Harvesting Two Heads from One Stock of Broccoli (Brassica oleracea L. var. Italica) ‘Yumehibiki’ by Pinching the Shoot Apical Bud in Autumn Cropping

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Axillary buds of broccoli (Brassica oleracea L. var. Italica) develop and produce lateral heads after the apical heads have been harvested; however, lateral heads are not used because of their small size, and only one apical head is generally harvested from one plant. In this study, we aimed to establish a new method to harvest two heads of 12 cm diameter from a plant by pinching the apical bud and growing two axillary buds (“V-shaping” process) in autumn cropping. First, we measured the probability of axillary bud generation (PA) at each leaf axil and calculated the integration of the PA (IPA). The PA from the 5th to 8th true leaves was especially high, and the IPA reached 4.7. Next, we investigated the period of harvest and yield of heads at different times (3rd, 5th, 7th, 9th, 11th, 13th, and 15th leaf stage) of V-shaping in Field 1 (Ibaraki Prefecture, Tsukuba City). In V-shaped plots from the 7th to 11th leaf stages, the number of marketable heads significantly increased in comparison to that of the control. It increased by 61% of that of the control at the 11th leaf stage. However, the period of harvest was delayed, and the quality of heads deteriorated by cold injury when V-shaping was conducted from the 11th stage onward. Finally, we assessed the applicability of V-shaping cultivation in other fields. V-shaping was conducted from the 9th to 11th leaf stage. The number of marketable heads increased by 69 and 62% in Field 2 (Ibaraki Prefecture, Tsukubamirai City) and Field 3 (Nara Prefecture, Uda City), respectively. However, it only slightly increased in Field 4 (Mie Prefecture, Tsu City). Comparison of cultivation conditions at these 4 fields revealed that early transplantation, to allow an approximate 300°C day increase in effective heat unit summation for harvesting before the daily minimum temperature fell below approximately 0°C, was important. In addition, improving the drainage of the field seems important, and the input of manure compost (long-term fertilizer effect) may improve the quality and yield of heads. Thus, we concluded that V-shaping cultivation enabled the harvesting of two heads by V-shaping and increased the number of marketable heads by more than 60% in a wide area.

Key Words: axillary bud, decapitation, lateral branch, nipping, vegetable production.

Introduction

In Japan, the total growing area for vegetables has decreased by 6.7% in the past 10 years, from 505,500 ha in 2006 to 471,600 ha in 2016, whereas the growing area for broccoli (Brassica oleracea L. var. Italica) has increased by 28.1%, from 11,400 ha to 14,600 ha, in the same period (MAFF, http://www.maff.go.jp/j/tokei/, 2016), since the demand for broccoli has increased.

Cultivars of broccoli that generate fewer lateral branches are generally preferred because only the apical head of the main stem is usually harvested (Le Strange et al., 1996). Conversely, to increase the yield, methods to harvest two large and commercially viable heads from one plant using lateral branches have been reported (Kodera, 1988; Pornsuriya and Teeraskulchon, 1997; Sato, 2015; Takahashi et al., 2018). Broccoli likely forms a premature flower head, called “buttoning”, when exposed to low temperatures during its early growth stages (Farnham and Björkman, 2011; Miller et al., 1985; Wurr et al., 1995). Sato (2015) transplanted a cultivar that was insensitive to cold in November and covered them with non-woven fabric to overwinter and reported that the plants could actively produce lateral
branches without buttoning, and that both apical and lateral heads could be harvested in April and May. However, whether the method can be applied to other seasons or areas is not yet known. Kodera (1988) showed increased yields by pinching the apical bud and harvesting two heads from one plant; however, the heads did not always reach the standard size for market (12 cm in diameter) in autumn, even though the plants were grown with a sparser planting density (about 2,800 plants per 10 a) than the typical density used in Japan (3,000–4,000 plants per 10 a). Pornsuriya and Teeraskulchon (1997) attempted to harvest a lateral head after an apical head was harvested by leaving one branch on the main stem but failed to grow lateral heads of a marketable size. In a previous study, we established a method called “L-shaping”, which enabled the harvesting of both apical and lateral heads from April to May by limiting the number of lateral branches to one or two before the apical head was harvested using the cultivar ‘Yumehibiki’, which is characterized by large lateral heads (Takahashi et al., 2018). The lateral heads produced by L-shaping were 10 cm in diameter. Although the heads 10 cm in diameter are less valuable than apical heads with a diameter of 12 cm, they still have marketability because the period from April to May is an off-crop season of broccoli in Japan (Sato, 2015; Takahashi et al., 2018). On the other hand, the heads 10 cm in diameter may not be acceptable from autumn to winter when the amount of broccoli is relatively abundant in the market (MCWM, http://www.shijou-tokei.metro.tokyo.jp/, 2018). Therefore, new techniques to produce two heads of 12 cm in diameter are needed, especially in autumn cropping.

