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Onion Cultivars and Set Planting Date during Summer for an Early Winter Harvest in Northern Japan

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Abstract

The effect of combinations of cultivars and planting dates during summer on onions harvested during early winter in northern Japan was investigated. For the mid-August planting, which encountered moderate daylengths and temperatures during plant and bulb growth with a low rate of small (< 50 mm in diameter) and immature bulbs for very early (daylength threshold for bulbing < 11.5 h) and early (12 h) maturing cultivars, marketable bulb yield was the highest. For onions planted in early August, the rate of small bulbs was high owing to relatively long daylengths and high temperatures for bulbing, which resulted in lower yields in the very early and early maturing cultivars. In onions planted in late August, among the planting dates with high immature bulb rates in all cultivars, marketable bulb yields were the lowest because of insufficient daylengths and temperatures for bulbing and maturing, particularly in the later maturing cultivars. For middle maturing cultivars (daylength threshold for bulbing is 13 h) in the all planting dates, marketable bulb yield was low because of high rates of bulb immaturity with insufficient daylength and temperature for bulbing. Commercially high marketable yield was obtained by planting onion sets in mid-August for early winter harvesting in some very early and early maturing cultivars.

Discipline: Horticulture
Additional key words: air temperature, bulb yield and weight, daylength, off-season crop, plant growth

Introduction

Worldwide, onion (*Allium cepa*. L.) is one of the most widely produced and consumed vegetable crops. In Japan, most onions are produced by transplanting nurseries, where they are grown using plug trays and harvested from spring to autumn. These onions are stored and supplied until spring. Other cultivation methods include planting sets, which are small bulbs, typically < 25 mm in diameter, to develop larger bulbs. Sets have a shorter growing season than plants that originate from seeds; thus, sets are utilized where rapid, early-season production is crucial. In Europe, at high latitudes that experience a late spring and short growing season, rapid production of a bulb crop using sets can be carried out (Brewster 2008).

Sets are also applied in warm regions including West and South Asia, but in this case, sets produced from spring sowing are replanted in late summer to produce a quickly maturing bulb crop for harvesting in December (Ansari 2007). A similar cultivation method is employed in the warmer areas of Japan at a comparatively low latitude (approximately 30°N-35°N) that involves planting sets from the end of August to the beginning of September, combined with the utilization of white-on-black mulch film to enhance initial plant growth and bulb yield at harvest. This allows fresh onions to be produced in December (Terabun & Yamane 1976, Yamashita et al. 1986) with a market price higher than that of normal dry onions.

The northern Tohoku region of Japan has a cool climate and comparatively high latitude (approximately 40°N). Here, few open-field vegetable crops, such as onions, are harvested and shipped at a high price during early winter from November to December. It may be economically advantageous for farmers to follow a cultivation method utilizing sets to harvest fresh onions during early winter. Kinoshita et al. (2018) reported that planting sets around August 12, which is approximately 3 weeks earlier than in warmer areas using white-on-black

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mulch film to enhance initial plant growth and bulb yield at harvest despite cooler climate, which were optimal adaptations for harvesting fresh onions in November with adequate marketable yield in the northern Tohoku region.

During onion cultivation periods, bulbing usually takes place under increasing daylength conditions from spring to summer. Longer daylengths and warmer temperatures (10°C-30°C) promote bulb growth and maturation (Heath 1945, Kato 1964, Khokhar 2008). Wright and Sobeih (1986) showed that when plants at an advanced stage of bulb development were transferred from long-day (16 h) to short-day (8 h) conditions, bulb development was inhibited and the plants reverted to vegetative growth. Additionally, bulbing is delayed or prevented below 10°C-15.5°C (Khokhar 2017). These findings clearly showed that long-day with warm temperature conditions induced and maintained onion bulb development, whereas it was inhibited under short-day conditions.

When onions are cultivated by planting sets during summer, they are grown under decreasing daylength and temperature conditions. Thus, cultivars that require shorter photoperiods for bulb promotion are employed. In Israel, sets of the short-day type cultivar ‘Bet alpha’ are planted in July or early August, and bulbs are harvested in December under decreasing daylength from 14 h to approximately 10 h; moreover, cultivars with a slightly longer daylength requirement for bulbing than ‘Bet alpha’ revert to leaf growth and fail to complete bulbing when grown from sets (Corgan & Kedar 1990), which indicates the importance of using cultivars that are suitable to cultivation periods that range from summer to winter. Planting sets that are suitable for bulbing and which have marketable yield is also important, because early planting dates lead to early bulbing and lower bulb weight under long daylengths and high temperatures (Kinoshita et al. 2018).

Based on these backgrounds, the aim of this study was to investigate suitable cultivar maturity types and planting dates that would enable the harvesting of onions in early winter using sets in the northern Tohoku region of Japan.

