Effects of Interplanting on Fruit Yield and Dry Matter Production in Greenhouse-grown Tomato by Integrating Two Different Crop Periods

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Abstract

We investigated the effects of interplanting on fruit yield in greenhouse-grown tomato by integrating the first (short) and second (long) crop periods in the cooler northern area of Japan. The marketable fruit yield was similar regardless of interplanting in the first crop period, whereas it increased with earlier planting dates in the second and total crop periods. Therefore, planting immediately after the harvest of the first fruit trusses of the first crop period was effective in achieving a continuous harvest and substantial yield improvement upon conclusion of the harvest of six trusses; moreover, there were no incidences of stem lowering in the first crop period. The plant dry weight was also similar regardless of interplanting in the first crop period. However, the total dry weight and fruit dry weight increased with early interplanting in the second and total crop periods. The marketable fruit yield and total dry matter production of the whole crop period increased when cultivation started in March compared with that in April. The dry matter allocation to the fruit was similar among the treatments in all crop periods. The total fresh and dry fruit yields were significantly correlated with the cumulative light interception over the total crop period. Therefore, fruit yield was the highest when cultivation started in March with interplanting in the early-summer resulting in the highest light interception and dry matter production.

Introduction

In Japan, tomato production is conducted in greenhouses to prevent plant diseases caused by rain. In low-altitude areas of warm regions in Japan, tomatoes are cultivated from fall to spring, but not during the summer, owing to the high temperature in the greenhouses. In the Tohoku region, located in the northern part of Japan, tomatoes are mainly cultivated from spring to fall, taking advantage of the cooler summer temperature. Since heating systems are rarely installed for spring-fall tomato cultivation, given their high cost, the spring-fall tomato crop period is typically shorter than the fall-spring crop period. Therefore, tomato fruit yield in the spring-fall crop period is generally lower than that obtained in the fall-spring crop period practiced in the warmer areas of Japan.

In recent years, new covering material or techniques, such as multilayered thermal curtains, water heat storage (Kawashima 2015), and double-layered air-inflated plastic films (Iwasaki 2008; Iwasaki et al. 2011), have been used to decrease the cost of greenhouse heating in Japan. These advancements have enabled long-term or year-round tomato cultivation and, consequently, higher fruit yields, especially in the Pacific coast area of the Tohoku region, which is characterized by sufficient solar radiation, cool summers, and mild winters.

In the Netherlands, the world leader in controlled intensification under controlled conditions (Costa & Heuvelink 2005), the annual yield of greenhouse tomato is more than 60 kg m^{-2}, accomplished through year-round tomato cultivation by adopting modern technology, such as the high-wire system (Vermeulen 2010). Recently, similar cropping systems with a single cultivation period annually have been introduced in the large-scale greenhouses of

Japan. However, approximately 80% of all greenhouses are small-scale pipe-framed greenhouses with low-level eaves; thus, it is challenging to introduce a long-term single cropping system or intensify crop management with practices such as stem lowering. Therefore, the integration of two or more cropping periods is necessary to establish a long-term cultivation system and increase the fruit yield in tomato. Interplanting is a cultivation method in which new seedlings are planted next to the old plants that are still being harvested (Dorais et al. 1991). Previous studies reported a higher total fruit yield from interplanting (Avila-Juarez et al. 2012; Miliev & Alexiev 1997; Nakkila et al. 2006). However, interplanting may also cause succulent growth of new plants and increase incidence of stem lowering owing to shading by old plants. Saito et al. (2007) reported that using the short-internode cultivar decreased the stem length and reduced the stem lowering frequencies compared with that in conventional normal-internode cultivars.

Here, we aimed to develop a long-term tomato cultivation system by integrating a short spring-summer crop period with a long summer-winter crop period to extend the conventional spring-fall crop period in the Tohoku region. We assumed that if the tomato plants in the first crop period were harvested until the plants of the second crop period started to yield, growers would avoid long harvest pauses of 6-8 weeks and achieve a net increase in the annual yield. On the contrary, tomato fruit yields depend on light interception by plants (Cockshull et al. 1992; Scholberg et al. 2000) and plant dry matter production (Higashide & Heuvelink 2009). However, the interplanting system has not been investigated for understanding the relationship between dry matter accumulation and fruit yield.

Thus, the objective of this paper is to investigate 1) the effect of interplanting dates and cultivation periods on fruit yield in relation to the leaf area index (LAI), light interception by plants, and dry matter production during the first, second, and total crop periods and 2) the adaptability of the short-internode cultivar to the interplanting cultivation system.

