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

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 (Faticchin 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
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 (Matsumani 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 \( \times \) 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 gau, 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 \( \times \) 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\(_2\)O\(_5\), and 10 g m\(^{-2}\) of K\(_2\)O 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.

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 environments.

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

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).
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 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$^2$ | Adjusted harvest index$^3$ | Total aboveground dry matter (g m$^{-2}$)-$^4$ | Fraction of solar radiation intercepted (%)$^5$ | Cumulative solar radiation intercepted (MJ)$^6$ | RUE (g MJ$^{-1}$)$^7$ |
|------|-----------------|-----------------|-----------------|---------------------|---------------------|---------------------|---------------------|
| 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 | *** | 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 (g m$^{-2}$) | Harvest index$^3$ | Adjusted harvest index$^4$ | Total aboveground dry matter (g m$^{-2}$)$^5$ | Fraction of solar radiation intercepted (%)$^6$ | Cumulative solar radiation intercepted (MJ)$^7$ | RUE (g MJ$^{-1}$)$^8$ |
|----------|--------------------|-----------------|-----------------|-----------------|---------------------|---------------------|---------------------|---------------------|
| Sachiyutaka | Normal | 533a | 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 | 0.702a |
| | Late sparse | 489a | 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 | 81.7c | 1475a | 0.719a |
| | Late sparse | 509a | 0.523a | 0.554a | 825a | 84.0a | 1087c | 0.759a |
| | Late dense | 678a | 0.534a | 0.555a | 1078a | 86.2a | 1187b | 0.908a |
| Sachiyutaka | Normal | 500a | 0.559a | 0.597a | 770b | 82.8b | 1166 | 0.664b |
| Sachiyutaka A1 gou | Normal | 545a | 0.561a | 0.594a | 829b | 83.2ab | 1203 | 0.696b |
| Akimaro | Normal | 569a | 0.490b | 0.525b | 988a | 84.0a | 1250 | 0.759a |
| | Late sparse | 529a | 0.464b | 0.527b | 969a | 83.8b | 1460 | 0.664b |
| | Late dense | 499a | 0.571a | 0.596a | 745b | 80.3c | 1022 | 0.727ab |
| Two-way ANOVA$^9$ | 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 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.
$^9$Values followed by the same letters were not significantly different based on Tukey’s multiple comparison at the 5% level.
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 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 (g m\(^{-2}\)) | Harvest index\(^a\) | Adjusted harvest index\(^b\) | Total above-ground dry matter (g m\(^{-2}\)) | Fraction of solar radiation intercepted (%\(^c\)) | Cumulative solar radiation intercepted (MJ m\(^{-2}\)) | RUE (g MJ\(^{-1}\)) |
|----------------|-------------------|---------------------------|---------------------|-----------------------------|---------------------------------------------|-----------------------------------------------|-----------------------------------------------|-------------------|
| Sachiyutaka    | Normal            | 472ab\(^7\)              | 0.528b              | 0.548b                      | 762a                                        | 79.7b                                          | 1320a                                         | 0.578b            |
|                | Late sparse       | 451b                     | 0.614a              | 0.611a                      | 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    | Normal            | 473a                     | 0.582a              | 0.597a                      | 696a                                        | 81.8b                                          | 1080b                                         | 0.653a            |
|                | Late sparse       | 478a                     | 0.582a              | 0.596a                      | 699a                                        | 81.9b                                          | 1086b                                         | 0.646a            |
|                | Late dense        | 441a                     | 0.522b              | 0.543b                      | 721a                                        | 82.9a                                          | 1176a                                         | 0.618a            |
| Sachiyutaka A1 gou | 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            |
| Akimaro        | Normal            | 473a                     | 0.582a              | 0.597a                      | 696a                                        | 81.8b                                          | 1080b                                         | 0.653a            |
|                | Late sparse       | 478a                     | 0.582a              | 0.596a                      | 699a                                        | 81.9b                                          | 1086b                                         | 0.646a            |
|                | Late dense        | 441a                     | 0.522b              | 0.543b                      | 721a                                        | 82.9a                                          | 1176a                                         | 0.618a            |
| Two-way ANOVA\(^e\) | Cultivar (C) | NS                        | ***                 | ***                          | NS                                         | **                                             | ***                                          | NS               |
|                | Sowing environment (E) | **                    | ***                 | ***                          | ***                                          | ***                                          | ***                                          | **               |
|                | C × E             | NS                        | NS                  | NS                           | NS                                          | NS                                            | NS                                          | NS               |