Materials and methods

1. Plant materials and experimental design

The experiments were carried out in 2016 and 2017 at the National Agriculture and Food Research Organization (NARO), Tohoku Agricultural Research Center in Morioka, Iwate, Japan (39°44′24″N, 141°7′48″E). In total, nine commercially grown onion cultivars, namely, ‘Sharm,’ ‘Sonic,’ ‘Turbo’ (Takii Seeds Co., Ltd., Kyoto, Japan), ‘Taka-nishiki,’ ‘Hama-emi,’ ‘Hama-sodachi’ (Kaneko Seeds Co., Ltd., Gunma, Japan), ‘Shippo Wase No. 7’ (Shippo Co., Ltd., Kagawa, Japan), ‘High Gold No. 1’ (Sakata Seeds Co., Ltd., Yokohama, Japan), and ‘Haru Ichiban’ (Matsunaga Seeds Co., Ltd., Aichi, Japan) were utilized in this study. ‘Turbo’ was used only in 2016. ‘Sharm’ is categorized as a very early maturing type and is conventionally employed in set cultivations for early winter harvesting in Japan. Other cultivars are conventionally sown in autumn and transplanted for cultivation. ‘Taka-nishiki,’ ‘Hama-emi’ ‘High Gold No. 1,’ and ‘Haru Ichiban’ are categorized as very early maturing types; ‘Sonic,’ ‘Hama-sodachi,’ and ‘Shippo Wase No. 7’ are early maturing types; and ‘Turbo’ is a middle maturing type in Japan. The threshold of daylength for bulbing is < 11.5 h in the very early maturing types, 12 h in the early maturing types, and 13 h in the middle maturing types (Abe et al. 1955). Seeds were sown on March 2 in both 2016 and 2017 in plug trays (300 mm × 600 mm × 40 mm) with 288 cells each (20 mm × 20 mm × 40 mm), filled with nursery soil (K-200, Yanmar Co., Osaka, Japan) mixed with 4% (w/w) slow-release fertilizer (Micro Long Total 280, J-cam Agri Co., Tokyo, Japan), and cultivated in an unheated greenhouse to grow the sets. The temperature inside the greenhouse ranged from 0°C to 22°C.

Cultivation of sets was terminated in mid-May when the average diameter of the sets was > 20 mm in each cultivar; they were then dried for 2 weeks in a shaded greenhouse. Afterward, the sets were stored for 3 weeks at 35°C to revive them from spontaneous dormancy. For each cultivar, sets with a diameter of 18 mm-24 mm were planted on August 2, 12, and 22, 2016, and on August 1, 11, and 21, 2017, in treatments dubbed as “early planting,” “middle planting,” and “late planting.” The sets were planted on field beds, 1.0 m wide and 0.15 m high, covered with white-on-black mulch film (Kokage Mulch, Okura Industrial Co., Ltd., Kagawa, Japan). The distance between each bed was 1.5 m. Each bed was planted with four rows of sets with a spacing of 12 cm between each set in a row and 24 cm between rows, resulting in a planting density of 22.2 plants per square meter. The experimental field was fertilized with nitrogen, phosphate, and potassium at levels of 0.015, 0.030, and 0.015 kg m^{-2}, respectively. The experiment was a split–plot design with three replications, where the planting date was treated as the main factor with the cultivar acting as the split factor. The individual plot size was 1.8 m^2 (1.2 m × 1.5 m) with 40 plants in each plot, of which 32 plants were utilized for the investigation.

2. Measurements

Lodged plants from each treatment were harvested once per week. Harvesting of all remaining plants, including dislodged plants, was completed on November 16, 2016, and November 14, 2017. The average harvest date was calculated by obtaining the average of the harvest dates of individual plants in each plot. The plant length (length from the base of the bulb to the top of the leaf) and the total leaf number of each plant were measured on each harvest day. Bulb weight and diameter were measured 1 week after harvest. The weather station at the NARO Tohoku Agricultural Research Center provided the temperature data. The daylength was calculated from sunrise to sunset data for Morioka, Iwate, Japan, from the National Astronomical Observatory of Japan (https://eco.mtk.nao.ac.jp/cgi-bin/koyomi/koyomix.cgi).

3. Data analysis

Two-way analysis of variance, correlation analysis, and Tukey multiple comparison tests at the 5% level were carried out using Microsoft Excel (Microsoft, Redmond, WA, USA) and the Bell Curve add-in for Excel, Version 3.20 (Social Survey Research Information Co., Tokyo, Japan).

Results

1. Daily average temperatures and daylength during cultivation

Figure 1 shows the daily mean air temperature and daylength during plant growth and accumulated