Materials and methods

1. General cultural practices

The two experiments were conducted in a greenhouse (120 m^2) covered with polyolefin film at the NARO Tohoku Agricultural Research Center, Morioka, Iwate, Japan (39°45′N, 141°8′E) during 2014-2015 (Expt.1) and 2015-2016 (Expt. 2). Prior to flowering, tomato seedlings (*Solanum lycopersicum*) were transplanted to a growing bed (80 cm length, 31.2 cm width, and 7.5 cm height)

filled with a mixed substrate consisting of cedar bark (approximately 50% in volume), akadama (red clay granular), pumice, and zeolite, as described by Kinoshita et al. (2016), to form a single line of plants. The distance between the plants was 20 cm. The beds were arranged in rows from south to north, with 1.5 m between the rows. The plant density was 3.33 plants per m^2 in each row. Each plant was irrigated 3-8 times per day using a drip tube (1.0 L h^{-1} per plant; Streamline 60, Netafim Japan Co., Tokyo, Japan) with a 24 h time switch. The nutrient solution had an electrical conductivity of approximately 1.2 dS m^{-1} and contained N (NO$_3$–N:NH$_4$–N = 9:1), P, K, Ca, and Mg at concentrations of 130, 26, 168, 82, and 18 mg L^{-1}, respectively, which are the conventional concentrations for tomato production in Japan. The daily drain percentage was maintained at approximately 30% of the total amount of irrigation.

As the plants grew, all lateral shoots and old leaves under the already harvested trusses of four plants from each plot were periodically removed, oven-dried (80°C, > 72 h), and weighed. The remaining single stem was trained vertically on a string attached to a horizontal wire at a height of 2 m. The flowering trusses were treated with 15 mg L^{-1} of p-chlorophenoxyacetic acid (4-CPA) to promote fruit set. Trusses were thinned to contain no more than five fruits. The greenhouse was heated at night to maintain a minimum temperature of 13°C, and ventilation was initiated during the daytime when the temperature was higher than 25°C. Carbon dioxide enrichment and artificial lighting were not used in the greenhouse.

2. Effects of interplanting date on fruit yield and plant growth (Expt. 1)

The crop schedule of each treatment is shown in Table 1. Japanese cultivar "Super Yubi" (Marutane Seed Co., Kyoto, Japan) was used in the first and second crop periods. In the first crop period, the seedlings were transplanted to the west side of the bed on April 8, 2014. The main stem was trained vertically on a string attached to a horizontal wire on the west side of the bed at a height of 2 m. The main shoot tips were removed on June 19, 2014, except for two leaves above the sixth truss, and the harvest was terminated and all plants were removed on July 31, 2014. Stem lowering was not conducted during the first crop period. In the second crop period, the seedlings were transplanted in parallel with the former plants on the east side of the bed on June 25, July 9, July 25, and August 4, 2014, after the harvest of the first (A1), third (A2), and fifth (A3) and all fruit trusses (A4) of the first crop, respectively. The main stem was trained on the string attached to the horizontal wire of the east side of the bed. After the plants of the first crop were removed, half of

the stems selected with every other plant trained on strings was moved to the horizontal wires on the west side of the bed. Thus, the stem was trained using both horizontal wires in the second crop period. The old leaves were pruned as described above, and the stems were lowered approximately 30 cm when they reached the horizontal wire. The main shoot tips were removed on December 17, 2014, except for two leaves above the flowering truss, and the harvest was terminated on March 11, 2015.

3. Effects of cultivar and cultivation initiation date on fruit yield and plant growth (Expt. 2)

The crop schedule of each treatment is shown in Table 1. In the first crop period, the seedlings ("Momotaro York"; Takii Seed Co., Kyoto, Japan), with normal stem nodes the same as those in "Super-Yubi," were transplanted to the west side of the bed on March 24 (early) and April 14 (late), 2015. The main stem was trained with the same method used in Expt. 1. The main shoot tips were removed on June 2 (early) and 18 (late), 2015, except for two leaves above the sixth truss, and the harvest was terminated, and all plants were removed on July 16 (early) and August 3 (late), 2015. In the second crop period, two cultivars, a normal-node type ("Momotaro York") and short-node type ("Rinka 409"; Sakata Seed Co., Kyoto, Japan) (Tanaka et al., 2013), were tested. These seedlings were transplanted to the east side of the bed on June 8 (early) and 22 (late), after the harvest of the first truss with interplanting, or August 5 (late), 2015, after the harvest of all the fruit trusses, respectively. The plants were managed in the same manner as that in Expt. 1. The main shoot tips were removed on December 2 (early) and 28 (late), 2015, except for two leaves above the flowering truss; the harvest was terminated on January 19 (early) and February 23 (late), 2016.

4. Measurements

In each experiment, mature fruits from six plants were harvested from each plot once or twice a week, and the fresh weight of each fruit was recorded. A fruit was defined as marketable when it weighed more than 80 g and had no physiological damage, such as blossom-end rot. We also estimated the fruit dry weight by multiplying the fruit fresh weight with the ratio of dry matter of the fruit. The fresh and dry weight of fruits were harvested several times during the first and second crop periods in each experiment, and the average value for each sampling date was used for the ratio. The ratio (g g^{-1}) was 0.0537 in Expt. 1 and 0.546 in Expt. 2 (same value for all treatments) in the first crop period; 0.0527 (A1), 0.0522 (A2), 0.0522 (A3), and 0.0516 (A4) in Expt. 1; and 0.0531 (B1), 0.0513 (B2), 0.0550 (B3), 0.0557 (B4), 0.0553 (B5), and 0.0552 (B6) in

Expt. 2 in the second crop period. The length (L; cm) and width (W; cm) of individual leaves from each treatment were measured several times during each experiment. The individual leaf area (LA, cm^2) of each cultivar was obtained using the following regression equation:

$$LA = a\,LW,$$

where "a" represents a proportionality factor for each cultivar (0.317, "Super Yubi"; 0.346, "Momotaro York"; 0.355, "Rinka 409"). The regression equations ($R^2 = 0.903$ to 0.945, $P < 0.01$ for all regressions) were obtained by destructive sampling conducted several times during the experiments as described by Higashide and Heuvelink (2009) and Kinoshita et al. (2016).

