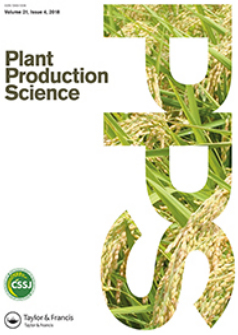

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REGULAR PAPER

Effects of late sowing on soybean yields and yield components in southwestern Japan

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ABSTRACT
Soybean production in southwestern Japan tends to be unstable owing to wet soils during the rainy season. Although late sowing after the rainy season can avoid excess water, information on its yield potential is limited. The objective of this study was to reveal the effect of late sowing on yields and yield components of new soybean cultivars developed for warm regions. The experiment was conducted in 2016 and 2017 in Fukuyama, Hiroshima, Japan. Upland fields converted from paddy fields with a subirrigation system were planted in June (normal) or July (late sparse or late dense). Lodging was prevented with a net. The effects of late sowing and dense treatment were analyzed in relation to solar radiation use. In 2016, differences in yield among cultivars and among environments were not significant. In 2017, yield was significantly reduced following late sparse sowing. The total aboveground dry matter at maturity was correlated with total solar radiation intercepted (r = 0.76) but not with radiation use efficiency (r = 0.47). Late sowing increased harvest index (HI) significantly from 0.464 to 0.571 in 2016 and from 0.524 to 0.585 in 2017, but density had no significant effect. The changes in HI were correlated with stem dry weight (r = −0.80 in 2016 and r = −0.79 in 2017) rather than seed yield (r = 0.08, n.s. in 2016 and r = 0.19, n.s. in 2017). Thus, under irrigation, late dense sowing might stabilize yield in southwestern Japan because of higher HI.

Abbreviations: DM: dry matter; FOEAS: farm-oriented enhancing aquatic system; HI: harvest index; RUE: radiation use efficiency

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Dry matter production; harvest index; late sowing; radiation use efficiency; seed set; soybean; yield

1. Introduction

Soybeans are an important crop for food, oil, and protein. In Japan, soybean is grown mainly as food, for which high yields and stable production are essential. However, soybean production per unit land area in Japan has stagnated compared with that in other major soybean-producing countries, such as the USA and Brazil (Katsura et al., 2009; Shimada et al., 2012). One reason is the excess soil moisture in southwestern Japan due to rainy season from June to July. In warm regions, most soybeans are grown in upland fields converted from paddy fields (Ministry of Agriculture, Forestry and Fisheries [MAFF], 2017): they are conventionally sown after wheat harvest, and plants establish during the rainy season. But the poor emergence of seedlings and their poor growth due to excess water contribute to the fluctuation in soybean production in converted paddy fields (Bajgain et al., 2015; Sugimoto & Satou, 1990; Takeda & Sasaki, 2013).

Late sowing after the rainy season offers a solution to these problems. However, it can create problems, such as shortening the growth duration and reducing yields (Ball et al., 2000; Takeda & Sasaki, 2013; Uchikawa et al., 2009). To prevent yield reduction, the use of late-maturing cultivars has proved effective (Fatichin et al., 2013; Kane et al., 1997). The leading cultivar in the Chugoku region is Sachiyutaka, developed in 2001 (Takahashi et al., 2004), but new cultivars adapted to southwestern Japan have been released. Akimaro, which matures late in southwestern Japan and is suitable for late sowing, was developed in 2011 (Takada et al., 2012). The shattering-resistant Sachiyutaka A1 gou, developed in 2012 by backcross-breeding, matures 1 day later and yields 1% higher than Sachiyutaka on average in the conventional growing season and matures 2 days later and yields 2% higher in late sowing in Tsukuba, Ibaraki Prefecture (Hajika et al., 2016). In the Chugoku region, Yamada et al. (2017) reported that Sachiyutaka A1 gou yields 19.2–70.8% higher than Sachiyutaka by machine harvesting. The combination of such new soybean cultivars with late sowing might contribute to more stable production in southwestern Japan.

Another problem of late sowing in warm regions is drought after sowing. After the rainy season, rainfall decreases until the middle of August. Following mid- to

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late-July sowing, this brings a risk of a decrease or delay in emergence due to drought (Takeda & Sasaki, 2013). However, FOEAS (Farm-Oriented Enhancing Aquatic System) subirrigation (Shimada et al., 2012; Wakasugi & Fujimori, 2009), which can promote uniform emergence and increase the rate of emergence (Takeda & Sasaki, 2013), is gradually spreading among farmers.

Changing the growing season can have another positive effect on yield. In the context of global warming, late sowing can reduce heat stress during growth. In the Tohoku region, late sowing reduced the reduction in yield seen in 2010, an extraordinarily hot year (Matsunami et al., 2013). Oh-E et al. (2007) analyzed the effect of high temperatures in Okayama Prefecture and suggested changing the growing season as an alternative management method under anticipated future higher temperatures. However, information about late sowing in southwestern Japan is still limited. To select the most effective combination of growing season and cultivar, it is necessary to evaluate the growing season of new cultivars so as to achieve stable production of soybeans.

To evaluate the effect of late sowing, measuring the solar radiation intercepted by the plant canopy during growth gives important information. Dry matter (DM) production is calculated as the cumulative solar radiation intercepted × radiation use efficiency (RUE). Thus, these factors must be quantified for better use of late sowing in southwestern Japan.

The objective of this study was to reveal the physiological effects of late sowing on soybean yield and yield components of new soybean cultivars in southwestern Japan under optimum conditions.

2. Materials and methods

2.1. *Location, environment, and materials*

Field experiments were conducted in 2016 and 2017 at the NARO Western Region Agricultural Research Center, Fukuyama, Hiroshima, Japan (34°30′N, 133°23′E, 1 m above sea level). Three cultivars (Sachiyutaka, Sachiyutaka A1 gou, and Akimaro) were grown in an upland field converted from a paddy field (a fine-textured [light clay] Gray Lowland soil), where a FOEAS had been installed. Seeds were sown on 27 June and 21 July 2016, and on 23 June and 25 July 2017. Soybeans were grown in the same field in both years. Previous crop was wheat in both years, and rice was cultivated in 2015. In June sowing, seeds were sown 0.15 m apart in rows 0.60 m apart (normal, 11.1 plants m^{-2}), as practiced in Hiroshima (Hiroshima Prefecture, 2017). In July (late) sowing, seeds were sown 0.15 m apart in rows either 0.60 m apart (late sparse) or 0.30 m apart (late dense, 22.2 plants m^{-2}). The treatments were arranged in a randomized block design with three replicates. The area of a single plot was 3.6 m × 3.45 m. The soil pH was adjusted with 100 g m^{-2} of magnesium lime in 2016 and 100 g m^{-2} of slug in 2017 approximately 1 week before sowing. Inorganic fertilizers were applied as a basal dressing at 3 g m^{-2} of N, 10 g m^{-2} of P_2O_5, and 10 g m^{-2} of K_2O 1 or 2 days before sowing. After seedling emergence, plants were thinned to one plant per hole, and gaps were filled by transplanting. The water table was maintained at −0.3 m during the growing season. Lodging was prevented by the installation of a net (0.3 m by 0.3 m mesh) at 0.3 m above the ground approximately 1 week before flowering. Intertillage and ridging were omitted in all environments in order to compare dense and normal sowing equally. Hand weeding was conducted until canopy closure instead of intertillage. Insecticides and fungicides were applied periodically to avoid biotic stresses.

