Increasing the Yield of Broccoli (*Brassica oleracea* L. var. *italica*) Cultivar ‘Yumehibiki’ during the Off-crop Season by Limiting the Number of Lateral Branches

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Lateral heads, which generate after the harvest of an apical head of broccoli (*Brassica oleracea* L. var. *italica*), are generally small and have a low market value. Our purpose in this study was to increase the yield of broccoli from April to May, when domestic broccoli production is low, by removing excess branches (dubbed the “L-shaping” process) and growing one or two large and marketable lateral heads with the cultivar ‘Yumehibiki’. First, we demonstrated that transplanting seedlings in late-January and early-February to a field covered by plastic mulch and tunnels enabled apical heads and marketable lateral heads to be harvested in April and May, respectively. The number of marketable lateral heads reached a maximum 81% of that of apical heads. Next, we derived the base temperature (BT; °C), effective heat unit summation (EHUS; °C·day) from transplanting to apical head harvest, and additional EHUS from apical head harvest to lateral head harvest. They were 1.76°C, 747°C·day, and 254°C·day in 2016, and 1.74°C, 675°C·day and 204°C·day in 2017, respectively. The favorable timing for transplanting to result in the highest marketable yield was estimated as when the average temperature reached 4.0°C, but was less than 7.1°C. Finally, we characterized the lateral branches that were most likely to produce marketable lateral heads. The branches that produced marketable heads showed significantly higher values for thickness of branch, length of branch, and number of leaves on branch than those that produced nonmarketable heads, although the diameters of the developing heads on the branches were not significantly higher. Further analysis revealed that the leaf area was also significantly higher in marketable lateral heads than in nonmarketable heads. Taken together, the possibility of a substantial increase in yield during the broccoli off-crop season by using L-shaped ‘Yumehibiki’ was demonstrated in this study.

Key Words: base temperature, effective heat unit summation, harvest period, plastic tunnel, vegetable production.

Introduction

The demand for broccoli (*Brassica oleracea* L. var. *italica*) is estimated to be stable or even increasing in Japan; the growing area for broccoli has increased by 28.1% in the past 10 years, from 11,400 ha in 2006 to 14,600 ha in 2016, whereas the total growing area for vegetables has decreased by 6.7%, from 505,500 ha to 471,600 ha over the same period (MAFF, <http://www.maff.go.jp/j/tokei/>, 2016).

Broccoli is a cool-season vegetable, and optimum growth is obtained when monthly air temperatures aver-

age 16–18°C (Le Strange et al., 1996). Yields can decrease when the temperature exceeds 24°C (Tindall, 1983), and floral development is disrupted by temperatures over 30°C (Björkman and Pearson, 1998; Farnham and Björkman, 2011). Vernalization is required for flower-bud differentiation of the head, which is the edible part of broccoli (Uptmoor et al., 2012; Wurr et al., 1995). However, when plants are exposed to low temperatures below 10°C during early growth stages, pre-mature flower heads can be formed, which is called “buttoning” (Grabowska et al., 2013; Miller et al., 1985). Furthermore, sub-zero temperatures can result in freezing injuries (Tan et al., 1999). Therefore, the level of broccoli production fluctuates seasonally, even though there is a stable demand for broccoli throughout year. It is particularly difficult to cultivate broccoli in mid-summer and mid-winter over a wide

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area in Japan. As a result, the price and import ratio of broccoli tends to increase from August to September and from April to May, which correspond to the harvest seasons of the above-mentioned cultivation periods, respectively (SBJ, <http://www.stat.go.jp/data/kouri/>, 2017). There are few techniques available to mitigate high temperatures in open fields, but it is relatively easy to keep plants warm in mid-winter using covering materials, such as plastic mulch or tunnels. However, this is not necessarily profitable, because the expense of such materials increases the cost of production. Consequently, an increase in the yield of broccoli from April to May is needed in order to balance the expenses.