The leaf area index (LAI) was calculated from the total data on the individual leaf areas of whole plants. The daily LAI was estimated using the LA value at each measurement day by the means of linear interpolation between each measurement day as described by Higashide et al. (2015). Four plants from each plot were collected for sampling at the end of the experiment. Each plant sample was separated into the stem and leaves. The plant tissues were dried in an open-air draught oven at 80°C for >72 h, and their dry weights were measured.

The light extinction within the plant canopy was estimated as described by Monsi and Saeki (2005):

$$I = I_0 e^{kL},$$

where I is the light intensity at a given point in the plant canopy, I_0 is the light intensity above the canopy, k is the light-extinction coefficient, and L is the cumulative LAI at that point in the canopy. To obtain the light-extinction coefficient for each treatment, we measured the photosynthetic photon flux density (PPFD) using a 1-m-long PPFD sensor (Li-191SA; LI-COR, Lincoln, NE, USA) under the closed plant canopy conducted three times for the first crop period, both crop periods, and the second crop period during the experiments. PPFD above the plant canopy was also measured with a PPFD sensor (TMS321FR-3; TASCO Japan, Co., Ltd., Osaka, Japan) at the same time. The light-extinction coefficient was calculated as the slope of the logarithmic regression of PPFD against the total LAI on the same day. The light-use efficiency (LUE) was calculated as the slope of the linear regression of the total cumulative dry matter production as a function of the integrated solar interception by the plants. The daily solar radiation intercepted by the plants in each treatment was calculated from LAI and the corresponding light-extinction coefficient. The light-extinction coefficient was 0.33 (Expt. 1) and 0.30 (Expt. 2), when only the first crop was planted, 0.35 (Expt. 1 and "Momotaro York" in Expt.2) and 0.36 ("Rinka 409" in Expt. 2) when the first and second crops were planted simultaneously, and 0.51 (Expt. 1), 0.48 ("Rinka 409" in Expt. 2), and

Table 1. Planting and harvest dates for tomato intercropping cultivation combined two cropping system in the each treatment

		Treatments			1st crop period			2nd crop period		
	No.	Planting date of the 2nd crop period			Planting date	Beginning of harvest	End of harvest	Planting date	Beginning of harvest	End of harvest
Expt. 1 (2014-15)	A1	Harvest of the 1st fruit truss			08-Apr-14	06-Jun-14	31-Jul-14	25-Jun-14	09-Aug-14	11-Mar-15
	A2	Harvest of the 3rd fruit truss						09-Jul-14	18-Aug-14	
	A3	Harvest of the 5th fruit truss						25-Jul-14	01-Sep-14	
	A4	Harvest of all fruits						04-Aug-14	22-Sep-14	
	No.	Cultivation start month	Inter planting	Cultivar type in the 2nd crop period[z]	Planting date	Beginning of harvest	End of harvest	Planting date	Beginning of harvest	End of harvest
Expt. 2 (2015-16)	B1	March	Yes	Short-internode	24-Mar-15	28-May-15	16-Jul-15	08-Jun-15	30-Jul-15	19-Jan-16
	B2			Normal-internode						
	B3	April	Yes	Short-internode	14-Apr-15	11-Jun-15	03-Aug-15	22-Jun-15	10-Aug-15	23-Feb-16
	B4			Normal-internode						
	B5		No	Short-internode				05-Aug-15	01-Oct-15	23-Feb-16
	B6			Normal-internode						

[z]Short-internode: "Rinka 409", Normal-internode: "Momotaro York"

Table 2. Effects of the date of interplanting during 2nd crop period on fruit yield (Expt. 1)

No.	Treatments Planting date of the 2nd crop period	Total fruit yield (kg m⁻²)			Marketable fruit yield (kg m⁻²)			Monthly marketable fruit yield (kg m⁻²)									
		1st	2nd	Total	1st	2nd	Total	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
A1	Harvest of the 1st fruit truss	13.6a	18.6a	32.2a	12.2a	16.7a	28.9a	6.9a	5.3a	2.6a	1.8ab	1.4b	3.5bc	1.9b	0.9a	3.3a	1.2a
A2	Harvest of the 3rd fruit truss	13.5a	16.5b	29.9b	12.2a	14.8b	27.0ab	6.5a	5.7a	1.2b	2.1a	2.3a	3.1c	2.0b	1.0a	2.6a	0.5b
A3	Harvest of the 5th fruit truss	14.0a	14.1c	28.1c	12.7a	13.0c	25.6b	6.9a	5.8a	0.0c	1.5bc	2.0a	4.3a	1.8b	0.8a	2.6a	0.1b
A4	Harvest of the all fruits	13.8a	13.6c	27.3c	12.6a	13.0c	25.6b	7.0a	5.6a	0.0c	0.5c	1.2b	3.8ab	2.9a	1.1a	3.1a	0.4b

Same letters represent non-significant differences at $P<0.05$ by Tukey's multiple comparison tests (n = 4).