2.2. *Measurements*

Daily solar radiation and temperature data were recorded by the NARO Western Region Agricultural Research Center. Dates of growth stages (R1, R5, R7, R8; Fehr & Caviness, 1977) were recorded. Canopy coverage was measured by digital image analysis twice a week after emergence until canopy closure according to Purcell (2000). RUE was estimated as daily intercepted solar radiation by interpolating the daily canopy coverage according to Shiraiwa et al. (2011). The estimation of RUE was based on total solar radiation. Yield was determined from 12 plants (1.06 m^{-2}) harvested from 1 replicate (24 plants in the late dense treatment). After 72 h oven-drying at 80°C, stems and pod shells were weighed. Attached leaves and petioles at R8 were collected, dried, and included in the total aboveground DM. Harvest index (HI) was calculated from seed dry weight (DW) and total aboveground DM including abscised leaves and petioles at R8. In addition to HI, adjusted HI was calculated from seed DW, stem DW, and DW of pod shells in order to avoid the effects of leaves and petioles. Yield components (total number of nodes per unit land area, total number of pods per unit land area, number of embryos [>1 mm diam.] per pod, seed set ratio [number of fertile seeds per embryo], and 100-seed weight) were estimated from six representative plants in each replicate.

Tukey's multiple comparison test was used to compare the effects of normal, late sparse, and late dense sowing between sowing environments and cultivars. The effects of cultivar, sowing environment, and year were tested by ANOVA. All analyses were conducted in BellCurve for Excel software v. 2.15 (Social Survey Research Information Co., Ltd., Tokyo).

3. Results

3.1. *Weather conditions and plant development*

Although the trends in mean air temperature from June to August were similar between years, that from September to November was 1.8–1.9°C higher in 2016 than in 2017 (Figure 1). Overall, that from June to November was 0.9°C higher in 2016. The trends in daily solar radiation obviously differed between years (Figure 1). The daily solar radiation from June to July averaged 0.4 MJ m^{-2} day^{-1} higher in 2017, that from late July to mid August averaged 2.9 MJ m^{-2} day^{-1} higher in 2016, and that from mid September to early October averaged 2.4 MJ m^{-2} day^{-1} higher in 2017.

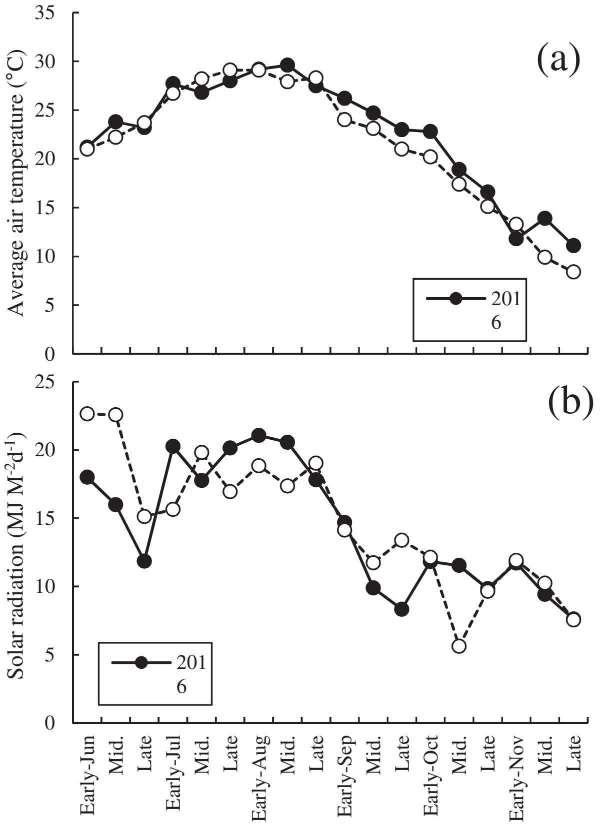

Figure 1. Changes in (a) mean temperature and (b) daily solar radiation at Fukuyama (34°30′N, 133°23′E) in 2016 and 2017.

Seedlings emerged on 2 July (normal sowing) and 25 July (late sparse and late dense sowing) in 2016, and on 28 June (normal sowing) and 30 July (late sparse and late dense sowing) in 2017. R1 (beginning of bloom) in the normal sowing ranged from 4 (Sachiyutaka and Sachiyutaka A1 gou) to 6 August (Akimaro) in 2016 and from 2 (Sachiyutaka) to 5 August (Akimaro) in 2017 (Table 1). R1 in the late sparse and dense sowing ranged from 21 (Sachiyutaka and Sachiyutaka A1 gou) to 24 August (Akimaro) in 2016 and from 25 (Sachiyutaka and Sachiyutaka A1 gou) to 26 August (Akimaro) in 2017. Differences in the growth stages among cultivars increased in the late reproductive stages (R7 and R8). Akimaro reached R8 12–13 days later than Sachiyutaka in all environments. Sachiyutaka A1 gou reached 9–10 days later than Sachiyutaka in 2016 and 1–6 days later in 2017.