To increase the yield of broccoli, lateral branches are often used. After the apical head is harvested, developed lateral heads can be continuously harvested at two- to four-day intervals for several months (Bouquet, 1950). The total yield can be increased by harvesting the lateral heads, but these heads are usually small and have a low market value, which may not be profitable in terms of the increased labor cost of harvesting (Kodera, 1988; Pornsuriya and Teeraskulchon, 1997). Therefore, excessive branching is undesirable, and only the apical head of the main stem is generally harvested (Le Strange et al., 1996). However, the concept of harvesting lateral heads as large as apical heads has been discussed (Pornsuriya and Teeraskulchon, 1997; Sato, 2015). Sato (2015) introduced a new technique for harvesting apical and lateral heads from April to May. In this technique, non-woven fabric is used to cover plants in order to protect them from cold temperatures during winter. However, the technique requires as long as seven months for cultivation with a late-maturing cultivar, from transplanting in November to harvest in May. As November and December are usually the months of highest harvest in Japan (Metropolitan Central Wholesale Market, <http://www.shijou-tokei.metro.tokyo.jp/>, 2017), the ideal time for transplanting, with the aim of harvesting from April to May, is in January or February, with early-maturing cultivars. Pornsuriya and Teeraskulchon (1997) limited the number of lateral branches and left one branch on the main stem, but failed to grow the lateral head to a marketable size. Although they did not succeed in growing a large lateral head, Pressman (1985) reported that each lateral head tends to be larger when the number of lateral branches is lower. This implies that the possibility of growing the lateral heads as large as the apical head increases if the number of lateral branches is limited in a suitable cultivar. The new cultivar ‘Yumehibiki’, launched in 2012, has a relatively low number of lateral branches, each of them tending to be large, and is an early-maturing cultivar. Therefore, it is worth examining the application of ‘Yumehibiki’ for harvesting both apical and large lateral heads from April to May by removing the excess lateral branches. Here, this removing process was denominated as “L-shaping”, based on the figure of the

long main stem in a vertical direction with the short branch in a lateral direction (Fig. 1a).

To introduce the new cultivar to each production site, generalized information about temperature to indicate the most suitable transplant and harvest times is necessary. The concepts of base temperatures (BT) and effective heat unit summation (EHUS) are convenient for this. BT is the minimum temperature in which the plants will grow, and EHUS is the sum of effective temperature (ET) for a certain period. ET is the daily mean temperature with the BT subtracted from it. With a linear regression between the periods (P) and temperature summations (TS) for P, Ebata (1990) demonstrated that BT and EHUS can be determined easily. Dufault (1997) showed the EHUS values from transplanting to harvest of four broccoli cultivars, which enabled prediction of harvests at each production site. Similarly, it is possible to adjust the timing of transplanting to allow the harvest of ‘Yumehibiki’ from April to May in each production site by determining its BT and EHUS.

In order to establish this cultivation, we first analyzed the transplant time that would enable harvesting of the apical and lateral heads from April to May. Next, we derived the BT and EHUS from transplanting to the harvesting of apical heads, and the additional EHUS from the apical head harvest to lateral head harvest. Finally, we characterized the lateral branches that were most likely to produce marketable lateral heads in this season.

Fig. 1. (a) The L-shaped figure of broccoli at the time of apical head harvesting. In order to recognize the whole structure easily, all leaves were removed. Capital letters represent the measurements for branch characterization: D, diameter of developing head on branch; T, thickness of branch; L, length of branch; and N, number of leaves on branch. (b) A developed lateral head at the time of harvesting. The large arrow indicates the cut-off section of the apical head and small arrows indicate traces of nipped branches.