Plants have the characteristic of apical dominance; the apical bud grows predominantly and inhibits the outgrowth of axillary buds (Cline, 1991; Phillips, 1975; Tanaka et al., 2006). Branches of intact plants with vigorous apical bud growth are not essential for the life cycle, and excessive branching can even be costly for ensuring the concentration of resources to the main stem (Doebley et al., 1997; Dun et al., 2006). Hence, the amount of resources provided to lateral heads is likely to be insufficient to become as large as the apical head, if the strong sink (apical bud) exists. Therefore, a promising way of harvesting two heads involves the pinching of the apical bud and growing only lateral heads, as revealed by Kodera (1988). This method with ‘Yumehibiki’ may enable the establishment of a practical method for harvesting two heads. In this study, the process of pinching the apical bud and leaving two axillary buds was denominated as “V-shaping”, after the figure framed by the branches (Fig. 1).

To establish the method of harvesting two heads of 12 cm in diameter in broccoli in autumn cropping by using V-shaping cultivation with a typical planting density (> 3,000 plants per 10 a), we aimed to elucidate the proper timing (leaf stage) for V-shaping to obtain the highest yield and show the applicability of this cultivation to various fields. First, we measured the probability of axillary bud generation (PA) at each leaf axil and calculated the integration of the PA (IPA) of a stock of broccoli to estimate the proper leaf stage for V-shaping. Next, we investigated the period of harvest and the yield of heads according to the different timings of V-shaping. Finally, we determined the applicability of this cultivation to three other fields in eastern and western Japan and found several important aspects for V-shaping and the value of effective heat unit summation (EHUS) from transplanting to harvest.

**Materials and Methods**

1. **Probability of axillary bud generation according to leaf position (Exp. 1)**

The experiments were conducted in 2017 in a field at NARO, Tsukuba City, Ibaraki Prefecture, Japan (Field 1), where the latitude, longitude, and altitude are 36°01’ N, 140°06’ E, and 21.5 m, respectively. Early-maturing broccoli (Brassica oleracea L. var. Italica) ‘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 were grown under a rain shelter. From two weeks after sowing, the seedlings were fertilized with N:P₂O₅·K₂O = 300:300:300 mg in the form of liquid fertilizer (OAT Agrio Co., Ltd., Japan) per cell tray. Seedlings were transplanted to the field with 160 cm between rows, two lines of plants in a...
row, 60 cm between two lines, and 40 cm between plants. The dates of sowing and transplanting and conditions of the field are shown in Table 1. The field was fertilized with chemical fertilizer, half of which was slow-release fertilizer. When apical heads reached 12 cm in diameter, we confirmed the presence of an axillary bud at each leaf axil by the naked eye. The number of axillary buds at a certain leaf axil in one replicate was divided by the number of plants in the replicate, and the value was expressed as the probability of axillary bud generation (PA). The integrated value of PA from the leaf axil of cotyledon to a certain leaf axil was expressed as the integration of the PA (IPA).

In all, eight plants were included in a replicate, and three replicates were performed.

2. Elucidation of the proper leaf stage for V-shaping (Exp. 2)

The cultivation conditions were the same as those in Exp. 1. We defined the leaf stage as x-th, when the x-th true leaf reached 2 cm in width and until the next true leaf also had the same width. If an apical bud was pinched at the x-th stage with the x-th true leaf in a plot, the plot was referred to as a “V-shaped plot at the x-th leaf stage”. The control plot and seven V-shaped plots (x = 3, 5, 7, 9, 11, 13, 15) were arranged, and the apical buds of each V-shaped plot were pinched on August 31 and September 6, 11, 15, 20, 25, and 29 in 2017, respectively. In all, 10 plants were included in a plot, and all plots had three replicates. When axillary buds started to elongate after pinching, two buds (the largest bud and the bud in the opposite direction from right above) were left intact, whereas the other buds and upper leaves that would become barriers for the two buds to elongate were removed. Heads were harvested when they reached 12 cm in diameter, and the length from the top of the head to the cut-off section were ensured to be 15 cm. The fresh weight (FW) of heads was measured after the leaves on the head were removed, since the length of leaf stalks left were within the width of the head diameter. The harvested amount was converted to the number of heads and yield per 10 a. The quality of heads was classified into ‘marketable’ or ‘non-marketable’ according to the appearance and existence of some disorders. Heads with even bead size, smooth surface, and solid dome were regarded as marketable (Dufault, 1996; Farnham and Björkman, 2011). Non-marketable heads were further classified into three categories: inferior shape (deformation, flat dome, loose head, and uneven surface, including “cateye”), cold injury (chlorosis of flower bud and anthocyanin coloration), and others (diseases, brawn beads, and leafy head). The first head harvested from a certain plant was referred to as “1st” and the second head was referred to as “2nd”.