3.2. *Yield and yield components*

Except for harvest indices, all traits were significantly higher in 2016 than in 2017 (Table 2). While HI was significantly lower in 2016, the difference in adjusted HI was not significant. Seed yield ranged from 388 to 678 g m^{-2} across all cultivars, sowing environments, and years (Tables 3 and 4). Although the differences in seed yield among cultivars were not significant, the difference among sowing environments was significant in 2017. Seed yield in the late dense sowing was significantly higher than that in the late sparse sowing in 2017. HI and adjusted HI ranged from 0.411 to 0.614 and from 0.465 to 0.631, with significant differences among cultivars, sowing environments, and years. Akimaro had significantly lower HI and adjusted HI. HI and adjusted HI were higher in the late sparse sowing and the late dense sowing than in the normal sowing across years. Total aboveground DM ranged from 566 to 1078 g m^{-2}, with significant differences among sowing environments in both years. Total aboveground DM was lower in the late sparse sowing. Akimaro had higher total aboveground DM in 2016. The fraction of solar radiation intercepted ranged from 79.4% to 86.9%, with significant differences among cultivars and sowing

Table 1. Growth stages of Sachiyutaka, Sachiyutaka A1 gou, and Akimaro at each sowing environments.

		Normal sowing				Late sowing			
		R1	R5	R7	R8	R1	R5	R7	R8
2016	Sachiyutaka	4 August	28 August	24 October	30 October	21 August	8 September	25 October	1 November
	Sachiyutaka A1 gou	4 August	28 August	28 October	8 November	21 August	8 September	30 October	11 November
	Akimaro	6 August	1 September	29 October	11 November	24 August	12 September	4 November	14 November
2017	Sachiyutaka	2 August	29 August	19 October	27 October	25 August	9 September	27 October	3 November
	Sachiyutaka A1 gou	3 August	31 August	23 October	2 November	25 August	11 September	29 October	4 November
	Akimaro	5 August	27 August	31 October	9 November	26 August	12 September	6 November	15 November

According to Fehr and Caviness (1977).

Table 2. Differences in seed yield, harvest indices, total aboveground dry matter, fraction of solar radiation intercepted, cumulative solar radiation intercepted, and radiation use efficiency (RUE) between 2016 and 2017.

Year	Seed yield[1] (g m^{-2})	Harvest index[2,3]	Adjusted harvest index[3,4]	Total aboveground dry matter (g m^{-2})[2]	Fraction of solar radiation intercepted (%)[3,5]	Cumulative solar radiation intercepted (MJ)[5]	RUE (g MJ^{-2})[5,6]
2016 (n = 27)	538	0.537	0.572	862	83.3	1206	0.718
2017 (n = 27)	464	0.562	0.579	705	82.2	1114	0.639
ANOVA	***[7]	***	NS	***	***	***	***

[1] With 15% moisture content.
[2] Including leaves and petioles attached at R8.
[3] Arc sine transformation was done before ANOVA.
[4] Calculated without leaves and petioles.
[5] Assessed for the period from emergence to R7.
[6] Radiation use efficiency is the value of the total above ground dry matter at maturity divided by cumulative solar radiation intercepted.
[7] ***Significance at $P < 0.001$. NS means nonsignificant at $P = 0.05$ level.

Table 3. Effects of late sowing and dense sowing on seed yield, harvest indices, total aboveground dry matter, fraction of solar radiation intercepted, cumulative solar radiation intercepted, and radiation use efficiency (RUE) in 2016.

Cultivar	Sowing environment	Seed yield[1] (g m^{-2})	Harvest index[2,3]	Adjusted harvest index[3,4]	Total aboveground dry matter (g m^{-2})[2]	Fraction of solar radiation intercepted (%)[3,5]	Cumulative solar radiation intercepted (MJ m^{-2})[5]	RUE (g MJ^{-1})[5,6]
Sachiyutaka	Normal	533a[7]	0.489b	0.562b	926a	83.5b	1439a	0.643a
	Late sparse	489a	0.593a	0.621a	701b	79.6c	973c	0.721a
	Late dense	479a	0.590a	0.609a	682b	85.3a	1086b	0.628a
Sachiyutaka A1 gou	Normal	534a	0.491b	0.555b	919a	83.9a	1465a	0.630a
	Late sparse	498a	0.597a	0.615a	708a	79.6b	1005c	0.702a
	Late dense	604a	0.596a	0.613a	860a	86.2a	1140b	0.754a
Akimaro	Normal	519a	0.411b	0.465b	1062a	84.0b	1475a	0.719a
	Late sparse	509a	0.523a	0.554a	825a	81.7c	1087c	0.759a
	Late dense	678a	0.534a	0.555a	1078a	86.3a	1187b	0.908a
	Sachiyutaka	500a	0.559a	0.597a	770b	82.8b	1166	0.664b
	Sachiyutaka A1 gou	545a	0.561a	0.594a	829b	83.2ab	1203	0.696b
	Akimaro	569a	0.490b	0.525b	988a	84.0a	1250	0.795a
	Normal	529a	0.464b	0.527b	969a	83.8b	1460	0.664b
	Late sparse	499a	0.571a	0.596a	745b	80.3c	1022	0.727ab
	Late dense	587a	0.576a	0.593a	873a	86.0a	1138	0.764a
Two-way ANOVA[8]	Cultivar (C)	NS	***	***	***	*	***	**
	Sowing environment (E)	NS	***	***	***	***	***	***
	C × E	NS	NS	NS	NS	NS	*	NS

[1] With 15% moisture content.
[2] Including leaves and petioles attached at R8.
[3] Arc sine transformation was done before Tukey's multiple test and two-way ANOVA.
[4] Calculated without leaves and petioles.
[5] Assessed for the period from emergence to R7.
[6] Radiation use efficiency is the value of the total aboveground dry matter at maturity divided by cumulative solar radiation intercepted.
[7] Values followed by the same letters were not significantly different based on Tukey's multiple comparison at the 5% level.
[8] *, **, ***Significance at $P < 0.05$; $P < 0.01$; $P < 0.001$, respectively. NS means nonsignificant at $P = 0.05$ level.

environments. It was higher in Akimaro and the late dense sowing. Cumulative solar radiation intercepted ranged from 904 to 1475 MJ m^{-2}, with significant differences among cultivars and sowing environments in both years, and a significant cultivar × sowing environment interaction in 2016. RUE ranged from 0.565 to 0.908 g MJ^{-1}, with a significant difference among sowing environments. RUE was lower in the normal sowing than in the late sparse sowing and the late dense sowing. Akimaro had higher RUE in 2016. Except for cumulative solar radiation intercepted in 2016, there was no cultivar × sowing environment interaction. Total aboveground DM at maturity was correlated with total solar radiation ($r = 0.76$, $P < 0.001$; Figure 2) but not with RUE ($r = 0.47$, n.s.).

Stem DW at R8, total number of nodes, total number of pods, number of pods per node, and 100-seed weight were significantly higher in 2016, but number

Table 4. Effects of late sowing and dense sowing on seed yield, harvest indices, total aboveground dry matter, fraction of solar radiation intercepted, cumulative solar radiation intercepted, and radiation use efficiency (RUE) in 2017.