Table 3. Organ dry weight, dry matter (DM) allocation to the fruits, cumulative light interception, and light use efficiency (LUE) in tomato plants in each treatment (Expt. 1)

No.	Treatments Planting date of the 2nd crop period	Dry weight (g m⁻²)												DM allocation to the fruits (g g⁻¹) Total	Cumulative light interception (MJ m⁻²) Total	LUE (g MJ⁻¹) Total
		Leaf			Stem			Fruit			Total					
		1st	2nd	Total	1st	2nd	Total	1st	2nd	Total	1st	2nd	Total			
A1	Harvest of the 1st fruit truss	282a	481a	763a	144a	303a	447a	728a	962a	1,690a	1,155a	1,746a	2,901a	0.583a	1,966a	1.48a
A2	Harvest of the 3rd fruit truss	289a	436b	724a	145a	275a	420ab	723a	861b	1,584b	1,157a	1,572b	2,728b	0.580a	1,893ab	1.44a
A3	Harvest of the 5th fruit truss	288a	371c	658bc	143a	233b	376bc	751a	737c	1,488c	1,182a	1,341c	2,523c	0.590a	1,850bc	1.36a
A4	Harvest of the all fruits	294a	348c	642c	147a	221b	369c	739a	715c	1,453c	1,180a	1,283c	2,464c	0.590a	1,789c	1.38a

Same letters represent non-significant differences at $P<0.05$ by Tukey's multiple comparison tests (n = 4).

0.50 ("Momotaro York" in Expt. 2) when only the second crop was planted, based on the values obtained for the plant canopy of A1, B1, and B2, respectively.

The air and water temperatures in the circulation tank were measured using T-type thermocouples. The total horizontal solar radiation was measured using a pyranometer (MS-602, Eiko Instruments Co., Ltd., Tokyo, Japan). Data were collected every 1 min, and the averages were recorded every 10 min using a data logger (ZR-RX45V; Omron Corp., Kyoto, Japan).

5. Experimental design and data analysis

In each experiment, a randomized complete block design with four blocks was used. Each block was a separate row and consisted of three 80 cm beds planted with four plants each. Thus, each treatment included four replicates of 12 plants each. Analysis of variance, Tukey's multiple comparison test, and regression analysis were performed using the statistical software Excel Tokei 2015 (SSRI, Tokyo, Japan).

Results

1. Climatic conditions in each experiment

The climatic conditions over the crop period are shown in Figs. 1A and B for Expt. 1 (2014-2015) and Expt. 2 (2015-2016), respectively. During both experimental periods, the daily maximum air temperature was 20°C-30°C, except in August, when it was 30°C-35°C. The daily minimum air temperature was approximately 13°C from March to May and gradually increased to approximately 20°C during the summer and decreased to 13°C after mid-October. The daily average air temperature was 15°C-20°C during the spring and gradually increased to approximately 25°C during the summer and then decreased to 15°C-18°C after mid-October. The daily cumulative solar radiation was approximately 10-15 MJ m^{-2} from March to August and decreased to 5 MJ m^{-2} after mid-October.

2. Effects of interplanting date on fruit yield and plant growth (Expt. 1)

The fruit yield in each treatment of the first, second, and total crop periods is shown in Table 2. In the first crop period, the total and marketable fresh fruit yields were similar among the treatments. The total and marketable fresh fruit yields were the highest in A1, followed by those in A2, A3, and A4 in the second and total crop periods. No significant differences were identified in the fruit yield among the treatments in June and July. The effect of interplanting on fruit yield was stronger in August and September and also in A1 and A2 than in A4. Although

the monthly fruit yield differed significantly after October, the cumulative fruit yield from October to the end of the harvest had no significant difference among the treatments (data not shown).

The LAI increased with early planting in the second crop period (Fig. 2). Significant differences were identified from July to September among the treatments. The LAI was approximately 2-4 m^2 m^{-2} from June (after plant canopy was closed) to December (before removing the shoot tips) in A1, whereas it was lower than 1 m^2 m^{-2} in August in A4.

The dry weight of all organs was similar among the treatments in the first crop period (Table 3). In the second and total crop periods, however, the fruit dry weight was the highest in A1, followed by that in A2, and was significantly lower in A3 and A4. The leaf, stem, and total dry weights followed a similar trend as with the fruit dry weight. The fraction of dry matter allocated to the fruit was similar among the treatments in the total crop period. The cumulative light interception increased with early planting in the second crop period and was higher in A1 than in A4. The LUE was similar among all the treatments.