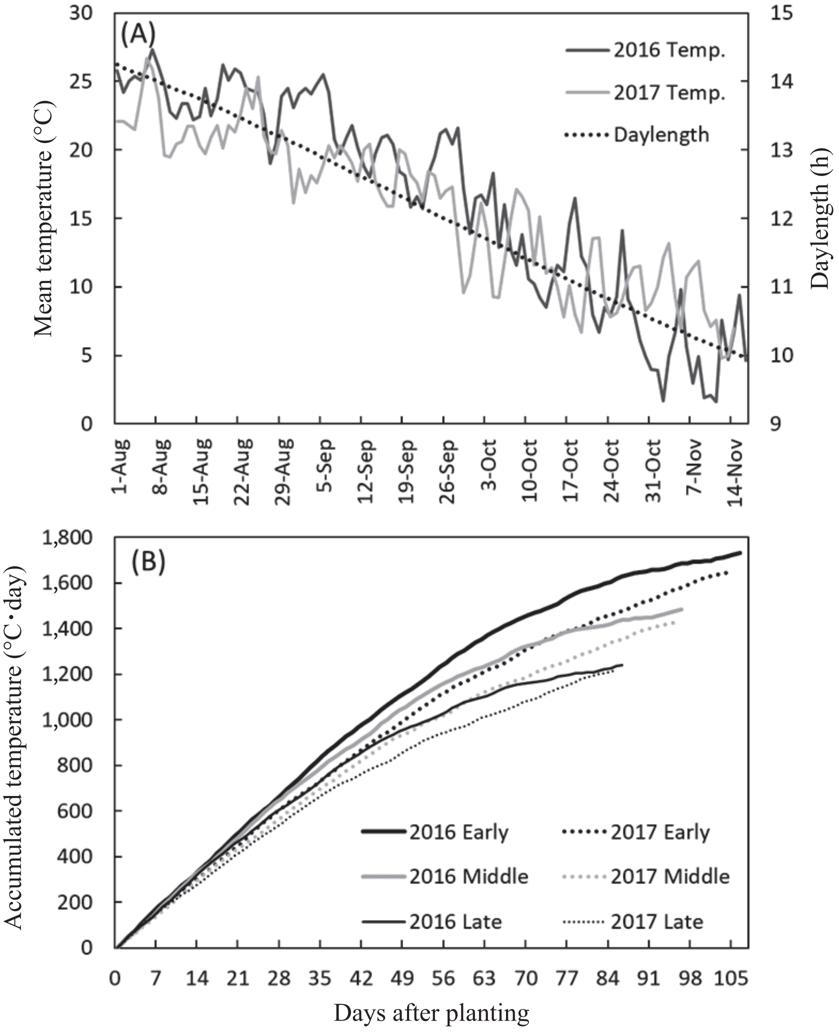

Fig. 1. Daily mean temperatures and daylength (A) and accumulated temperature from planting to harvest (B)

Daylength is shown only for 2016 as no difference in daylength between years was virtually observed.

temperature from planting to harvest. In 2016, the daily mean temperature was approximately 25°C in August, which gradually decreased to below 15°C by October, and below 10°C by November. In 2017, the daily mean temperature was lower than in 2016 from August to early October and was higher than in 2016 after late October. Daylength gradually decreased from approximately 13 h-14 h in August to 10 h in mid-November. Accumulated temperatures from planting to harvest were higher in 2016 than on similar planting dates (early, middle, and late planting) in 2017.

2. Average harvest date, plant lodging rate, and plant growth

Tables 1 and 2 respectively show the average harvest date, plant lodging rate, and plant growth at harvest for the plots in 2016 and 2017. In both years, there were significant effects of the maturing type factor, planting date factor, and their interaction on the average harvest date and plant lodging rate. Among the same planting dates, the harvest dates were earlier, and the lodging rates were higher in the very early maturing cultivars than those in the other maturing cultivars. Out of the very early maturing cultivars, 'Haru Ichiban' tended to have

Table 1. Effects of cultivars and planting dates on lodging plant rate, plant growth, and bulb yield and weight at harvest in 2016