Cultivar	Sowing environment	Seed yield[1] (g m^{-2})	Harvest index[2,3]	Adjusted harvest index[3,4]	Total aboveground dry matter (g m^{-2})[2]	Fraction of solar radiation intercepted (%)[3,5]	Cumulative solar radiation intercepted (MJ m^{-2})[5]	RUE (g MJ^{-1})[5,6]
Sachiyutaka	Normal	472ab[7]	0.528b	0.548b	762a	79.7b	1320a	0.578b
	Late sparse	451b	0.614a	0.631a	624b	79.4b	904c	0.690a
	Late dense	498a	0.603a	0.613a	702ab	86.4a	1015b	0.692a
Sachiyutaka A1 gou	Normal	526a	0.556a	0.573a	804a	80.0b	1325a	0.607a
	Late sparse	388b	0.584a	0.596a	566b	79.8b	919c	0.617a
	Late dense	519a	0.607a	0.620a	727ab	85.8a	1016b	0.715a
Akimaro	Normal	456a	0.487b	0.512c	795a	81.0b	1406a	0.565a
	Late sparse	425a	0.556a	0.574a	650a	80.7b	1007c	0.645a
	Late dense	443a	0.524a	0.543b	718a	86.9a	1116b	0.644a
	Sachiyutaka	473a	0.582a	0.597a	696a	81.8b	1080b	0.653a
	Sachiyutaka A1 gou	478a	0.582a	0.596a	699a	81.9b	1086b	0.646a
	Akimaro	441a	0.522b	0.543b	721a	82.9a	1176a	0.618a
	Normal	484a	0.524b	0.545b	787a	80.2b	1350a	0.583b
	Late sparse	421b	0.585a	0.600a	613b	80.0b	943c	0.651a
	Late dense	487a	0.578a	0.592a	716a	86.4a	1049b	0.684a
Two-way ANOVA[8]	Cultivar (C)	NS	***	***	NS	**	***	NS
	Sowing environment (E)	**	***	***	***	***	***	**
	C × E	NS	NS	NS	NS	NS	NS	NS

[1] With 15% moisture content.
[2] Including leaves and petioles attached at R8.
[3] Arc sine transformation was done before Tukey's multiple test and two-way ANOVA.
[4] Calculated without leaves and petioles.
[5] Assessed for the period from emergence to R7.
[6] Radiation use efficiency is the value of the total aboveground dry matter at maturity divided by cumulative solar radiation intercepted.
[7] Values followed by the same letters were not significantly different based on Tukey's multiple comparison at the 5% level.
[8] *, **, ***Significance at $P < 0.05$; $P < 0.01$; $P < 0.001$, respectively. NS means nonsignificant at $P = 0.05$ level.

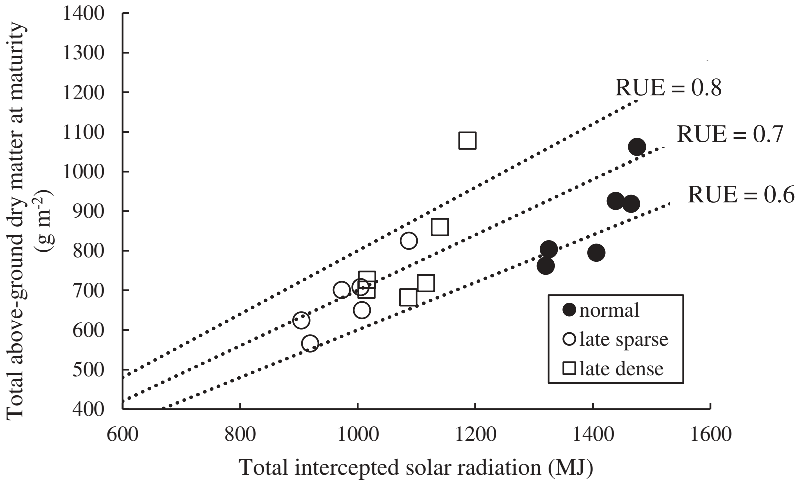

Figure 2. Relationship between total solar radiation intercepted and total aboveground dry matter at maturity in three sowing environments in 2016 and 2017. Values were significantly correlated ($r = 0.76$***).

of embryos per pod, seed set ratio, and number of fertile seeds per pod were significantly higher in 2017 (Table 5). Differences in all yield components were significant among cultivars and sowing environments in 2016 (Table 6), but differences in number of embryos per pod, seed set ratio, and number of fertile seeds per pod among cultivars and in 100-seed weight among environments were not significant in 2017 (Table 7). Except for stem DW at R8 in 2016, there was no significant cultivar × sowing environment interaction.

Table 5. Differences in stem DW and yield components between 2016 and 2017.

Year	Stem DW at R8 (g m^{-2})	Total no. of nodes (m^{-2})	Total no. of pods (m^{-2})	No. of pods/node	No. of embryos/pod	Seed set ratio (%)[1]	No. of fertile seeds/pod	100-seed weight (g)[2]
2016 (n = 27)	224	601	930	1.58	2.05	76.1	1.56	37.9
2017 (n = 27)	175	556	772	1.42	2.09	85.6	1.72	35.4
ANOVA	*[3]	***	***	***	*	***	***	***

[1] Arc sine transformation was done before ANOVA.
[2] With 15% moisture content.
[3] *, ***Significance at $P < 0.05$; $P < 0.001$, respectively.

Table 6. Effects of late sowing and dense sowing on stem DW and yield components in 2016.