Materials and Methods

General conditions for plant growth and experiments

The experiments were conducted in 2016 and 2017 at the Institute of Vegetable and Floriculture Science, Tsukuba, Ibaraki Prefecture, Japan. Each experiment is named by the year (e.g., 2016 experiment) hereafter. In each experiment, broccoli (*Brassica oleracea* L. var. *italica*) cultivar ‘Yumehibiki’ (Nanto Seed Co., Ltd., Japan) seeds were sown in cell trays (25 mL × 128 cells) filled with compost (N:P₂O₅:K₂O = 50:500:100 mg·L⁻¹) (NAPLA type S, YANMAR Co., Ltd., Japan), and grown in a greenhouse (Takahashi et al., 2018). Three weeks after sowing, the seedlings were fertilized with 1 L of OK-F-1 liquid fertilizer (N:P₂O₅:K₂O = 150:80:170 mg·L⁻¹) (OAT Agrio Co., Ltd., Japan) per cell tray. The temperature in the greenhouse was maintained at higher than 10°C. In order not to expose seedlings to the severe cold of the field immediately, they were subjected to low temperatures of more than 1°C for 3 to 5 days just before transplanting. Seedlings with three true leaves were transplanted to the study field with 80 cm between rows and 40 cm between plants (3,000 plants/10a), with black plastic mulch and transparent low plastic tunnels (PVC film, 0.075 mm thickness). The field was fertilized with N:P₂O₅:K₂O = 30:35:24 kg/10a in 2016 in accordance with Koderá (1988), and 39:39:30 kg/10a in 2017 in accordance with Sato (2015). To avoid the intense heat in the daytime and maintain warmth at nighttime, the tunnel was opened in the morning and shut in the evening on sunny days, or kept shut for the whole day on rainy or cloudy days. As the optimum growth of broccoli is obtained when air temperatures average 16–18°C (Le Strange et al., 1996), the tunnel was removed when the daily mean temperature reached around 16°C; this was on April 14 in 2016, and April 10 in 2017. Each plant was L-shaped during cultivation (Fig. 1). Apical heads were harvested when they reached 12 cm in diameter (Fig. 2a), while lateral heads were harvested when they reached 10 cm in diameter (Fig. 2b, c). Fresh weights of heads were measured after removing the leaves and where the length from the top of the head to the cut-off section measured 15 cm (Fig. 2). Lateral heads were classified into marketable or nonmarketable according to the head quality, which was evaluated by appearance, bead uniformity, and smoothness (Fig. 2b, c). The harvested amount was converted into the number of heads and yield per 10a.

1. Effect of the transplanting date on the number of heads, yield, and period of harvest

In the 2016 experiment, seeds were sown on December 15 and 25 in 2015, and January 4 and 14 in 2016 (four sowing dates × two replicates = eight plots, eight plants per plot). The seedlings of these plants were transplanted on January 26 and February 5, 15,

Fig. 2. A standardized (a) apical head (12 cm in diameter), (b) marketable lateral head (10 cm in diameter), and (c) nonmarketable lateral head. The average weight ($\pm$ SE) of each head in all plots in 2016 and 2017 experiments is shown ($n = 17$).

and 25, respectively. Plants were L-shaped when the apical head was harvested. Branches with sizes ranging from medium to large were selected in each plot. In the 2017 experiment, seeds were sown on December 5, 15, and 25 in 2016 (three sowing dates × three replicates = nine plots, 12 plants per plot). The seedlings of these plants were transplanted on January 16, 26, and February 5, respectively. In order to concentrate photosynthates more on one branch, plants were L-shaped at about 10 days before harvesting the apical head. The largest branch was left intact, but if another similarly large branch existed in the opposite direction, it was also left on the stock. The percentage of stocks left with two branches was 26%.

2. Derivation of base temperature and effective heat unit summation for apical and lateral head harvest

The BT (°C) and EHUS (°C·day) for the growth of broccoli were determined by regression analysis of the temperature summations (TS; °C·day) and periods (P; days) from transplanting to apical head harvest of all plots in each year. The inclination and intercept of the regression line indicate the BT and EHUS, respectively, based on the following equation (Ebata, 1990):

$$TS = BT \cdot P + EHUS$$

where TS is the sum of the daily average temperature of the field observation for the period from transplanting to the apical head harvest. The temperature of the field was measured every 30 min in the natural ventilation shelter (CYG-41303, Climatec Inc., Japan) at 20 cm above the ground, indicating the temperature in the plastic tunnels before they were removed (indicated as solid lines and referred to as ‘Field observation’ in Fig. 3). The additional EHUS from the apical head har-

Fig. 3. Daily average temperatures in (a) 2016 and (b) 2017. Field observation (solid line) indicates the value observed in the natural ventilation shelter, which indicates the temperature in the plastic tunnels before their removal, and the temperature in the field thereafter. Meteorological observations (dotted line) indicate the air temperature obtained from the nearest weather station at Tateno, Tsukuba.

vest to lateral head harvest was derived by summing the ET for the period.

3. Branch characterization and lateral head quality

We measured the following parameters of the branches in the January 26 and February 5 transplanting plots in the 2016 experiment at the time of apical head harvesting (Fig. 1a): the diameter of the developing head on the branch (hereafter diameter), if the head was too small to be recognized, it was regarded as 0 mm; thickness of the branch, the longest stem diameter at 1 cm above the joint of the branch and the main stem (hereafter thickness); length of the branch, stem length from the joint to the top of branch (hereafter length); and number of leaves more than 1 cm wide on the branch (hereafter number of leaves). We measured the leaf areas (LA) of branches in the 2017 experiment using an area meter (LI-3100, Meiwafoods Co., Ltd., Japan) when the lateral heads were harvested (Fig. 1b). These factors were compared according to the quality of the lateral heads.