Maturing type	Cultivar name	Planting date (date-month)	Average harvest date^{z} (date-month)	Days from planting to harvest^{y} (days)	Plant lodging rate^{u} (%)	Plant length (cm)	Total leaf number (/plant)	Total bulb yield (kg•m^{-2})	Marketable bulb yield^{x} (kg•m^{-2})	Weight per bulb^{x} (g)	Marketable bulb rate^{xs} (%)	Small bulb rate^{ws} (%)	Bulb rot rate^{s} (%)	Immature bulb rate^{vs} (%)	Divided bulb rate^{s} (%)	Missing plant rate^{s} (%)
Very early	Haru Ichiban	2-Aug	2-Oct	61	93.1	34.7	4.7	0.96	0.41	78	23.6	59.7	12.5	0.0	0.0	4.2
		12-Aug	27-Oct	76	88.9	47.5	6.8	2.34	1.87	114	73.6	13.9	9.7	1.4	0.0	1.4
		22-Aug	12-Nov	82	38.9	52.3	8.6	1.93	1.18	104	51.4	4.2	34.7	9.7	0.0	0.0
	Taka-nishiki	2-Aug	12-Oct	71	88.9	40.1	6.2	2.01	1.55	120	58.3	25.0	12.5	1.4	0.0	2.8
		12-Aug	1-Nov	81	76.4	55.8	9.1	3.81	3.24	190	76.4	2.8	16.7	0.0	0.0	4.2
		22-Aug	15-Nov	85	6.9	70.2	11.1	2.94	2.05	169	55.6	1.4	29.2	6.9	1.4	5.6
	Sharm	2-Aug	2-Oct	61	98.6	47.6	7.0	1.88	1.48	91	73.6	11.1	13.9	0.0	0.0	1.4
		12-Aug	30-Oct	79	80.6	65.5	8.7	3.52	2.93	159	83.3	0.0	16.7	0.0	0.0	0.0
		22-Aug	16-Nov	86	0.0	76.4	11.5	2.06	1.53	101	68.1	0.0	18.1	12.5	0.0	1.4
	Hama-emi	2-Aug	18-Oct	77	83.3	43.4	7.2	2.84	2.13	152	62.5	18.1	16.7	2.8	0.0	0.0
		12-Aug	9-Nov	89	37.5	64.6	10.9	4.66	3.58	232	69.4	0.0	27.8	0.0	1.4	1.4
		22-Aug	15-Nov	85	8.3	69.3	11.3	2.92	1.87	157	54.2	0.0	34.7	2.8	2.8	5.6
	High Gold No. 1	2-Aug	18-Oct	77	83.3	49.2	8.6	2.50	1.61	151	47.2	20.8	26.4	4.2	0.0	1.4
		12-Aug	10-Nov	90	36.1	70.2	10.2	4.21	3.66	211	77.8	4.2	12.5	2.8	0.0	2.8
		22-Aug	15-Nov	85	2.8	76.6	12.2	2.28	1.75	129	58.3	2.8	16.7	15.3	0.0	6.9
	Mean values of very early maturing type cultivars	2-Aug	10-Oct	69e^{t}	89.4a	43.0d	6.7e	2.04bcd	1.44de	118b	53.0b	26.9a	16.4b	1.7c	0.0	2.0
		12-Aug	3-Nov	83cd	63.9c	60.7c	9.1cd	3.71a	3.06a	181a	76.1a	4.2c	16.7ab	0.8c	0.3	2.0
		22-Aug	14-Nov	85cd	11.4de	69.0b	10.9b	2.43bc	1.68cd	132b	57.5ab	1.7c	26.7a	9.4c	0.8	3.9
Early	Sonic	2-Aug	18-Oct	77	93.1	52.1	7.3	2.35	1.68	128	56.9	16.7	23.6	0.0	0.0	2.8
		12-Aug	14-Nov	94	11.1	75.3	10.2	3.33	2.67	173	69.4	0.0	16.7	5.6	0.0	8.3
		22-Aug	16-Nov	86	0.0	81.4	11.6	2.00	1.34	112	52.8	0.0	13.9	30.6	0.0	2.8
	Shippo Wase No. 7	2-Aug	26-Oct	85	72.2	48.0	8.1	2.32	1.86	136	61.1	26.4	6.9	0.0	0.0	5.6
		12-Aug	15-Nov	95	16.7	68.3	10.2	3.33	2.66	160	75.0	2.8	19.4	2.8	0.0	0.0
		22-Aug	15-Nov	85	1.4	70.7	10.9	1.45	0.50	107	20.8	0.0	5.6	63.9	0.0	9.7
	Hama-sodachi	2-Aug	22-Oct	81	69.4	50.3	8.6	2.26	1.62	141	52.8	12.5	19.4	0.0	0.0	15.3
		12-Aug	13-Nov	93	22.2	72.2	11.0	3.79	2.97	232	58.3	2.8	26.4	0.0	0.0	12.5
		22-Aug	16-Nov	86	1.4	72.7	12.1	1.55	0.71	122	26.4	0.0	30.6	29.2	0.0	13.9
	Mean values of early maturing type cultivars	2-Aug	22-Oct	81d	78.2b	50.1d	8.0de	2.31b	1.72cd	135b	56.9ab	18.5b	16.6ab	0.0c	0.0	7.9
		12-Aug	14-Nov	94b	16.7d	71.9b	10.4bc	3.48a	2.77ab	188a	67.6ab	1.9c	20.8ab	2.8c	0.0	6.9
		22-Aug	15-Nov	86c	0.9f	74.9ab	11.5b	1.67d	0.85e	114b	33.3c	0.0c	16.7ab	41.2b	0.0	8.8
Middle	Turbo	2-Aug	15-Nov	105a	4.2ef	69.0b	14.2a	2.56b	2.27bc	136b	75.0a	0.0c	4.2c	16.7c	0.0	4.2
		12-Aug	16-Nov	96b	0.0f	82.0a	13.1a	1.87cd	1.09de	122b	40.3bc	0.0c	0.0c	54.2b	0.0	5.6
		22-Aug	16-Nov	86c	0.0f	78.3ab	11.4b	0.96e	0.08f	87c	4.2d	0.0c	6.9bc	84.7a	0.0	4.2
ANOVA^{u}	Maturing type (A)			***	***	***	***	***	***	***	***	***	***	***	NS	NS
	Planting date (B)			***	***	***	***	***	***	***	***	***	NS	***	NS	NS
	(A) × (B)			***	***	***	***	***	***	*	***	***	NS	***	NS	NS

[z] The values were calculated by averaging the harvest dates of individual plants.

[y] Days from planting date to average harvest date.

[x] Marketable bulb was defined that the diameter was > 50 mm without devided and rot bulb.

[w] Small bulb rate was defined that the diameter was < 50 mm and leaf expansion was terminated.

[v] Immature bulb was defined that the diameter was < 50 mm and leaf expansion was not terminated.

[u] ANOVA was conducted on the mean values for each maturing type cultivar. NS, *, **, and *** indicate non-significant or significant differences at $P < 0.05$, 0.01, and 0.001 (n = 3).

[t] Values with the same letter were not significantly different at $P < 0.05$ in each cultivar by Tukey-Kramer test in the same column, respectively (n = 3).

[s] Percentage data were analyzed following arcsin transformation.

the earliest harvest date and the highest lodging rate. The harvesting date was earlier for the early planting date, and this trend was more evident in the earlier maturing cultivars. In 2016, there was a trend for the lodging rate to be higher than in 2017.

In both years, there were significant effects of maturing type, planting date, and their interaction on plant length and total leaf number. These values were the smallest in the early planting date in the very early and early maturing cultivars. The total leaf number was significantly correlated with the accumulated temperature from planting to harvest in the early and middle planting treatments (Fig. 2).