Cultivar	Sowing environment	Stem DW at R8 (g m^{-2})	Total no. of nodes (m^{-2})	Total no. of pods (m^{-2})	No. of pods/node	No. of embryos/pod	Seed set ratio (%)[1]	No. of fertile seeds/pod	100-seed weight (g)[2]
Sachiyutaka	Normal	236a[3]	494a	968a	1.96a	2.04a	74.5b	1.52b	36.2b
	Late sparse	122c	435b	738b	1.70a	2.13a	82.1a	1.75a	38.1ab
	Late dense	153b	535a	696b	1.30b	2.12a	83.4a	1.77a	38.9a
Sachiyutaka A1 gou	Normal	254a	570ab	1015a	1.77a	2.02a	67.1b	1.36b	38.8a
	Late sparse	134b	460b	759a	1.64a	2.04a	79.1a	1.61a	40.6a
	Late dense	208a	635a	927a	1.46a	2.08a	77.6a	1.62a	40.3a
Akimaro	Normal	376a	798a	1198a	1.49a	1.93b	63.3b	1.22b	35.0a
	Late sparse	195b	613b	899a	1.48a	2.05a	78.2a	1.60a	35.2a
	Late dense	340a	871a	1166a	1.34a	2.04a	79.0a	1.62a	35.9a
	Sachiyutaka	171	488c	801b	1.65a	2.10a	80.0a	1.68a	37.7b
	Sachiyutaka A1 gou	199	555b	900b	1.63a	2.05ab	74.6b	1.53b	40.0a
	Akimaro	304	761a	1088a	1.44b	2.01b	73.5b	1.48b	35.4c
	Normal	289	621b	1060a	1.74a	2.00b	68.3b	1.34b	36.7b
	Late sparse	150	503c	799b	1.61a	2.07a	80.0a	1.66a	38.0a
	Late dense	234	680a	930ab	1.37b	2.08a	79.8a	1.67a	38.4a
Two-way ANOVA[4]	Cultivar (C)	***	***	***	***	**	***	***	***
	Sowing environment (E)	***	***	***	***	**	***	***	**
	C × E	**	NS	NS	NS	NS	NS	NS	NS

[1] Arc sine transformation was done before Tukey's multiple test and two-way ANOVA.
[2] With 15% moisture content.
[3] Values followed by the same letters were not significantly different based on Tukey's multiple comparison at the 5% level.
[4] *, **, ***Significance at $P < 0.05$; $P < 0.01$; $P < 0.001$, respectively. NS means nonsignificant at $P = 0.05$ level.

Stem DW ranged from 103 to 376 g m^{-2}. Total number of nodes ranged from 362 to 871 m^{-2}. Total number of pods ranged from 557 to 1198 m^{-2}. Number of pods per node ranged from 1.13 to 1.96. Number of embryos per pod ranged from 1.93 to 2.15. Seed set ratio ranged from 63.3% to 88.2%. Number of fertile seeds per pod ranged from 1.22 to 1.88. The 100-seed weight ranged from 32.9 to 40.6 g.

Adjusted HI was negatively correlated with stem DW at R8 among environments in 2016 ($r = -0.80$, $P < 0.001$) and 2017 ($r = -0.79$, $P < 0.001$) rather than seed yield ($r = 0.08$, n.s. in 2016 and $r = 0.19$, n.s. in 2017).

4. Discussion

By changing the planting date and density of soybean 'Tamahomare' at the same experimental station as in our study, Shimada et al. (1990) obtained seed yields of 337.9–595.5 g m^{-2} without preventing lodging. They considered that higher solar radiation in August and September, good soil fertility, and adequate water management contributed to the higher yields, although they did not analyze this. In comparison, our yields ranged from 388 to 678 g m^{-2} using new cultivars with preventing lodging artificially. We measured cumulative solar radiation intercepted during growth duration with changing the sowing date and density at same place, making quantitative analysis possible.

RUE tended to be lower in June sowing (Figure 2), possibly because the soybean canopy closed earlier than in the late sowing and was able to intercept the stronger solar radiation fully from late June to August, as Nakaseko and Gotoh (1983) reported a decrease in RUE under higher solar radiation. RUE is affected by the ratio of direct radiation to diffuse radiation (Sinclair & Muchow, 1999). The higher

Table 7. Effects of late sowing and dense sowing on stem DW and yield components in 2017.

Cultivar	Sowing environment	Stem DW at R8 ($g\ m^{-2}$)	Total no. of nodes (m^{-2})	Total no. of pods (m^{-2})	No. of pods/node	No. of embryos/pod	Seed set ratio (%)[1]	No. of fertile seeds/pod	100-seed weight (g)[2]
Sachiyutaka	Normal	221a[3]	589a	886a	1.51a	2.08a	70.3b	1.47b	36.5a
	Late sparse	103c	422b	675b	1.60a	2.13a	87.5a	1.86a	36.1a
	Late dense	160b	571a	779ab	1.36a	2.06a	86.2a	1.77a	36.1a
Sachiyutaka A1 gou	Normal	192a	653a	934a	1.43a	2.06a	76.2b	1.57b	35.9a
	Late sparse	108b	362b	557b	1.56a	2.13a	88.2a	1.88a	37.2a
	Late dense	164a	618a	759ab	1.23a	2.11a	87.2a	1.84	37.2a
Akimaro	Normal	271a	706a	923a	1.31b	1.98c	75.7b	1.50b	32.9a
	Late sparse	147c	436b	706b	1.62a	2.10b	86.9a	1.83a	33.0a
	Late dense	207b	645a	728b	1.13b	2.15a	84.9a	1.82a	33.4a
	Sachiyutaka	162b	527b	780a	1.49a	2.09a	81.3a	1.70a	36.3a
	Sachiyutaka A1 gou	155b	544b	750a	1.41ab	2.10a	83.9a	1.76a	36.8a
	Akimaro	208a	595a	786a	1.35b	2.08a	82.5a	1.72a	33.1b
	Normal	228a	649a	914a	1.42b	2.04b	74.1b	1.51b	35.1a
	Late sparse	120c	406b	646c	1.59a	2.12a	87.5a	1.86a	35.5a
	Late dense	177b	611a	755b	1.24c	2.10ab	86.1a	1.81a	35.6a
Two-way ANOVA[4]	Cultivar (C)	***	**	NS	*	NS	NS	NS	***
	Sowing environment (E)	***	***	***	***	*	***	***	NS
	C × E	NS	NS	NS	NS	NS	NS	NS	NS

[1] Arc sine transformation was done before Tukey's multiple test and two-way ANOVA.
[2] With 15% moisture content.
[3] Values followed by the same letters were not significantly different based on Tukey's multiple comparison at the 5% level.
[4] *, **, ***Significance at $P < 0.05$; $P < 0.01$; $P < 0.001$, respectively. NS means nonsignificant at $P = 0.05$ level.