4. Statistical analysis

Statistical analysis was performed using R software (R Core Team, [http://www.R-project.org.](http://www.R-project.org/), 2015).

Results

1. Effect of the transplanting date on the number of heads, yield, and period of harvest

Higher temperatures in the low plastic tunnels (Field observation, in Fig. 3) were maintained than those in the open field (Meteorological observation, in Fig. 3) in 2016 and 2017, and the temperatures after removing the tunnels were also higher than the average value (Fig. 3). Total rainfall amounts from January to May in 2016 and 2017 were 92.3% and 66.1%, respectively, of the average precipitation, 420.8 mm, for 30 years (from 1981 to 2010) (JMA, <http://www.jma.go.jp/jma/menu/menureport.html>, 2017).

In the 2016 experiment, apical heads were harvested from the mid to end of April, and lateral heads were harvested from the end of April to the beginning of May in the January 26 transplanting plot (Fig. 4a). As the transplanting dates were delayed, the harvest periods of both the apical and lateral heads were delayed accordingly (Fig. 4a, b, c, d). In addition, the ratio of marketable lateral heads also decreased accordingly (Fig. 4b, c, d).

In the 2017 experiment, the periods of harvest in the January 16 and 26 transplanting plots overlapped with each other (Fig. 4e, f). The period of harvest was delayed by six to eight days more in the February 5 transplanting plot than those of the January 16 and 26 transplanting plots (Fig. 4g). The mean date of harvest of apical and lateral heads in the January 26 and February 5 transplanting plots in the 2017 experiment was two to three days earlier than that in the plots of the same transplanting dates in the 2016 experiment (Fig. 4a, b, f, g).

All of the apical heads harvested were marketable. The number of apical heads showed no significant difference among the plots of different years or transplanting dates, and was 2,667–3,000/10a (Table 1). The sum of marketable and nonmarketable lateral heads harvested was 2,166–3,000/10a in the 2016 experiment, where one branch was left on each stock, and 2,917–3,500/10a in the 2017 experiment, where one or two branches were left on a stock. Regarding the ratio of marketable lateral heads compared to the number of apical heads, 72% and 29% of the lateral heads in the January 26 and February 5 transplanting plots could be harvested, respectively, whereas marketable lateral heads were rarely harvested in the plots transplanted on February 15 and 25 in the 2016 experiment. The number of marketable lateral heads in the January 26 transplanting plot was significantly higher than those of the others (Table 1). In the 2017 experiment, 79–81% of the marketable lateral heads in the January 16 and 26 transplanting plots and 51% of the marketable lateral heads in the February 5 transplanting plot were harvested. No significant difference was observed among them (Table 1). However, because the weight of

Fig. 4. The number of heads and the harvest period according to the transplanting date. Mean values of the two replicates in the 2016 experiment ((a) to (d)), and three replicates in the 2017 experiment ((e) to (g)) are shown. Black or gray arrows with dates indicate the mean harvest date of the apical and lateral heads, respectively.

a lateral head was about half that of an apical head (Fig. 2), the ratio of yield (total weight) of lateral heads compared to the yield of apical heads was reduced by half against the ratio of the number (Table 2).

2. Derivation of base temperature and effective heat unit summation for apical and lateral head harvests

All parameters of regression analyses of TS by P in the 2016 and 2017 experiments were significantly different to zero ($P < 0.05$), and regression lines showed relatively high coefficients of determination ($R^2 = 0.66$ in 2016, 0.52 in 2017) (Fig. 5). The BT and EHUS ($\pm$ SE) from planting to apical head harvest were estimated as 1.76°C and $747 (\pm 2.7) ^\circ\text{C}\cdot\text{day}$ in 2016, and 1.74°C and $675 (\pm 3.3) ^\circ\text{C}\cdot\text{day}$ in 2017, respectively. Subsequently, the additional EHUS values from apical head harvest to lateral head harvest were calculated as 254 (± 13.9) $^\circ\text{C}\cdot\text{day}$ in 2016, and 204 (± 4.5) $^\circ\text{C}\cdot\text{day}$ in 2017, respectively.