3. Applicability to various fields (Exp. 3)

The experiments were conducted in 2017 at Fields 2–4 with the cultivar ‘Yumehibiki’. The method of cultivation, schedule of sowing and transplanting, amount of fertilizer, use of covering material, and planting density followed the practical methods for each field are shown in Table 1. Plants were V-shaped at the 9th to 11th leaf stages. The harvested amount was converted to the number of heads and yield per 10 a. The days after transplanting to the mean date of harvest in a plot was expressed as DAT. The EHUS for DAT was derived for each field with a base temperature of 1.75°C (Ebata, 1990; Takahashi et al., 2018).

1) Cultivation at Field 2

The cultivation was conducted in a field at NARO, Tsukubamirai City, Ibaraki Prefecture, Japan, where the latitude, longitude, and altitude are 36°00' N, 140°02' E, and 22.2 m, respectively. The conditions of sowing and nursing seedlings were the same as those in Exp. 1. Seedlings were transplanted to the field with 160 cm

| Field | Date of sowing | Date of transplanting | Period of nursing seedlings (days) | Planting density (plants per 10 a) | Covering material | Soil type | Fertilizer components originally contained in the field (mg/100 g dried soil) | Total amounts of chemical fertilizer (kg/10 a) | Compost (per 10 a) | Soil composition (%) |
|-------|----------------|-----------------------|-----------------------------------|----------------------------------|------------------|-----------|----------------------------------|----------------------------------------|----------------|----------------------|
|       | Date: Aug. 1 | Date: Aug. 25 | 24 | 3,125 | Black plastic mulch | Light colored andosol | 2.0 | 2.9 | 31 | 30 | 25 | --- | 19.4 | 21.3 | 37.5 | 21.7 |
| 2     | Date: Aug. 2 | Date: Aug. 24 | 23 | 3,125 | Light colored andosol | 1.0 | 2.7 | 48.5 | 30 | 30 | 25 | --- | 16.5 | 21.3 | 39.4 | 22.8 |
| 3     | Date: Aug. 2 | Date: Aug. 22 | 20 | 4,082 | White plastic mulch | Sandy loam | 1.5 | 62.0 | 33.9 | 10 | 6 | 7 | 8 t of cattle manure compost | 57.1 | 19.6 | 8.1 | 15.2 |
| 4     | Date: Aug. 4 | Date: Aug. 31 | 27 | 4,762 | Non-volcanic andosol | 0.8 | 49.9 | 69.0 | 30 | 10 | 30 | --- | 16.3 | 16.4 | 33.3 | 34.0 |

* The year of all dates is 2017.
between rows, two lines of plants in a row, 60 cm between two lines, and 40 cm between plants. The field was fertilized with chemical fertilizer, half of which was slow-release fertilizer, and cattle manure compost was also applied at 2 t/10 a (Table 1). The apical buds of the V-shaped plots were pinched on September 20. In all, 20 plants in a plot and both the control and V-shaped plots had two replicates. Heads were harvested and processed as per the methods described in Exp. 2.

2) Cultivation at Field 3

The cultivation was conducted on a farm in Uda City, Nara Prefecture, Japan, where the latitude, longitude, and altitude are 34°31' N, 136°56' E, and 317.4 m, respectively. Seeds were sown in cell trays (14 mL × 200 cells) filled with compost (N:P:K = 85:90:85 mg L⁻¹; TM-1; TAKII & Co., Ltd., Japan) and were grown in a greenhouse. Seedlings were transplanted to the field with 140 cm between rows, two lines of plants in a row, 40 cm between two lines, and 35 cm between plants. The field was fertilized with chemical fertilizer, and cattle manure compost was also applied at 8 t/10 a (Table 1). The apical buds of the V-shaped plot were pinched on September 20. In all, six plants were included in a plot, and both the control and V-shaped plots had two replicates. Heads were harvested and processed as those in Exp. 2 except for the removal of all leaf stalks.