The stem length, the number of harvested fruit trusses, and the frequency of stem lowering in the second crop are shown in Table 4. The stem length under the fifth truss increased with early planting, and thus, it was significantly longer in A1 than in A4. The length of stem between the fifth and tenth truss and that above the tenth truss differed among the treatments and increased significantly with early planting. The number of harvested fruit trusses and the frequency of stem lowering were the highest in A1, followed by that in A2, and significantly lower in A3 and A4.

3. Effects of cultivar and cultivation period on fruit yield and plant growth (Expt. 2)

The fruit yield in each treatment of the first, second, and total crop period is shown in Table 5. The marketable fresh fruit yield was higher in B1 than in B3, B4, B5, and B6 in the first crop period. The total and marketable fresh fruit yields were the highest in B1 and B2, followed by those in B3, B4, B5, and B6 in the second and total crop periods. The fruit yields in June and August were higher in B1 and B2 than in other treatments; however, the yield in July was lower in B1 and B2 than in other treatments. The effect of interplanting on the fruit yield was stronger in August and September among the treatments with cultivation starting in April (B3-B6). The cumulative fruit yields after November were lower in B1 and B2 than in the other treatments, owing to the early termination of cultivation (data not shown). In the same cultivation period and interplanting condition, the monthly and total
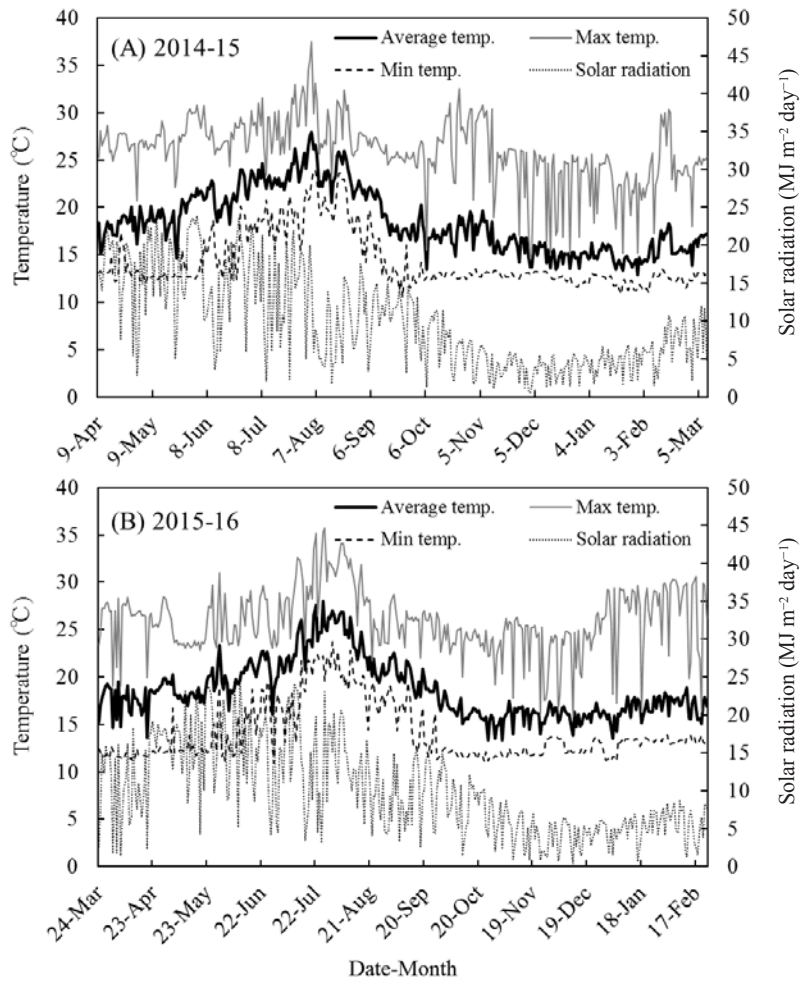
Fig. 1. Daily average, maximum, and minimum air temperatures, and cumulative solar radiation in the greenhouse over the total crop period
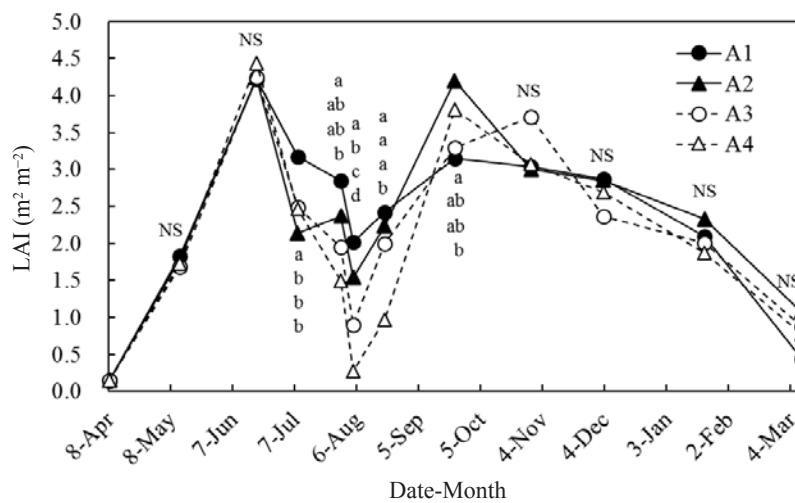

Fig. 2. Changes in the leaf area index (LAI) in each treatment over the crop period in Expt. 1

The same letters over the symbols for each day indicate non-significant differences at $P < 0.05$, evaluated by Tukey's multiple comparison tests (n = 4).