3. Characterization of branches and the quality of lateral heads

The branches that produced marketable heads showed significantly higher values for thickness, length and number of leaves, but not diameter, than those that produced nonmarketable heads in the 2016 experiment (Table 3). The LA values of branches that produced marketable heads were also significantly higher than those that produced nonmarketable heads in the 2017 experiment (Table 4).

Discussion

1. Increased number of heads and yields by lateral head harvest

It was demonstrated that harvesting large lateral heads was possible from April to May with L-shaped 'Yumehibiki' broccoli (Fig. 1). As transplanting started in mid-January and the harvest of lateral heads finished in May, the cultivation period in the field was less than five months. In fact, it was impossible or difficult to harvest large lateral heads in this period with some other cultivars in our preliminary examination (data not

Table 1. Number of heads harvested according to the transplanting date in 2016 and 2017.

Year	Head	Number of heads harvested (per 10a)				
		Jan. 16 ^z	Jan. 26	Feb. 5	Feb. 15	Feb. 25
2016	Apical head	—	3,000 ^y a ^w	2,833 a	2,667 a	2,667 a
	Marketable lateral head	—	2,167 a (72%) ^x	833 b (29%)	0 b (0%)	333 b (12%)
	Nonmarketable lateral head	—	833 b (28%)	2,000 a (71%)	2,167 a (81%)	1,833 a (69%)
2017	Apical head	2,833 a	3,000 a	2,917 a	—	—
	Marketable lateral head	2,250 a (79%)	2,417 a (81%)	1,500 a (51%)	—	—
	Nonmarketable lateral head	1,000 a (35%)	1,083 a (36%)	1,417 a (49%)	—	—

^z Date of transplanting.

^y Mean value of replicates in 2016 (n=2) and 2017 (n=3).

^x Percentage of the number of lateral heads to that of apical heads in the same column.

^w The same letters within the same line indicate not significantly different at $P < 0.05$ by Tukey's test (n=2 in 2016 and n=3 in 2017).

Table 2. Yield according to the transplanting date in 2016 and 2017.

Year	Head	Yield (kg/10a)				
		Jan. 16 ^z	Jan. 26	Feb. 5	Feb. 15	Feb. 25
2016	Apical head	—	1,156 ^y a ^w	1,151 a	1,147 a	1,194 a
	Marketable lateral head	—	433 a (37%) ^x	197 b (17%)	—	82 b (7%)
	Nonmarketable lateral head	—	134 b (12%)	401 b (35%)	450 a (39%)	338 b (28%)
2017	Apical head	1,101 a	1,208 a	1,180 a	—	—
	Marketable lateral head	463 a (42%)	484 a (40%)	315 a (27%)	—	—
	Nonmarketable lateral head	177 a (16%)	211 a (17%)	261 a (22%)	—	—

^z Date of transplanting.^y Mean value of replicates in 2016 (n=2) and 2017 (n=3).^x Percentage of the yield of lateral heads to that of apical heads in the same column.^w The same letters within the same line indicate not significantly different at $P < 0.05$ by Tukey's test (n=2 in 2016 and n=3 in 2017).

shown). Only 'Yumehibiki' was suited to this technique as far as we have tested. Pornsuriya and Teeraskulchon (1997) could not enlarge lateral heads in their experiment, in which only one cultivar 'Mascot' was used. Hence, selecting a suitable cultivar is one of the important factors for harvesting lateral heads.

Although we expected the lateral heads to be as large as apical heads at first, several lateral heads became rough in appearance and lost their market value just before reaching 12 cm in diameter. Therefore, the standard size of lateral heads was determined to be 10 cm in diameter (Fig. 2). In regard to the amount of fertilizer, it was suggested to fertilize the field with 25–30 kg/10a (Kodera, 1988) or 40 kg/10a (Sato, 2015) of N to harvest two heads; thus, we tried fertilizing with 30 kg/10a of N in 2016. However, since the leaves on some of the