incident solar radiation can be a reason for lower RUE in normal sowing. Kawasaki et al. (2016) measured RUE at Takatsuki, Japan (34°51′N), in the same way and the same duration used in this experiment and reported RUE values of 0.45–0.63 $g\ MJ^{-1}$. We recorded RUEs of 0.565–0.908 $g\ MJ^{-1}$ and relatively higher than previous report. While Kawasaki et al. (2016) measured cumulative radiation of 1225–1560 $MJ\ m^{-2}$ in Takatsuki, the value of cumulative solar radiation intercepted in this study ranged from 1350 to 1460 $MJ\ m^{-2}$ and there was no clear difference. The difference in cultivars can be a reason. We used relatively new cultivars, Sachiyutaka, Sachiyutaka A1 gou, and Akimaro as compared with Enrei, Tachinagaha, and Tamahomare, used in previous study and there is a possibility that RUEs were improved in new cultivars. In addition, the difference in water management also can be a reason. While fallow irrigation was conducted in previous report, we maintained water table during growing season and avoid water stress systematically. The RUEs in 2017 are lower than in 2016 in Fukuyama. The difference in soil fertility can be a reason to explain the difference in RUEs. The experiment in Fukuyama was conducted in the same field throughout 2016 and 2017, and 2017 is the second year after converting paddy field to upland field. The amount of soil N in 2017 may be lower than 2016 due to the decomposition of soil organic matter. If we consider that the differences in RUEs were caused by difference in cultivars, soil fertility, or irrigation methods, the RUEs in our experiment are reasonable. And the differences in RUEs between normal sowing and late sowing were consistent throughout 2 years and relatively smaller than the differences in cumulative solar radiation intercepted. Total aboveground DM at maturity was significantly related to cumulative solar radiation intercepted in the absence of lodging (Figure 2).

Whereas DM production was determined mainly by cumulative solar radiation intercepted, HI and adjusted HI were significantly higher in the late sowing than in the normal sowing. In addition, the differences in HI and adjusted HI were not significant between planting density. Although HI was higher in 2017, adjusted HI was stable between 2 years. That means attached leaves and petioles were larger in 2016. However, the trends in HI and adjusted HI were quite similar and the effect of attached leaves and petioles on HI was thought to be limited. The increases of HI and adjusted HI in late sowing were mainly due to the decrease in the stem DW at R8 with smaller change in seed yield. The larger stem DW in normal sowing may partially reflect the amount of vegetative growth caused by longer vegetative growth duration. Our results suggest that the assimilates were converted or translocated to seeds effectively in late sowing. Ikejiri and Takahashi

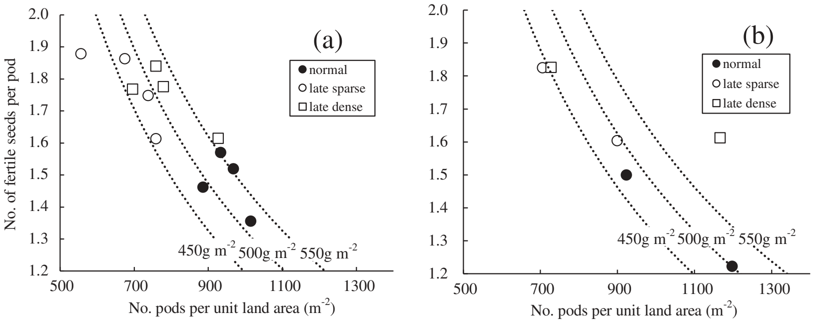

Figure 3. Differences in number of pods per unit land area and number of fertile seeds per pod among sowing environments (normal, late sparse, and late dense sowing). (a) Sachiyutaka and Sachiyutaka A1 gou. Dotted curves show indicated seed yields. The 100-seed weight of dotted curves was calculated as 37.7 g, the overall mean. (b) Akimaro. Dotted curves show indicated seed yields. The 100-seed weight of dotted curves was calculated as 34.3 g, the overall mean.

(2016) found no yield reduction in early July sowing of 'Sachiyutaka' in Yamaguchi Prefecture because of an increase in the 100-seed weight as compared with mid. June sowing. Yet, we observed a reduction in 100-seed weight of 'Sachiyutaka' in 2016, probably due to the high temperature during the seed-filling period (Matsuda et al., 2011; Tacarindua et al., 2012). On the other hand, we found significant increase in seed set ratio in late sowing.

One of our most important findings is an increase in the seed set ratio with late sowing under well irrigated conditions (Figure 3). The number of fertile seeds per pod is calculated as the number of embryos per pod × seed set ratio; our results reveal a larger contribution of seed set than of number of embryos per pod. Consequently, the number of fertile seeds per pod increased in the late sowing. Suzuki et al. (2017) also observed such an increase in July sowing as compared with June sowing in the Kanto region, which they attributed to drought and damage by insects. However, Ikeda and Fukazawa (1983) reported that the seed set ratio fluctuated even under complete insect management and proposed the occurrence of physiological abortion. Suzuki et al. (2017) reported a smaller range of damaged seed ratio than of number of fertile seeds per pod and attributed the decrease in number of fertile seeds to other factors also. In our experiment, with insects well managed during the reproductive stage, the seed set ratio was significantly lower in the normal sowing. Kato (1964) and Saitoh et al. (1999) reported a decrease in seed set ratio under drought in pot experiments. In conventional field experiments, it is difficult to distinguish the effects of drought and high temperature, but our experiment excluded the effect of drought.

Unlike drought and insect damage, temperature and daylength differed between normal and late sowings. Matsuo et al. (2013) compared yield components among sowing dates in a FOEAS field in Kyushu. They sowed Sachiyutaka on 8 and 16 July (normal sowing) and on 30 July (late sowing). There was no significant difference in the number of fertile seeds per pod between sowing dates. At a −0.35-m water level, the number of fertile seeds per pod in normal and late sowing was 1.75 and 1.82 in 2008, and 1.77 and 1.70 in 2010, similar to the values in our July sowing and higher than in our June sowing. The difference in sowing date between late June and mid July may have a large effect on seed set. On the other hand, HI was stable under different daylength treatments (Spaeth et al., 1984). The number of fertile seeds per pod obtained by Matsuo et al. (2013) tended to decrease in 2010, a hot year. The authors also observed a decrease in 2016, another hot year. Oh-E et al. (2007) measured seed set ratio of 'Enrei' sown in mid-June in a temperature gradient chamber in Okayama. Although the effect of high temperature on seed set ratio was not clear in the treatment in each year, the seed set ratio fluctuated among years and increased significantly in cool year. On the other hand, the total number of pods reported in Oh-E et al. (2007) was lower in cool year. In our experiment, the total number of pods was higher in 2016, a hot year. Gibson and Mullen (1996) reported that the high night temperature increased the total number of pods. Zheng et al. (2002) reported that the high night temperature increased the total number of flowers but the change in seed yield was not significant due to smaller seed size. The increase in the total number of pods in 2016 in the present study may be affected by high temperature. And there is a possibility that the large number of pods in normal sowing caused the relative deficiency in assimilate supply and decreased the seed set ratio. In addition, canopy respiration also increases due to high temperature in normal sowing and may promote the deficit in assimilates during seed filling period. Although climate and weather are presumed to contribute to differences in seed set ratio, further study is needed to reveal the main factors.