Table 4. Effect of planting date on the number of harvested fruit truss and the frequencies of stem lowering in the second crop (Expt. 1)

Treatments		Stem length (cm)			Number of harvested fruit trusses[z]	Frequencies of stem lowering[y]
No.	Planting date of the 2nd crop period	Under 5th truss	5th to 10th truss	Above 10th truss		
A1	Harvest of the 1st fruit truss	185 a	151 a	191 a	16.0 a	7.5 a
A2	Harvest of the 3rd fruit truss	181 ab	149 b	149 b	14.8 b	6.0 b
A3	Harvest of the 5th fruit truss	182 ab	143 c	74 c	12.3 c	5.0 c
A4	Harvest of the all fruits	173 b	137 d	64 c	11.7 c	5.0 c

[z]The main shoot tips of the plants were removed on 17 December 2014 leaving two leaves above the flowering truss.
[y]The main stem was lowered approximately 30 cm when the stem reached the horizontal wire for training.
Same letters represent non-significant differences at $P < 0.05$ by Tukey's multiple comparison tests (n = 4).

fruit yields did not differ significantly between cultivars.

The LAI increased with interplanting in the second crop period among the treatments with cultivation which started in April (B3-B6) (Fig. 3); it was approximately 2-4 $m^2 m^{-2}$ from June to December in B3 and B4 and lower than 1 $m^2 m^{-2}$ during the summer in B5 and B6, as observed in Expt. 1. The LAI in the treatments with cultivation starting in March (B1 and B2) was higher from March to May and lower after November than that in B3-B6.

In the first crop period, the leaf and total dry weights were the highest in B5, and the stem dry weight was higher in B5 than in B1 and B4 (Table 6). The fruit dry weight was similar among the treatments. In the second crop period, the leaf and total dry weights were the highest in B1 and B3, followed by those in B2 and B4, and the lowest in B5 and B6. The fruit dry weight was significantly higher in B1, B2, and B3 than that in B5 and B6. The dry weight of each organ in the total crop period showed a similar trend to that in the second crop period. The fraction of

dry matter allocated to the fruit was similar among the treatments in the total crop period. The cumulative light interception was the highest in B1, followed by that in B2, B3, B4, B5, and B6. The LUE was similar among the treatments.

The stem length, number of harvested fruit trusses, and frequency of stem lowering in the second crop period are shown in Table 7. The stem length under the fifth truss was shorter in "Rinka 409" than in "Momotaro York" for the same interplanting conditions. The length under the fifth truss and above the tenth truss increased due to interplanting with the same cultivar; thus, it was significantly longer in B3 and B4 than in B5 and B6, respectively. The number of harvested fruit trusses was larger in B1-B4 than in B5 and B6, also owing to interplanting. The frequency of stem lowering incidences was also increased by interplanting, but decreased when a short-internode cultivar, "Rinka 409," was used.
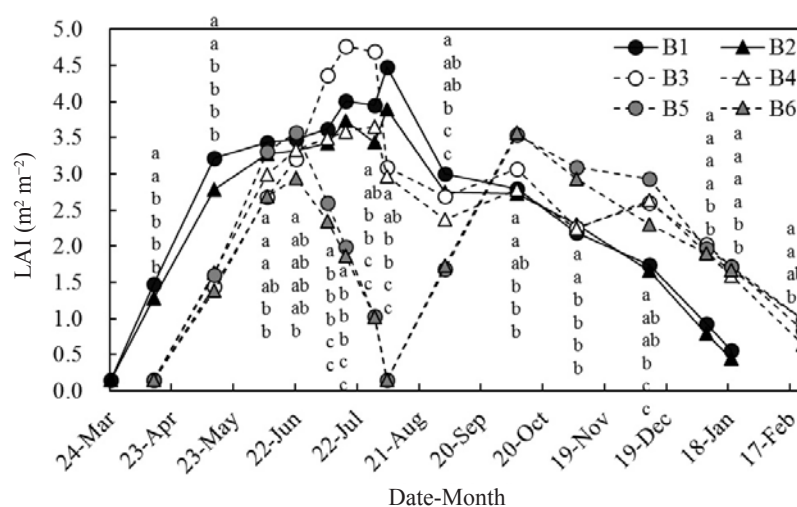

Fig. 3. Changes in the leaf area index (LAI) in each treatment over the crop period in Expt. 2
The same letters over the symbols for each day indicate non-significant differences at $P < 0.05$, evaluated by Tukey's multiple comparison tests (n = 4).