3. Bulb yield and weight

Tables 1 and 2 respectively show bulb yield and weight per bulb at harvest for the plots in 2016 and 2017. In both years, there were significant differences between maturing type, planting date, and their interaction effects on the total bulb yield, marketable bulb yield, and weight per bulb. For the middle planting treatments, except for ‘Turbo’ in both years, the bulb yield and weight per bulb were higher. For the other planting treatments, the marketable yield was lowest in the early planting treatments in the very early maturing type, and it was lowest in the late planting treatments in the early and middle maturing types. High marketable yield (over

Table 2. Effects of cultivars and planting dates on lodging plant rate, plant growth, and bulb yield and weight at harvest in 2017

Maturing type	Cultivar name	Planting date (date-month)	Average harvest date[z]	Days from planting to harvest[y] (days)	Plant lodging rate[u] (%)	Plant length (cm)	Total leaf number (/plant)	Total bulb yield (kg•m^{-2})	Marketable bulb yield[x] (kg•m^{-2})	Weight per bulb[x] (g)	Marketable bulb rate[xs] (%)	Small bulb rate[ws] (%)	Bulb rot rate[s] (%)	Immature bulb rate[vs] (%)	Divided bulb rate[s] (%)	Missing plant rate[s] (%)
Very early	Haru Ichiban	1-Aug	21-Oct	81	84.7	35.0	6.0	0.85	0.44	86	22.9	56.3	0.0	2.1	4.2	14.6
		11-Aug	30-Oct	80	80.6	43.4	7.1	2.35	1.96	122	72.2	11.1	9.7	1.4	1.4	4.2
		21-Aug	13-Nov	84	15.3	54.1	9.4	2.20	1.84	109	75.0	2.8	8.3	12.5	1.4	0.0
	Taka-nishiki	1-Aug	25-Oct	85	81.9	41.0	7.8	1.36	1.09	101	48.6	34.7	0.0	2.8	2.8	11.1
		11-Aug	3-Nov	84	61.1	55.9	9.0	3.44	2.84	177	72.2	9.7	4.2	5.6	6.9	1.4
		21-Aug	13-Nov	84	6.9	66.4	10.9	2.43	1.82	128	63.9	0.0	8.3	22.2	4.2	1.4
	Sharm	1-Aug	2-Nov	93	76.4	50.4	8.4	1.81	1.52	106	64.6	31.3	0.0	4.2	0.0	0.0
		11-Aug	12-Nov	93	22.2	70.3	10.6	3.57	3.51	167	94.4	0.0	1.4	2.8	0.0	1.4
		21-Aug	14-Nov	85	0.0	76.6	11.6	1.16	0.30	87	15.3	0.0	9.7	73.6	0.0	1.4
	Hama-emi	1-Aug	29-Oct	89	72.2	46.8	8.2	1.91	1.36	111	54.2	33.3	2.1	0.0	8.3	2.1
		11-Aug	9-Nov	90	37.5	62.7	10.3	4.07	3.08	199	69.4	4.2	12.5	1.4	9.7	2.8
		21-Aug	13-Nov	84	2.8	68.2	12.7	2.04	1.16	134	38.9	1.4	15.3	36.1	6.9	1.4
	High Gold No. 1	1-Aug	4-Nov	95	70.8	60.7	11.2	1.68	1.32	109	54.2	27.1	4.2	4.2	0.0	10.4
		11-Aug	11-Nov	92	25.0	71.9	12.1	3.37	3.01	178	75.0	2.8	4.2	15.3	0.0	2.8
		21-Aug	14-Nov	85	0.0	71.7	13.3	1.86	0.91	132	30.6	1.4	5.6	58.3	1.4	2.8
	Mean values of very early maturing type cultivars	1-Aug	28-Oct	89b[t]	77.2a	46.8e	8.3d	1.52bc	1.15b	103b	48.9b	36.5a	1.3b	2.7c	3.1	7.6a
		11-Aug	6-Nov	88b	45.3b	60.8c	9.8c	3.36a	2.88a	169a	76.6a	5.6b	6.4ab	5.3c	3.6	2.5b
		21-Aug	13-Nov	84b	5.0c	67.4b	11.6a	1.94b	1.21b	118b	44.7b	1.1b	9.4ab	40.5b	2.8	1.4b
Early	Sonic	1-Aug	7-Nov	98	54.2	56.6	10.5	1.05	0.59	80	33.3	47.2	0.0	15.3	1.4	2.8
		11-Aug	13-Nov	94	8.3	82.6	11.7	2.69	2.27	136	75.0	0.0	11.1	13.9	0.0	0.0
		21-Aug	14-Nov	85	0.0	72.6	11.4	1.00	0.06	94	2.8	0.0	8.3	87.5	1.4	0.0
	Shippo Wase No. 7	1-Aug	7-Nov	98	47.2	54.0	10.0	1.68	1.21	97	56.3	35.4	2.1	4.2	2.1	0.0
		11-Aug	13-Nov	94	4.2	74.7	11.6	2.69	2.12	143	66.7	0.0	12.5	16.7	2.8	1.4
		21-Aug	14-Nov	85	0.0	68.5	11.1	0.86	0.00	-	0.0	0.0	13.9	86.1	0.0	0.0
	Hama-sodachi	1-Aug	3-Nov	94	63.9	52.0	10.4	1.81	1.39	110	56.9	30.6	5.6	4.2	0.0	2.8
		11-Aug	12-Nov	93	22.2	72.7	12.1	3.68	3.25	172	84.7	0.0	6.9	8.3	0.0	0.0
		21-Aug	14-Nov	85	0.0	59.7	12.8	1.49	0.49	120	18.1	0.0	22.2	59.7	0.0	0.0
	Mean values of early maturing type cultivars	1-Aug	5-Nov	97a	55.1b	54.2d	10.3b	1.51bc	1.06b	96b	48.8b	37.7a	2.6b	7.9c	1.2	1.9b
		11-Aug	12-Nov	94a	11.6c	76.6a	11.8a	3.02a	2.55a	150a	75.5a	0.0b	10.2a	13.0c	0.9	0.5b
		21-Aug	14-Nov	85b	0.0c	66.9b	11.7a	1.12c	0.18c	107b	7.0c	0.0b	14.8a	77.8a	0.5	0.1b
ANOVA[u]	Maturing type (A)			***	***	***	***	**	***	***	***	NS	*	***	NS	***
	Planting date (B)			***	***	***	***	***	***	***	***	***	***	***	NS	***
	(A) × (B)			**	**	***	**	*	**	**	***	NS	NS	***	NS	**

[z] The values were calculated by averaging the harvest dates of individual plants.