The seed set ratio increased in late sowing not only in Sachiyutaka but also in Sachiyutaka A1 gou and Akimaro, new cultivars bred for southwestern Japan. One of our aims was to reveal the potential of these new cultivars under optimum condition. Sachiyutaka A1 gou and Akimaro matured later than Sachiyutaka in Fukuyama, although the dates of maturity differed between 2016 and 2017. While Akimaro tended to produce more DM, nodes and pods per unit area than Sachiyutaka and Sachiyutaka A1 gou, Akimaro showed lower HI than the others. That means the improvement of the reproductive growth efficiency is important for exhibiting the yield potential of Akimaro. On the other hand, Akimaro showed higher HI and number of embryos per pod in late sowing. These results suggest that Akimaro has high yield potential in late sowing than other cultivars. In order to exhibit the yield potential of Akimaro, the selection of sowing date is thought to be important than other cultivars. The average seed yield of Sachiyutaka A1 gou was marginally higher than that of Sachiyutaka, but not significant. However, the seed yield of Sachiyutaka A1 gou can be significantly higher than Sachiyutaka in the machinery harvesting in farmers' field due to the shattering resistant trait. The seed yield of Akimaro ranged from 97% to 136% of that of Sachiyutaka at several sites in Hiroshima Prefecture (Takada et al., 2012). The ratio of damaged seeds caused by insects was significantly higher in Sachiyutaka than in Akimaro in a farmer's field in Hiroshima Prefecture (Uefuji et al., 2012). In our experiment, insecticides and fungicides were applied systematically. The new cultivars might tolerate stresses better than standard cultivars, and so the difference in yield is enhanced in farmers' fields. Overall, our results do not preclude the possibility of high-yielding ability of Sachiyutaka A1 gou and Akimaro. Our results suggest that the seed set ratio is a key trait for normal sowing, and that higher DM and pod production are key traits in late sowing (Figures 2 and 3). These traits can be a target for breeding new high-yielding cultivars for specific sowing dates. Lodging at R5 can reduce yield by >30% (Saitoh et al., 2012). As we prevented lodging in our experiment, lodging must be taken into consideration in the selection of planting density.

We elucidated the quantitative relationship between DM production and cumulative solar radiation intercepted while changing sowing date and planting density of new cultivars. Late sowing increased the seed set ratio under well irrigated conditions. The combination of late sowing with dense sowing led to higher HI and higher DM production caused by higher cumulative solar radiation intercepted, which can achieve similar yields as in normal sowing under irrigation. These results can be used in the development of guidelines to avoid flooding injury during the rainy season in southwestern Japan, as a standard for evaluating production in southwestern Japan under optimum conditions, and for breeding new high-yielding cultivars for southwestern Japan.

5. Conclusion

Changes in total DM production in late sowing and dense sowing were associated with differences in total solar radiation intercepted rather than in solar RUE. Late sowing increased HI because of a decrease in stem DW with maintaining seed yield. Under well irrigated conditions, late sowing can achieve stable production if combined with dense sowing in southwestern Japan.

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Disclosure statement

No potential conflict of interest was reported by the authors.

References

*In Japanese.
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Bajgain, R., Kawasaki, Y., Akamatsu, Y., Tanaka, Y., Kawamura, H., Katsura, K., & Shiraiwa, T. (2015). Biomass production and yield of soybean grown under converted paddy fields with excess water during the early growth stage. *Field Crops Research*, 180, 221–227.

Ball, R. A., Purcell, L. C., & Vories, E. D. (2000). Optimizing soybean plant population for a short-season production system in the southern USA. *Crop Science*, *40*, 757–764.

Fatichin, Zheng, S.-H., Narasaki, K., & Arima, S. (2013). Genotypic adaptation of soybean to late sowing in southwestern Japan. *Plant Production Science*, *16*, 123–130.

Fehr, W. R., & Caviness, C. E. (1977). Stages of soybean development. *Iowa Cooperative Extension Service Special Report*, *80*, 1–12.

Gibson, L. R., & Mullen, R. E. (1996). Influence of day and night temperature on soybean seed yield. *Crop Science*, *36*, 98–104.

Hajika, M., Funatsuki, H., Yamada, T., Takahashi, K., Hishinuma, A., Hirata, K., … Matsunaga, R. (2016). Development of a new pod dehiscence-resistant soybean cultivar 'Sashiyutaka A1 gou'. *Bulletin of NARO Institute of Crop Science*, *16*, 1–34..**

Hiroshima Prefecture. (2017). Guideline for cultivating rice, barley, wheat and soybean. Retrieved 2017,December 5th, from https://www.pref.hiroshima.lg.jp/uploaded/attachment/237295.pdf.*

Ikeda, F., & Fukazawa, N. (1983). Injury of soybean by bean bug (*Riportus clavatus* Thunberg) and its chemical control. *Bulletin of Shizuoka Agricultural Experiment Station*, *28*, 25–32.***.

Ikejiri, A., & Takahashi, T. (2016). Seed yield of soybean cultivar "Sachiyutaka" does not decrease by sowing Early-July compared to Mid-June due to heavier seed weight and higher harvest index. *Japanese Journal of Crop Science*, *85*, 10–15..**

Kane, M. V., Steele, C. C., & Grabau, L. J. (1997). Early-maturing soybean cropping system: 1. Yield responses to planting date. *Agronomy Journal*, *89*, 454–458.

Kato, I. (1964). Histological and embryological studies on fallen flowers, pods and abortive seeds in soybean. *Glycine Max (L.). Bulletin of the Tokai-Kinki National Agricultural Experiment Station*, *11*, 1–52.***.

Katsura, K., Yoshihira, T., Homma, K., Purcell, L. C., Katsube-Tanaka, T., & Shiraiwa, T. (2009). Field studies on factors causing the widening gaps in soybean yield between Japan and USA. – Field observation reports in USA –. *Journal of Crop Research*, *54*, 149–154.*.

Kawasaki, Y., Tanaka, Y., Katsura, K., Purcell, L. C., & Shiraiwa, T. (2016). Yield and dry matter productivity of Japanese and US soybean cultivars. *Plant Production Science*, *19*, 257–266.

Matsuda, H., Shibata, Y., Mori, S., & Fujii, H. (2011). Effect of temperature during the ripening period on the 100-grain weight of soybean in Shonai district of Yamagata prefecture. *Japanese Journal of Crop Science*, *80*, 43–48.**.