lateral branches were a lighter color than those on the main stem, implying a shortage of fertilizer, the field was fertilized with 39 kg/10a of N in 2017. As a result, the number of lateral heads in 2017 increased, and reached 79–81% that of apical heads in the January 16 and January 26 transplanting plots (Table 1); however, the yield was 40–42% because the weight of a lateral head is about half that of an apical head (Fig. 2). The best total marketable yield, 1,692 kg/10a (1,208 + 484 kg/10a) in the January 26 transplanting plot in 2017, significantly exceeded the average yield in Japan, which is 975 kg/10a (MAFF, <http://www.maff.go.jp/j/tokei/>, 2016). Broccoli is usually shipped by a certain number of heads per box according to the size. It is difficult to clearly indicate how much a shipment increases because the standard differs in each production area of Japan. For example, the Japan Agricultural Cooperative (JA) defines the standard as heads 12 cm in diameter should be 12 to a box, and heads 10 cm in diameter should be 16 to a box (JA Zen-Noh Hiroshima, <http://www.jazhr.jp/syukkakikaku/index.html>, 2018). If this standard is applied here, the 81% increase in the number of 10 cm heads (lateral heads) is equivalent to an increase of 61% ($81\% \times 12/16$) in the shipments of 12 cm heads (apical heads).

Fig. 5. The regression analysis of temperature summations (°C·day) and the period (days) from transplanting to apical head harvest.**Table 3.** Characterization of branches according to the quality of lateral heads.

Quality of lateral heads	Diameter (mm)	Thickness (mm)	Length (mm)	Number of leaves
Marketable	17.3 ± 1.8 ^z	15.7 ± 0.6	91.9 ± 4.9	9.2 ± 0.4
Nonmarketable	11.6 ± 2.6	12.6 ± 1.1	72.4 ± 7.4	7.1 ± 0.5
<i>t</i> -test ^y	NS	*	*	**

^z Each value indicates the mean value ± SE in 2016 (n=16–17).^y **, *, and NS indicate significant difference at $P < 0.01$, $P < 0.05$, and no significant difference by *t*-test, respectively (n=16–17).

Table 4. Leaf area of branches according to the quality of lateral heads.

Quality of lateral heads	Leaf area of a branch (cm ²)
Marketable	2,214.3 ± 120.8 ^z
Nonmarketable	1,856.0 ± 86.4
<i>t</i> -test ^y	*

^z Values indicate the mean value ± SE of nine plots in 2017 (three sowing dates × three replicates).

^y * Indicates significant difference at $P < 0.05$ by *t*-test ($n = 9$).

plots, the BT and EHUS were estimated as 1.76°C and 747°C·day in 2016, and 1.74°C and 675°C·day in 2017, respectively (Fig. 5). These values of BT and EHUS enable accurate prediction of the harvest date at each production site (Perry et al., 1993). The high coincidence of BT between the 2016 and 2017 experiments despite the differences in conditions, such as the transplanting date and the amount of fertilizer, enhances the reliability of the result. Our results of the estimated EHUS also seem to be reasonable because the previous study of four cultivars transplanted on February 16 showed that the EHUS from transplanting to finishing harvest ranged from 699–769°C·day (Dufault, 1997). The difference in EHUS between the 2016 and 2017 experiments (747–675 = 72°C·day) may be due to the difference in the amount of fertilizer, the addition of which in 2017 enhanced plant growth and shortened the period of cultivation, but this hypothesis needs to be verified by another experiment.

Based on this BT, the additional EHUS values from the apical head harvest to the lateral head harvest were calculated as 254°C·day in 2016, and 204°C·day in 2017, respectively. Note that this additional EHUS does not mean the whole EHUS for lateral branch growth from the start of elongation to the lateral head harvest, because branches had started to elongate before the apical head harvest. However, this additional EHUS is convenient for practical use to calculate the total EHUS required from planting to lateral head harvest by summing as follows: 1,001°C·day (747 + 254°C·day) in 2016 and 879°C·day (675 + 204°C·day) in 2017. One reason for the difference of 50°C·day (254–204°C·day) in the additional EHUS between the two years may also originate from the difference in the amount of fertilizer. However, because plants in 2017 were L-shaped around 10 days earlier than in 2016, photoassimilate must have become more concentrated in the branch, which may have also shortened the period for lateral head growth in 2017. In addition, although the plastic tunnels were removed in mid-April, maintaining high temperatures at night with the tunnels for the whole cultivation period in order to satisfy the EHUS earlier may have promoted growth and could have affected the period of harvest.