[y] Days from planting date to average harvest date.

[x] Marketable bulb was defined that the diameter was > 50 mm without devided and rot bulb.

[w] Small bulb rate was defined that the diameter was < 50 mm and leaf expansion was terminated.

[v] Immature bulb was defined that the diameter was < 50 mm and leaf expansion was not terminated.

[u] ANOVA was conducted on the mean values for each maturing type cultivar. NS, *, **, and *** indicate non-significant or significant differences at *P* < 0.05, 0.01, and 0.001 (n = 3).

[t] Values with the same letter were not significantly different at *P* < 0.05 in each cultivar by Tukey-Kramer test in the same column, respectively (n = 3).

[s] Percentage data were analyzed following arcsin transformation.

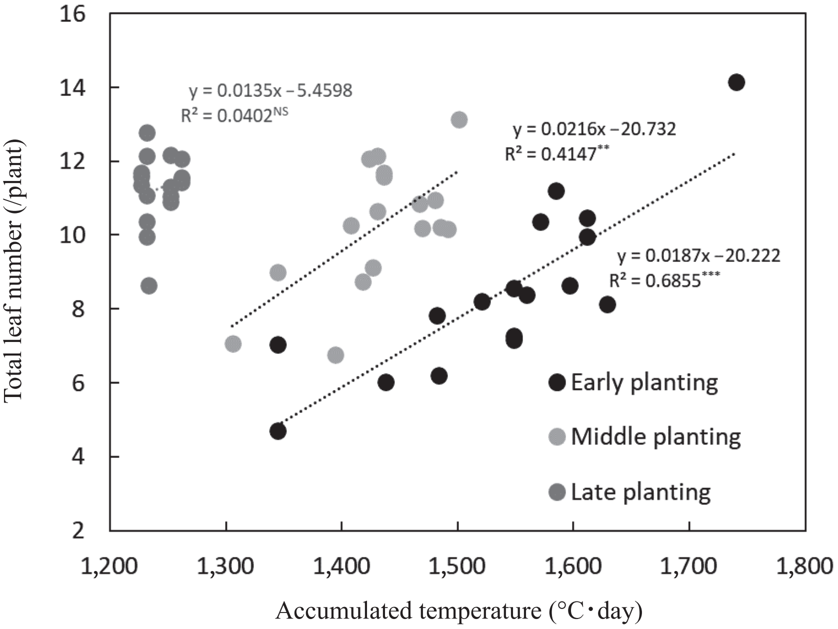

Fig. 2. Relationship between the accumulated temperature from planting date to average harvest date and the total leaf number at harvest for each planting treatment, including both experimental years

NS, **, and *** indicate non-significant at $P < 0.05$, or significant at $P < 0.01$, and 0.001, respectively.

3.0 kg m^{-2}) was obtained for 'Taka-nishiki,' 'Hama-emi,' and 'High Gold No. 1' cultivars in 2016, and for 'Sharm,' 'Hama-emi,' 'High Gold No. 1,' and 'Hama-sodachi' cultivars in 2017.

The marketable bulb rate, except for 'Turbo,' was the highest in the middle planting treatment in both years. The marketable bulb rate tended to be higher in the middle planting treatments in the very early and early maturing types in both 2016 and 2017 and higher in the early planting treatments in the middle maturing type in 2016. The small bulb rate was the highest in the early planting treatment, in the very early and early maturing cultivars. By contrast, the immature bulb rate was the highest in the late planting treatment among the planting dates. In each maturing type, there was a slight trend in the bulb rot rate among the planting treatments. In all treatments, the divided bulb and missing rates were comparably low.

4. Correlation between bulb yield and yield components

Table 3 shows the correlation between the marketable bulb yield and yield components. In both years, the marketable bulb yield showed a positive correlation with total bulb yield, weight per bulb, and marketable bulb rate, whereas it had a negative correlation with immature bulb rate in the case of including all planting dates. Notably, the marketable bulb yield had a strong negative correlation with the small bulb rate in the early planting treatment and with the immature bulb rate in the late planting treatment in both years.

Discussion

Onion bulb size and yield are influenced by planting date (Boyhan et al. 2009, Brewster et al. 1986, Caruso et al. 2014, Ikeda et al. 2019, Lancaster et al. 1996, Mondal et al. 1986), because temperature and daylength are extremely important environmental variables that affect bulbing in onions, with different cultivars that show variation in their responses to these variables (Brewster 2008, Khokhar 2017, Ikeda et al. 2019). Nevertheless, most reports for suitable planting dates focus on the main cultivation period (autumn or spring planting and summer harvesting onions), in which bulbing occurs under increasing temperature and daylength. Few studies on bulbing, targeted to summer planting and early winter harvesting onions, reported that bulbing takes place under decreasing temperatures and daylengths. Kinoshita et al. (2018) revealed suitable planting dates of sets in the very early maturity type cultivar 'Sharm' to enable the harvesting of fresh onions in November with a sufficient