Table 5. Effects of cultivation start month, interplanting and cultivar during 2nd crop period on fruit yield in both and total cropping periods (Expt. 2)

	Treatments			Total fruit yield (kg m⁻²)			Marketable fruit yield (kg m⁻²)			Monthly marketable fruit yield (kg m⁻²)									
No.	Cultivation start month	Inter planting	Cultivar type in the 2nd crop period[z]	1st	2nd	Total	1st	2nd	Total	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.
B1	March	Yes	Short-internode	14.8 a	22.0 a	36.8 a	14.0 a	19.6 a	33.6 a	0.2 a	9.7 a	4.1 b	5.6 a	4.1 a	3.5 a	2.9 b	2.0 b	0.6 c	0.0 c
B2			Normal-internode	14.5 a	21.2 a	35.7 a	13.7 ab	18.7 a	32.4 a	0.2 a	8.8 a	4.7 b	5.4 a	3.2 ab	2.9 a	2.9 b	3.1 ab	0.9 c	0.0 c
B3	April	Yes	Short-internode	13.8 a	20.3 ab	34.1 ab	12.6 b	17.8 ab	30.3 ab	0.0 a	3.3 b	8.5 a	3.9 b	3.2 ab	3.7 a	3.8 b	2.1 b	1.0 bc	0.7 ab
B4			Normal-internode	14.1 a	17.2 bc	31.2 bc	12.6 b	15.1 b	27.8 b	0.0 a	3.4 b	8.2 a	3.1 b	2.7 b	2.8 ab	3.7 b	2.8 b	0.6 c	0.4 bc
B5		No	Short-internode	13.8 a	14.8 c	28.6 c	12.7 b	13.3 c	25.9 c	0.0 a	3.8 b	8.0 a	1.0 c	0.0 c	2.1 ab	4.0 ab	4.5 a	1.5 a	1.1 a
B6			Normal-internode	13.6 a	14.7 c	28.3 c	12.3 b	12.8 c	25.1 c	0.0 a	3.9 b	7.6 a	0.8 c	0.0 c	1.4 b	5.0 a	4.3 a	1.5 ab	0.6 ab

[z]Short-internode: "Rinka 409", Normal-internode: "Momotaro York"
Same letters represent non-significant differences at $P<0.05$ evaluated by Tukey's multiple comparison tests (n = 4).

Table 6. Organ dry weight, dry matter (DM) allocation to the fruits, cumulative light interception, and light use efficiency (LUE) in tomato plants in each treatment (Expt. 2)

	Treatments			Dry weight (g m⁻²)												DM allocation to the fruits (g g⁻¹)	Cumulative light interception (MJ m⁻²)	LUE (g MJ⁻¹)
				Leaf			Stem			Fruit			Total					
No.	Cultivation start month	Inter planting	Cultivar type in the 2nd crop period[z]	1st	2nd	Total	1st	2nd	Total	1st	2nd	Total	1st	2nd	Total	Total	Total	Total
B1	March	Yes	Short-internode	260 ab	378 a	638 a	117 b	162 ab	279 ab	788 a	1,167 a	1,955 a	1,165 ab	1,707 a	2,872 a	0.681 a	1,972 a	1.46 a
B2			Normal-internode	250 b	339 b	589 ab	119 ab	189 a	308 a	773 a	1,090 a	1,864 a	1,143 ab	1,618 ab	2,761 ab	0.675 a	1,907 ab	1.45 a
B3	April	Yes	Short-internode	259 ab	394 a	653 a	120 ab	185 a	305 a	752 a	1,115 a	1,867 a	1,130 b	1,694 a	2,824 a	0.661 a	1,846 b	1.53 a
B4			Normal-internode	254 ab	336 b	590 ab	117 b	174 ab	291 a	782 a	954 ab	1,737 ab	1,153 ab	1,464 b	2,618 b	0.664 a	1,820 b	1.44 a
B5		No	Short-internode	293 a	272 c	564 bc	135 a	144 b	279 ab	789 a	818 b	1,607 bc	1,217 a	1,233 c	2,450 c	0.656 a	1,596 c	1.54 a
B6			Normal-internode	269 ab	244 c	513 c	122 ab	136 b	258 b	741 a	814 b	1,555 c	1,132 b	1,194 c	2,326 c	0.668 a	1,527 c	1.52 a

[z]Short-internode: "Rinka 409", Normal-internode: "Momotaro York"
Same letters represent non-significant differences at $P<0.05$ evaluated by Tukey's multiple comparison tests (n = 4).

Table 7. Effect of planting date on the number of harvested fruit truss and the frequencies of stem lowering in the second crop period (Expt. 2)

No.	Treatments			Stem length (cm)			Number of harvested fruit trusses[y]	Frequencies of stem lowering[x]
	Cultivation start month	Inter planting	Cultivar type in the 2nd crop period[z]	Under 5th truss	5th to 10th truss	Above 10th truss		
B1	March	Yes	Short-internode	158 c	110 a	120 a	14.6 a	4.0 b
B2			Normal-internode	177 b	118 a	126 a	14.9 a	5.0 a
B3	April	Yes	Short-internode	176 b	109 a	96 a	14.4 a	3.0 cd
B4			Normal-internode	199 a	125 a	104 a	14.5 a	4.0 b
B5		No	Short-internode	159 c	116 a	41 b	11.3 b	2.5 d
B6			Normal-internode	176 b	119 a	35 b	11.2 b	3.5 bc

[z]Short-internode: "Rinka 409", Normal-internode: "Momotaro York"

[y]The main shoot tips of the plants were removed on 2 and 28 December 2015 leaving two leaves above the flowering truss. Cultivation was started in March and April, respectively.