3) Cultivation at Field 4

The experiments were conducted in a field at NARO, Tsu City, Mie Prefecture, Japan, where the latitude, longitude, and altitude are 34°46' N, 136°26' E, and 58.7 m. The condition of sowing was the same as that in Exp. 1. Seedlings were grown in a greenhouse and provided with nourishing solution (N:P:K = 33:15:51 mg L⁻¹; OAT Agrio Co., Ltd., Japan) once a day. The seedlings were transplanted to the field with 60 cm between rows and 35 cm between plants. The field was fertilized with N:P:K = 10:10:10 kg/10 a, all of which was slow-release fertilizer, and was additionally fertilized with N:P:K = 20:0:20 kg/10 a on September 29 (Table 1). The apical buds of the V-shaped plot were pinched on September 28. In all, 20 plants were included in a plot, and both the control and V-shaped plots had two replicates. Heads were harvested and processed as per the methods described in Exp. 2.

4. Statistical analysis

Statistical analysis was performed using R software (R Core Team, http://www.R-project.org., 2015). To detect the effect of V-shaping and the field on the number of marketable heads, marketable yield, and EHUS in Exp. 3, a two-way analysis of variance (ANOVA) was conducted.
The 11th leaf stage compared to that in the control plot. The major reason for the degradation of the heads in the V-shaped plots from the 5th to 11th leaf stages was the inferior shape (Table 2). However, both the number of heads and the rate of marketable heads tended to decrease in the V-shaped plots from the 13th leaf stages onward because of cold injury (Table 2).

3. Applicability to various fields (Exp. 3)

1) Field 2

In the control plot, the apical heads were harvested from mid-October to early-November (Fig. 4a-1). In the V-shaped plot, heads were harvested from early-November to mid-December with a high rate of marketability, resulting in an increase in the number of marketable heads to as much as 69% (Fig. 4a-2; Table 3).

2) Field 3

In the control plot, apical heads were harvested from early- to mid-October (Fig. 4b-1). In the V-shaped plot, heads were harvested from mid- to late-November, resulting in an increase in the number of marketable heads by as much as 62% (Fig. 4b-2; Table 3). Since the method of processing heads (leaf stalks on heads were completely removed) was different from that in the other fields, the FW of a marketable head was lighter than that in the other fields in both plots.

3) Field 4

In the control plot, apical heads were harvested from late-October to mid-November (Fig. 4c-1). In the V-shaped plot, heads were harvested from late-November to mid-February, although the number of marketable heads did not greatly increase because of the degradation of their quality by cold injury (Fig. 4c-2; Table 3).

4) EHUS in Fields 1–4 and two-way ANOVA of V-shaping and fields

The DAT in the control plots ranged from 59–70 days, and in the V-shaped plots from 79–130 days (Table 4). The EHUS for the DAT in the control plots ranged from 930–1,223°C day, and in the V-shaped plots from 1,234–1,546°C day (Table 4). Except for the interaction effect on EHUS, the effects of V-shaping, field, and their interaction on the number of marketable heads, marketable yield, and EHUS were detected (Table 5).

Discussion

1. Proper leaf stage for V-shaping

Pinching an apical bud can release axillary buds of broccoli from apical dominance and promote axillary bud elongation (Kodera, 1988; Pressman et al., 1985); however, at least two axillary buds are required for V-shaping. Because not all axillary buds are capable of elongating vigorously, and because the directions of two buds should be opposite to reduce the risk of physical contact with each other (Takahashi et al., 2018), selecting two ideal buds out of several candidates is necessary.

Exp. 1 revealed that the PA of ‘Yumehibiki’ differed according to the position of axils and was high from the axil of the 5th to 8th true leaves but became lower with
the distance from these axils (Fig. 2). Since the IPA value exceeded 2 at the 6th true leaf, V-shaping should be conducted from the 7th leaf stage onward. In fact, \( \text{Number of heads (per 10 a)} \)

| Number of heads (per 10 a) |
|-----------------------------|
| 500                        |
| 1,000                      |
| 1,500                      |

(a-1) 1st marketable
2nd marketable
Nonmarketable
0
500
1,000
1,500
(a-2)
1st marketable
2nd marketable
Nonmarketable
0
500
1,000
1,500