Table 3. Correlation coefficients between the marketable bulb yield and each factor

Year	Planting date	Average harvest date	Plant lodging rate	Plant length	Total leaf number	Total bulb yield	Weight per bulb	Marketable bulb rate	Small bulb rate	Bulb rot rate	Immature bulb rate	Divided bulb rate	Missing plant rate
2016	2-Aug	0.75 *	−0.56 $^{\text{NS}}$	0.70 *	0.71 *	0.94 ***	0.79 *	0.83 **	−0.86 **	−0.14 $^{\text{NS}}$	0.53 $^{\text{NS}}$	–	−0.07 $^{\text{NS}}$
	12-Aug	−0.10 $^{\text{NS}}$	0.20 $^{\text{NS}}$	−0.18 $^{\text{NS}}$	−0.17 $^{\text{NS}}$	0.98 ***	0.85 **	0.65 *	−0.22 $^{\text{NS}}$	0.74 *	−0.77 *	0.38 $^{\text{NS}}$	−0.09 $^{\text{NS}}$
	22-Aug	−0.16 $^{\text{NS}}$	0.14 $^{\text{NS}}$	−0.09 $^{\text{NS}}$	0.04 $^{\text{NS}}$	0.96 ***	0.76 *	0.91 **	0.29 $^{\text{NS}}$	0.55 $^{\text{NS}}$	−0.90 ***	0.56 $^{\text{NS}}$	−0.28 $^{\text{NS}}$
	All	0.33 $^{\text{NS}}$	0.12 $^{\text{NS}}$	0.07 $^{\text{NS}}$	0.07 $^{\text{NS}}$	0.98 ***	0.88 ***	0.83 ***	−0.29 $^{\text{NS}}$	0.20 $^{\text{NS}}$	−0.61 ***	0.17 $^{\text{NS}}$	−0.19 $^{\text{NS}}$
2017	1-Aug	0.34 $^{\text{NS}}$	−0.07 $^{\text{NS}}$	0.41 $^{\text{NS}}$	0.36 $^{\text{NS}}$	0.97 ***	0.92 **	0.98 ***	−0.95 ***	0.52 $^{\text{NS}}$	−0.43 $^{\text{NS}}$	−0.18 $^{\text{NS}}$	−0.52 $^{\text{NS}}$
	11-Aug	0.35 $^{\text{NS}}$	−0.18 $^{\text{NS}}$	0.21 $^{\text{NS}}$	0.37 $^{\text{NS}}$	0.90 **	0.81 *	0.69 *	−0.33 $^{\text{NS}}$	−0.65 $^{\text{NS}}$	−0.29 $^{\text{NS}}$	0.06 $^{\text{NS}}$	−0.25 $^{\text{NS}}$
	21-Aug	−0.88 **	0.83 *	−0.56 $^{\text{NS}}$	−0.33 $^{\text{NS}}$	0.97 ***	0.55 $^{\text{NS}}$	0.99 ***	0.63 $^{\text{NS}}$	−0.28 $^{\text{NS}}$	−0.98 ***	0.56 $^{\text{NS}}$	0.26 $^{\text{NS}}$
	All	0.29 $^{\text{NS}}$	0.06 $^{\text{NS}}$	0.20 $^{\text{NS}}$	0.02 $^{\text{NS}}$	0.97 ***	0.88 ***	0.92 ***	−0.31 $^{\text{NS}}$	−0.12 $^{\text{NS}}$	−0.62 ***	0.16 $^{\text{NS}}$	−0.18 $^{\text{NS}}$

NS, *, **, and *** indicate non-significant or significant correlation at $P < 0.05$, 0.01, and 0.001.

marketable yield in the northern Tohoku area of Japan. Moreover, other similar maturing-type cultivars employed in Japan could potentially be adapted to this cultivation period.

Marketable bulb yield was the highest in the middle planting treatments (August 11 or 12) for all cultivars in the very early and early maturing cultivars (Tables 1 and 2). These cultivars had relatively high total bulb yield, marketable bulb weight, and marketable bulb rate and comparably low small and immature bulb rates in all planting date treatments. Bulb enlargement takes place when daylength exceeds the threshold for bulb initiation in warm temperatures (Heath 1945, Kato 1964, Khokhar 2017). Nevertheless, no bulbing takes place if the daylength is too short even at warm temperatures (Khokhar 2008, Steer 1980). Leaf area at bulb initiation is strongly related to bulb weight at harvest (Kato 1964), and early winter harvesting of onions in the warmer areas of Japan (Yamashita et al. 1986). Among Japanese onion cultivars, the daylength threshold for bulbing is 13 h in the middle maturing cultivars, 12 h in the early maturing cultivars, and < 11.5 h in the very early maturing cultivars (Abe et al. 1955). In the cultivar 'Sharm,' planting sets around August 12 were optimal adaptations for harvesting fresh onions in November with sufficient marketable yield in the northern Tohoku region because the assumed onset of bulbing was in mid-September, when the daylength was approximately 12.2 h (longer than the threshold for bulbing < 11.5 h), and former plant growth was adequate (Kinoshita et al. 2018). Although identifying the onset of bulbing from the present study is challenging, it would be close to that of 'Sharm' in the most very early and early maturing cultivars, as shown by the similar average harvest date, plant length, and total leaf number with lower immature bulb rate compared to that of 'Sharm.' Thus, planting sets on August 11-12 would maximize the marketable bulb yield in the very early and early Japanese onion cultivars due to the low rate of small and immature bulbs and high weight per bulb.