[x]The main stem was lowered approximately 30 cm when the stem reached the horizontal wire for training.

Same letters represent non-significant differences at P <0.05 evaluated by Tukey's multiple comparison tests (n = 4).

Discussion

In the present study, we investigated the effects of interplanting dates and cultivation periods on the fruit yield in relation to the LAI, light interception by plants, and dry matter production during the first, second, and total crop periods and the adaptability of the short-internode cultivar in the interplanting cultivation system integrating a short spring-summer crop period with a long summer-winter crop period. The fruit yield did not differ among the treatments in the first crop period in the case of the same cropping periods (Tables 2 and 5), probably because the leaves were located relatively high and did not affect light interception. Since interplanting reduced the time of harvest pause between the first and second crop period, the fruit yield was increased by interplanting in both experiments. The total marketable fruit yields increased with planting after the harvest of the first fruit trusses, which were higher (3.3 kg m^{-2} [Expt. 1]; 2.7-4.4 kg m^{-2} [Expt. 2]) than those in the non-interplanting treatment (Tables 2 and 5). Therefore, planting immediately after the harvest of the first fruit trusses of the first crop period was effective to achieve a continuously substantial harvest and yield improvement when the harvest of six trusses was concluded without any stem lowering in the first crop period. In addition, the marketable fruit yield of whole crop period increased by starting cultivation in March rather than in April, with similar total cultivation periods and number of fruit trusses in Expt. 2 (Table 5).

To better understand the differences in fruit yield, we analyzed the contribution of growth characteristics to fruit yield and dry matter according to the methods of Higashide and Heuvelink (2009). Differences in the fresh fruit yield were mainly caused by changes in the fruit dry yield, because the fruit dry matter contents were similar among the treatments. The fruit dry yield can be divided into the total dry matter yield and the fraction of dry matter to fruit. No significant differences were identified in the latter parameter (Tables 3 and 6). Therefore, differences in the fruit dry yield were mainly caused by changes in the total dry matter yield.

The total dry matter yield can be divided based on light interception and LUE. Interplanting treatments with larger light interception by the plants resulted in a higher total dry matter yield. On the other hand, the LUE did not differ significantly among the treatments (Tables 3 and 6). Therefore, the fresh fruit yield was affected by light interception, which is in agreement with the general theory that the fruit yield has a linear relationship with solar radiation in tomato (Cockshull et al. 1992; Scholberg et al. 2000). The LAI is a very important factor for enhancing light interception and fruit yield. The fraction of light intercepted by the tomato canopy shows a positive, saturating-type response to increased LAI; the intercepted light increases with the increasing LAI until 3-4 m^2 m^{-2}, whereas any further increase in LAI has only a marginal effect on the canopy light interception (Heuvelink & Dorais 2005). Our results showed that LAI was approximately 2.5-4.5 m^2 m^{-2} from June to December in the interplanted plants, whereas it remained lower than 2 m^2 m^{-2} from July to September in the non-interplanted plants (Figs. 2 and 3). Therefore, interplanting maintained the LAI near the suitable range prior to stem pinching. The higher marketable fruit yield for the whole crop period in the cultivation period starting in March was caused by a larger total dry matter production (Table 6) owing to a higher cumulative light interception than that in the cultivation period starting in April. The mean daily cumulative solar radiation differed depending on the cultivation period, because the LAIs were similar between the two cultivation periods. Our results are in agreement with that reported by Hosoi (2003), i.e., that the annual fruit yield was the

highest when the seedlings were planted on March in a year-round tomato soilless cultivation conducted in Aichi Prefecture, a warmer area of Japan.

The plants that were interplanted earlier had a longer stem, mainly because of the longer growth duration and light competition in the first crop period. Although the number of harvested fruit trusses was increased, the frequency of stem lowering increased with early planting in the second crop period, resulting in an increased labor (for stem lowering and leaf pruning) time for crop management (Tables 4 and 7). Using the short-internode cultivar decreased the stem length especially at lower positions and resulted in a reduced stem lowering frequency, as reported by Saito et al. (2007), without decreasing the fruit yield. Therefore, it is useful to introduce short-internode cultivars to decrease the labor time for crop management in interplanting programs without decreasing the fruit yields.

Conclusions

Our results show that fruit yield increased by 2.7-4.4 kg m^{-2} when the seedlings were planted immediately after the harvest of the first fruit truss of the previous crop instead of being planted after the end of the harvest of the first crop period. In the Tohoku region, planting seedlings in March in the first cropping period is probably sufficient to achieve a higher yield. Moreover, using the short-internode cultivar decreased the stem lowering frequency even in long cultivation periods.

Acknowledgments

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