\(^a\)With 15% moisture content.
\(^b\)Including leaves and petioles attached at R8.
\(^c\)Arc sine transformation was done before Tukey’s multiple test and two-way ANOVA.
\(^d\)Calculated without leaves and petioles.
\(^e\)Assessed for the period from emergence to R7.
\(^f\)Radiation use efficiency is the value of the total aboveground dry matter at maturity divided by cumulative solar radiation intercepted.
\(^g\)Values followed by the same letters were not significantly different based on Tukey’s multiple comparison at the 5% level.
\(^h\), **, ***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***).
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 (%) | 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                 |

1, **Significance at P < 0.001; P < 0.05, 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 (%) | No. of fertile seeds/pod | 100-seed weight (g)² |
|-------------------|--------------------|------------------------|--------------------------|-------------------------|-----------------|-------------------|--------------------|--------------------------|----------------------|
| Sachiyutaka       | Normal             | 236a                  | 494a                     | 968a                    | 1.96            | 2.04              | 74.5               | 1.55                     | 36.2b                |
|                   | Late sparse        | 122c                  | 435b                     | 738b                    | 1.70            | 2.13              | 82.1               | 1.75                     | 38.1ab               |
|                   | Late dense         | 153b                  | 535a                     | 696b                    | 1.30            | 2.12              | 83.4               | 1.77                     | 38.9a                |
| Sachiyutaka A1 gou| Normal             | 254a                  | 570ab                    | 1015a                   | 1.77            | 2.02              | 67.1               | 1.36                     | 38.8a                |
|                   | Late sparse        | 134b                  | 460b                     | 759a                    | 1.64            | 2.04              | 79.1               | 1.61                     | 40.6a                |
|                   | Late dense         | 208a                  | 635a                     | 927a                    | 1.46            | 2.08              | 77.6               | 1.62                     | 40.3a                |
| Akimaro           | Normal             | 376a                  | 798a                     | 1198a                   | 1.49            | 1.93              | 63.3               | 1.22                     | 35.0a                |
|                   | Late sparse        | 195b                  | 613b                     | 899a                    | 1.48            | 2.05              | 78.2               | 1.60                     | 35.2a                |
|                   | Late dense         | 340a                  | 871a                     | 1166a                   | 1.34            | 2.04              | 79.0               | 1.62                     | 35.9a                |
| Sachiyutaka       | Normal             | 171                   | 488c                     | 801b                    | 1.65            | 2.10              | 80.0               | 1.68                     | 37.7b                |
|                   | Late sparse        | 199                   | 555b                     | 900b                    | 1.63            | 2.05ab             | 74.6               | 1.53                     | 40.0a                |
|                   | Late dense         | 304                   | 761a                     | 1088a                   | 1.44            | 2.01b             | 73.5b               | 1.48b                    | 35.4c                |
| Two-way ANOVA⁴    | Cultivar (C)       | ***                   | ***                      | ***                     | ***             | ***               | ***                 | ***                      | ***                  |
|                   | Sowing environment | ***                   | ***                      | ***                     | ***             | ***               | ***                 | ***                      | ***                  |
|                   | E                  | **                    | NS                       | NS                      | NS              | NS                | NS                  | NS                       | NS                  |

1, **Significance at P < 0.001; P < 0.05, respectively.

2With 15% moisture content.

3Values 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
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

### 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 (%) | No. of fertile seeds/pod | 100-seed weight (g) |
|-------------------|--------------------|-----------------------|--------------------------|-------------------------|-----------------|------------------|-------------------|-------------------------|----------------------|
| Sachiyutaka       | Normal             | 221a                  | 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                     | 779b                    | 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                     | 759b                    | 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       | Normal             | 162b                  | 527b                     | 780a                    | 1.49a           | 2.09a            | 83.1a             | 1.70a                  | 36.3a                |
|                   | Sachiyutaka A1 gou| 155b                  | 444b                     | 750a                    | 1.41b           | 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           | 2.10a            | 86.1a             | 1.81a                  | 35.6a                |

Two-way ANOVA:

| Cultivar (C)   | Sowing environment (E) | C × E | ** | 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.
(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 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.

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