In the middle planting treatments, the marketable yield ranged widely (1.1-3.7 kg m^{-2}) among the very early and early maturing-type cultivars. The marketable yield of 'Haru Ichiban' was the lowest because of its smaller bulb weight and high small bulb rate, although the immature bulb rate was low (Tables 1 and 2). The smaller bulb weight in 'Haru Ichiban' was probably caused by shorter periods and smaller accumulated temperatures from planting to harvest, which resulted in less plant length and total leaf number than in other cultivars (Tables 1, 2). Thus, the daylength threshold for bulbing in 'Haru Ichiban' would be shorter than that in the other very early maturity cultivars. The cultivars that obtained a high marketable yield (> 3.0 kg m^{-2}) had a low immature bulb rate, longer period, and greater accumulated temperature from planting to harvest, which resulted in greater plant growth by encountering moderate daylengths and temperatures.

In the early planting treatment (August 1 or 2), marketable bulb yield was lower than that in the middle planting treatment except for 'Turbo,' and it exhibited a negative correlation with a small bulb rate (Table 3). Particularly, the yield was lower in the very early maturing cultivar groups with a high small bulb rate. Plant growth likely affected bulb yield and weight because the immature bulb rate was low in the early planting treatments. A strong positive correlation between accumulated temperature and total leaf number existed (Fig. 2). A lower total leaf number leads to lower bulb yield and weight (Usuki & Muro 2018), which was observed in the very early maturing cultivar groups (Tables 1, 2). Bulb initiation and development are promoted by longer daylengths and warmer temperatures (10°C-30°C) (Heath 1945, Kato 1964, Khokhar 2008). In the current experiments, onion sets that were planted earlier encountered longer daylengths and higher temperatures with adequately long daylengths (>11.5 h) and temperatures (> 10°C) from planting to the beginning of October (Fig. 1), which resulted in a lower yield and smaller bulb weight in the very early maturing cultivar groups.

In the late planting treatments (August 21 or 22), marketable bulb yield had a negative correlation with the immature bulb rates in both experimental years (Table 3). Particularly, the yield was lower in the early and middle maturing cultivar groups with high immature bulb rate than in the very early maturity cultivar groups, although the plants in these maturity cultivar groups would encounter sufficiently long daylengths (> 13 h) and temperatures (> 15°C) for all maturity type cultivars from planting to the beginning of September (Fig. 1). The accumulated temperature requirement suggests a minimum size requirement for bulbing (Lancaster et al. 1996). Terabun and Yamane (1976) reported that for bulbing in Japanese cultivars in summer planting and early winter harvesting periods, a sufficient daylength of more than 30 days was required. Brewster (1977) found that plants must have a certain number of leaves to enable bulbing when the daylength appropriate to the cultivar was reached. By contrast, the shifting of bulbing plants to noninductive short-day conditions caused a reversal of the bulbing process and renewal of vegetative growth (Kato 1964, Wright & Sobeih 1986). Bulbing is delayed or prevented below 10°C and 15.5°C (Khokhar 2017). At the experimental sites, daylength was below 12 h after the end of September and the daily mean temperature was below 15°C at the beginning of October (Fig. 1). Thus, the transition of environment to insufficient daylength and temperature before bulbing was reached produced high immature bulb rates, and leaf expansion was continued with inadequate bulb development, particularly in the later maturing cultivar groups.

By contrast, marketable bulb yield in the middle maturity type cultivar, ‘Turbo’ was higher in the earlier planting treatments, unlike the other maturity type cultivars. The onset of bulbing in ‘Turbo’ was probably delayed due to a longer daylength threshold for bulbing, which resulted in greater plant growth when compared with that of other cultivars. Additionally, a sufficient number of days above the daylength threshold (> 13 h) is required to initiate bulbing were maintained for more than 30 days from planting (August 2) to the end of September, and subsequent warm temperatures (> 15°C) until the beginning of October (Fig. 1) enhanced bulb development and decreased the number of immature bulbs. Nevertheless, the level of marketable bulb yield was low (< 3.0 kg m^{-2}), even in the early planting treatments (Table 1).

When all planting dates were considered, marketable bulb yield had a positive correlation with total bulb yield, marketable weight per bulb, and marketable bulb rate but was negatively correlated with small bulb and immature bulb rate (Table 3). These findings revealed that to achieve high marketable bulb yield, the optimum planting date must be determined based on the balance of leaf and bulb growth with encountering moderate daylengths and temperatures.

Conclusions

Among the planting dates, the middle planting treatments (August 11-12) produced the highest marketable bulb yield and weight per bulb with very early or early maturing cultivar groups, which resulted in an increase in marketable bulb yield from a lower rate of small and immature bulbs, due to moderate daylengths and temperatures during plant and bulb growth. Planting onion sets around August 11-12, with the simultaneous use of white-on-black mulch film, is an optimal adaptation to the cropping type for early winter harvesting in the very early and early maturing cultivar groups. Some cultivars have obtained commercially high marketable yields (> 3.0 kg m^{-2}). By contrast, marketable bulb yield was low (< 3.0 kg m^{-2}) for middle maturing cultivars in all planting treatments because of high rates of bulb immaturity with insufficient daylengths and temperatures for bulbing and maturing. The climate conditions of this cultivation period are unusual for onion production because of the decreasing daylengths and temperatures. To determine the effects of decreasing daylengths and temperatures on bulb growth, further research is required.

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