3. Favorable timing for transplanting

Harvesting apical and lateral heads from April to

May was possible by transplanting ‘Yumehibiki’ to our experimental field from January to February (Fig. 4). However, transplanting later should be avoided to increase the quality of lateral heads (Tables 1, 2). The number of abnormal lateral heads increased with the increase in temperature in May (Figs. 3, 4), in accordance with the knowledge that high temperatures impede the development of heads (Farnham and Björkman, 2011). As a result, the number of marketable lateral heads started to decrease in the February 5 transplanting plots in 2016 and 2017, and decreased sharply in the February 15 and 25 transplanting plots (Table 1). The average temperature in the plastic tunnels at the beginning of February (in 2016 and 2017) was 7.1°C, while that in mid-February (in 2016) was 10.7°C.

We stopped transplanting after mid-February in the 2017 experiment, and instead, tried transplanting earlier, on January 16, expecting an earlier harvest period than that of the January 26 transplanting plot. Contrary to our expectation, the mean date of harvest of the January 16 transplanting plot was no earlier than that of the January 26 transplanting plot (Fig. 4e, f). The delay of growth in the January 16 transplanting plot may have been caused by severe cold; the average minimum temperature was –5°C in mid-January in 2017, which could certainly arrest the development of broccoli (Tan et al., 1999). Despite this severe cold, the number of marketable heads was not significantly decreased in the January 16 transplanting plot compared to that of the January 26 transplanting plot (Table 1). This indicates that it was adequate to transplant between the two dates for the highest marketable yield, during which the average temperature was 4.0°C.

Therefore, we concluded that the most favorable timing for transplanting is the time when the average temperature in tunnels reaches 4.0°C but is less than 7.1°C, and it is too late to transplant when the temperature reaches 10.7°C. After transplanting, the period of harvesting for apical and lateral heads can be estimated when the EHUS reaches 675–747°C·day and 879–1,001°C·day, respectively, when the amount of N fertilizer used is 30–40 kg/10a. The most favorable timing for sowing can also be decided by counting backward from the timing of transplanting.

4. Branch characterization and lateral head quality

L-shaping eliminates the risk of lateral heads being distorted by the physical contact of leaves from other branches, and the risk of branches competing for resources against other branches. On the other hand, it is required to select just one branch that seems the most likely to produce marketable lateral heads. Thus, we tried to characterize the branches according to the quality of lateral heads in the 2016 experiment. As mentioned above, most of the lateral heads in the February 15 and 25 transplanting plots were abnormal due to the high temperature, regardless of the characteristics of the

branch. Therefore, only lateral branches in the January 26 and February 5 transplanting plots were used to analyze this. We measured four factors, the diameter, thickness, length, and number of leaves (Fig. 1), and found that branches that eventually produced marketable lateral heads had showed significantly higher values for thickness, length, and number of leaves (Table 3). Firstly, a thicker stem on the lateral branch indicates a higher water and carbon transport capacity (De Schepper and Steppe, 2010) and the tendency to have a larger LA (Vertessy et al., 1995). Secondly, a longer stem on the lateral branch indicates a longer period of vegetative growth (Pressman et al., 1985). Finally, a branch with more leaves has more potential to increase the LA; it was demonstrated that branches with marketable heads showed a significantly larger LA in the 2017 experiment (Table 4). Thus, these factors related to the length of vegetative growth and capacities for translocation and photosynthesis can be reasonable indicators of the future development and quality of the lateral heads. On the other hand, the extent of head development (indicated by diameter) at the moment of apical head harvest was revealed to be less related to the quality (Table 3).

In the 2017 experiment, the number of marketable lateral heads increased more than that in the 2016 experiment (Table 1), the reasons for which seem to be the addition of extra fertilizer, leaving two branches on the main stem, and, where possible, selection of the most developed lateral branches in terms of thickness, length, and number of leaves. As other factors not observed in this study, such as the amount of roots, damage from harvesting of the apical head, and the effect of leaves left on the main stem, may also influence the development of lateral heads, it is difficult to confirm that the distinct criteria of thickness, length, and number of leaves indicate the marketable quality; however, the possibility of producing marketable heads can be increased by selecting branches with the highest values of these three factors.

Taken together, the utilization of lateral heads in L-shaped ‘Yumehibiki’ enhanced yields of broccoli from April to May, and the results of this comprehensive study on temperature requirement and branch characterization suggest that this cultivation method has the potential to resolve the scarcity of broccoli during its off-crop season in Japan.

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