase in pods m⁻². The results reported by Robinson et al. (2009) showing that the yield increase with early planting was driven mainly by the increase in pods m⁻² may support our conclusion.

Here, the photoperiod during the reproductive stage was longer in the early planting compared to that in the normal planting. It was reported that photoperiod extension after the R3 stage [i.e. pod .5 mm long at the four

uppermost nodes with a completely unrolled leaf, Fehr et al. (1971)] increased the soybean yield, mainly due to an increase in the pod or seed number per unit area (Kantolic & Slafer, 2007; Kantolic et al., 2013). In the present study, however, the effect of photoperiod expansion with early planting during the reproductive stage on pods m⁻² differed among the cultivars. A longer photoperiod during the reproductive stage might be suitable for the pod formation and/or development of all of the U.S. cultivars and Suzuyutaka, but not for the other four Japanese cultivars. Early planting also increased sterile pod rates of these four Japanese cultivars (Table 6) and sterile pod rate was negatively correlated with seed yield (Table 7). To increase seed yield by early planting, the ability to produce fertile pods may be one of the key factors. In the present studies, however, the reason why cultivar differences of pod formation and/or development in response to photoperiod during reproductive stage occurred was unclear. Further studies are necessary to clarify the reason why the pod formation, pod development, and/or seed growth in response to the photoperiod differs among cultivars.

Pedersen and Lauer (2004) and Robinson et al. (2009) demonstrated that there was no planting date × cultivar interaction on seeds pod⁻¹. They also showed a significant main effect of cultivar on seeds pod⁻¹. Their results indicated that seeds pod⁻¹ was a stable trait regarding the planting date and that it was cultivar-specific. Our present findings do not coincide with their results. The number of cultivars used in the present study ($n = 12$) differed from those in the Pedersen and Lauer (2004) and Robinson et al. (2009) studies ($n = 3$). A significant interaction might thus be easily detected in this study. Our results indicated that the early planting reduced the seeds pod⁻¹ for some cultivars, but the response of seeds pod⁻¹ to the planting date may be site- or cultivar-specific. In the early planting, the seed yield was positively correlated with seeds pod⁻¹ (Table 7), indicating that cultivars with larger seeds pod⁻¹ might be advantageous for early planting to obtain high yields.

Robinson et al. (2009) found that the 100-seed weight increased as the planting date was delayed, regardless of the cultivar. However, Bruns (2011) reported that the 100-seed weight increased as the planting date advanced. He also found that the effect of the planting date on the 100-seed weight differed among experimental sites. Thus, it is difficult to make a unified conclusion about the effect of the planting date on the 100-seed weight. In the present study, we used 12 cultivars whose 100-seed weight ranged from 13.7 to 28.7 g (averaged across planting dates). The 100-seed weights in previous studies were less than 20 g. The wide range of 100-seed weights in this study might have led to the different result from previous studies. Our findings indicate that the effect of the planting date on the

100-seed weight was greatly influenced by the cultivar in this environment.

The seed yield was negatively correlated with the 100-seed weight in the early planting (Table 7), indicating that the cultivars with lower 100-seed weights, such as the U.S. cultivars used in this study, might be suitable for early planting. However, the trend was not true for Sachiutaka whose 100-seed weight was the highest among cultivars used: seed yield of Sachiutaka in early planting was higher than that in normal planting. Therefore, further studies will be needed to clarify the relationship between seed yield and seed weight in response to planting date using more cultivars with wide range of 100-seed weight.

Reports of the effects of the cultivar and/or planting date on the protein and oil contents have differed among researchers. Kane et al. (1997) and Robinson et al. (2009) found that the protein content increased and the oil content decreased as the planting date was delayed. Pedersen and Lauer (2003) reported that early planting increased the oil content but the planting date did not influence the protein content. They also noted that the effect of the planting date on the protein and oil contents differed among cultivars and experimental sites.

Because protein and oil contents are largely influenced by temperature after the R5 stage [i.e. beans beginning to develop at one of the four uppermost nodes with a completely unrolled leaf; Fehr et al. (1971)] (Gibson & Mullen, 1996; Robinson et al., 2009), it might be difficult to draw a conclusion regarding the effects of the planting date and/or cultivar on protein and oil contents. Although we observed no significant correlation between the seed yield and the protein and oil contents in the normal planting, the protein contents and the oil contents were negatively and positively correlated, respectively, with the seed yield in the early planting (Table 7).

Wilcox and Shibles (2001) reported that the seed yield was positively and negatively correlated with the oil and protein contents, respectively, but they did not describe the planting date and it is thus unclear whether there was a correlation between the yield and protein or oil contents under various planting dates. Our present findings suggest that a significant correlation between the seed yield and protein or oil contents might exist in early planting under the present environment. Our results also indicate that early planting will increase the seed yield if cultivars with a lower protein content and higher oil content, such as the U.S. cultivars used in this study, are planted in the environment studied herein.

Conclusion

Our results clearly demonstrated that early planting significantly increased the seed yield of U.S. cultivars and two of

five Japanese cultivars (Suzuyutka and Sachiutaka), but the yield potential of U.S. cultivars in early planting was greater than that of Japanese cultivars. Among the U.S. cultivars, the seed yields of UA4910 and 5002T planted early achieved yields that were 70% greater than that of Fukuyutaka planted in mid- to late July, which is the conventional cultivation practice in southwestern Japan. A linear regression analysis revealed that the seed yield was positively correlated with pods m^{-2} , seeds pod^{-1} , and oil contents, but negatively correlated with sterile pod rate, 100-seed weight, and protein content in early planting. Compared with the Japanese cultivars, the U.S. cultivars planted early had greater pods m^{-2} , seeds pod^{-1} and oil content, and lower sterile pod rates, 100-seed weights, and protein content. Therefore, the characteristics of the U.S. soybean cultivars may be suitable to achieve high yields with early planting.

Among the yield components measured, there was a clear difference in pods m^{-2} between U.S. cultivars and Japanese cultivars in response to planting date. Increase in fertile pods m^{-2} is essential to achieve high seed yield in early planting. Cultivar differences of pod formation and/or development in response to photoperiod during reproductive stage need to be investigated in future studies. Also, further studies are needed to examine different cultivation practices, such as much earlier (April) planting and narrow rows, to further increase the soybean yield potential in southwestern Japan.

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Disclosure statement

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