Matsunami, T., Inoue, K., Kudoh, T., Itoh, S., Nagasawa, K., Shibata, Y., … Yamashita, N. (2013). Effects of the abnormally high summer temperature in 2010 on the growth, yield, and quality of soybean cultivated in the Tohoku region of Japan. *Japanese Journal of Crop Science*, *82*, 386–396.*.

Matsuo, N., Takahashi, M., Nakano, H., Fukami, K., Tsuchiya, S., Morita, S., … Tasaka, K. (2013). Growth and yield responses of two soybean cultivars grown under controlled ground water level in southwestern Japan. *Plant Production Science*, *16*, 84–94.

Ministry of Agriculture, Forestry and Fisheries. (2017). Data collection related to soybean. Retrieved 2017,December 5th, from http://www.maff.go.jp/j/seisan/ryutu/daizu/d_data/attach/pdf/index-12.pdf.*

Nakaseko, K., & Gotoh, K. (1983). Comparative studies on dry matter production, plant type and productivity in soybean, azuki bean and kidney bean. □. An analysis of the productivity among the three crops on the basis of radiation absorption and its efficiency for dry matter accumulation. *Japanese Journal of Crop Science*, *52*, 49–58.***.

Oh-E, I., Uwagoh, R., Jyo, S., Kurahashi, T., Saitoh, K., & Kuroda, T. (2007). Effects of rising temperature on flowering, pod set, dry-matter production and seed yield in soybean. *Japanese Journal of Crop Science*, *76*, 433–444.**.

Purcell, L. C. (2000). □Soybean canopy coverage and light interception measurements using digital imagery. *Crop Science*, *40*, 834–837.

Saitoh, K., Mahmood, T., & Kuroda, T. (1999). Effect of moisture stress at different growth stages on flowering and pod set in determinate and indeterminate soybean cultivars. *Japanese Journal of Crop Science*, *68*, 537–544.**.

Saitoh, K., Nishimura, K., & Kitahara, T. (2012). Effect of lodging on seed yield of field-grown soybean -Artificial lodging and lodging preventing treatments-. *Japanese Journal of Crop Science*, *81*, 27–32.**.

Shimada, S., Hamaguchi, H., Kim, Y., Matsuura, K., Kato, M., Kokuryu, T., … Fujimori, S. (2012). Effects of water table control by farm-oriented enhancing aquatic system on photosynthesis, nodule nitrogen fixation, and yield of soybeans. *Plant Production Science*, *15*, 132–143.

Shimada, S., Hirokawa, F., & Miyagawa, T. (1990). Effects of planting date and planting density on a high yielding soybean cultivar grown at drained paddy field in sanyo district. *Japanese Journal of Crop Science*, *56*, 257–264.**.

Shiraiwa, T., Kawasaki, Y., & Homma, K. (2011). Estimation of crop radiation use efficiency. *Japanese Journal of Crop Science*, *80*, 360–364.*.

Sinclair, T. R., & Muchow, R. C. (1999). Radiation use efficiency. *Advances in Agronomy*, *65*, 215–265.

Spaeth, S. C., Randall, H. C., Sincalir, T. R., & Vendeland, J. S. (1984). Stability of soybean harvest index. *Agronomy Journal*, *76*, 482–486.

Sugimoto, H., & Satou, T. (1990). Excess moisture injury of soybeans cultivated in an upland field converted from paddy. 4. The significance of nodulation under excess moisture condition. *Japanese Journal of Crop Science*, *59*, 727–732.**.

Suzuki, D., Iinuma, D., Shibasaki, S., Shibuya, M., Itoh, Y., Matsui, D., & Isobe, K. (2017). Effects of late sowing and dense planting on the yield and occurrence of delayed stem senescence in Soybean (*Glycine max* (L.) Merr.) cultivars in Kanto, Japan. *Japanese Journal of Crop Science*, *80*, 347–357.**.

Tacarindua, C. R. P., Shiraiwa, T., Homma, K., Kumagai, E., & Sameshima, R. (2012). The response of soybean seed growth characteristics to increased temperature under near-field conditions in a temperature gradient chamber. *Field Crops Research*, *131*, 26–31.

Takada, Y., Saruta, M., Okabe, A., Kikuchi, A., Ono, S., Yagasaki, K., & Nishimaki, K. (2012). A new soybean cultivar, ‘Akimaro’, with high yield in late sowing cultivation and suitability for miso (Soybean paste) production. *Bulletin of NARO Western Region Agricultural Research Center*, *11*, 27–39.***.

Takahashi, M., Matsunaga, R., Komatsu, K., Nakazawa, Y., Hajika, M., Sakai, S., & Igita, K. (2004). New soybean cultivar“Sachiyutaka”. *Bulletin of NARO Kyushu Okinawa Region Agricultural Research Center*, *45*, 15–39.***.

Takeda, H., & Sasaki, R. (2013). Effects of ground water level control on the establishment, growth and yield of soybeans seeded during and after the rainy season. *Japanese Journal of Crop Science*, *82*, 233–241.**.

Uchikawa, O., Tanaka, K., Miyazaki, M., & Matsue, Y. (2009). Effects of planting pattern on growth, yield and nitrogen fixation activity of soybean cropped with late planting and non-intertillage cultivation method in northern Kyushu. *Japanese Journal of Crop Science*, *78*, 163–169.**.

Uefuji, M., Hoshina, T., Kaifuchi, Y., & Fujii, K. (2012). The cultivation, and the processing characteristic and stably high yielding methods of the new soybean cultivar ‘Akimaro’ in Hiroshima Prefecture. *Bulletin of the Hiroshima Prefectural Technology Research Institute Agricultural Technology Research Center*, *88*, 1–13.***.

Wakasugi, K., & Fujimori, S. (2009). Subsurface water level control system “FOEAS” that promotes the full use of paddy fields. *Journal of the Japanese Society of Irrigation, Drainage and Rural Engineering*, *77*, 705–708.*.

Yamada, T., Hajika, M., Funatsuki, H., Takahashi, K., Hirata, K., Hishinuma, A., & Tanaka, J. (2017). Causal analysis of yield-increase by introgression of shattering resistance gene *pdh1* in soybean. *Japanese Journal of Crop Science*, *86*, 251–257.**.

Zheng, S.-H., Nakamoto, H., Yoshikawa, K., Furuya, T., & Fukuyama, M. (2002). Influences of high night temperature on flowering and pod setting in soybean. *Plant Production Science*, *5*, 215–218.