(b-1) 1st marketable
2nd marketable
Nonmarketable
0
500
1,000
1,500
(b-2)
1st marketable
2nd marketable
Nonmarketable
0
500
1,000
1,500

(c-1) 1st marketable
2nd marketable
Nonmarketable
0
500
1,000
1,500
(c-2)
1st marketable
2nd marketable
Nonmarketable
0
500
1,000
1,500

Fig. 4. Number of heads and the period of harvest according to the experimental field. (a-1) Control and (a-2) V-shaped plots in Field 2; (b-1) control and (b-2) V-shaped plots in Field 3; (c-1) control and (c-2) V-shaped plots in Field 4. Mean values of two replicates are shown. The 1st and 2nd marketable heads from one stock are shown in black and gray, respectively. The 1st and 2nd nonmarketable heads are shown in a dotted pattern.

| Plot | Fresh weight of a marketable head (g) | Number of heads (per 10 a) | Number of marketable heads (per 10 a) | Marketable yield (kg/10 a) | Heads (%) |
|------|--------------------------------------|-----------------------------|---------------------------------------|-----------------------------|-----------|
|      |                                      | a                         | d                                      | bc                          | 1,132     | 100       | a*  | 0  | 0  | 0  | 75.0 | — | 0 | 25.0 | 0  |
| Control | 362 (362)                            | a*                         | 3,125                                  | d                           | 3,125     | bc        | 1,132 | a  | 106 | (9) | 9 | 75.0 | — | 0 | 25.0 | 0  |
| 3rd   | 374 (103)*                            | —                          | 379 (12)                               | —                           | 284 (9)   | —         | 106   | (9) | —   | —   | 87.5 | ab | 10.5 | 0  | 2.0 |
| 5th   | 281 (78)                             | b                          | 4,546 (145)                            | c                           | 3,977 (127)| ab        | 1,120 | (99)| a   | 1,215 (107) | a  | 80.0 | bc | 16.7 | 0  | 3.3 |
| 7th   | 267 (74)                             | b                          | 5,682 (182)                            | ac                          | 4,546 (145)| a         | 1,120 | (99)| a   | 1,215 (107) | a  | 80.0 | bc | 16.7 | 0  | 3.3 |
| V-shaped | 9th | 270 (75)                             | b                          | 6,156 (197)                            | a                          | 4,830 (155)| a         | 1,306 | (115)| a   | 1,306 (115) | a  | 82.8 | bc | 9.4  | 3.1 | 4.7 |
|        | 11th | 263 (73)                             | b                          | 6,061 (194)                            | ab                         | 5,019 (161)| a         | 1,320 | (117)| a   | 1,320 (117) | a  | 82.8 | bc | 9.4  | 3.1 | 4.7 |
|        | 13th | 277 (77)                             | b                          | 5,587 (179)                            | ac                         | 3,693 (118)| ac        | 1,029 | (91) | ab  | 1,029 (91)   | a  | 66.1 | bc | 8.5  | 18.6 | 6.8 |
|        | 15th | 271 (75)                             | b                          | 4,924 (158)                            | bc                         | 2,368 (76) | e         | 653   | (58) | b   | 653 (58)   | b  | 48.1 | e  | 11.5 | 34.6 | 5.8 |

* The leaf stage of pinching.

% Percentage (%) of the number of heads or the fresh weight of the plot to that of the control.

The data were statistically analyzed after arcsine transformation.

Because the number of axillary buds was always restricted to two, the increase of the IPA value became less effective with an increase in the number of heads in the V-shaped plots from the 7th leaf stage onward. However, the high IPA value enabled the selection of two ideal buds, which were in opposite directions and elongating vigorously, resulting in the slight increase in the number of marketable heads in the V-shaped plots from the 7th to the 11th leaf stage (Table 2). On the other hand, if the release of the apical dominance is delayed, the period of harvest is successively delayed (Fig. 3), which increases the risk of encountering low temperature and causing cold injury in the V-shaped plots from the 11th to 15th leaf stage (Table 2). Thus, V-shaping at such late stages is also unfavorable regardless of the high IPA value.

Therefore, we concluded that the 7th to 11th leaf stage is the optimum period for conducting V-shaping during the autumn cropping of ‘Yumehibiki’. In terms of the higher IPA value, plants were V-shaped at the 9th to 11th leaf stages in Exp. 3.

Table 2. Effects of V-shaping on the number of heads, yield, and quality of broccoli according to the stage of pinching.
Table 3. Effects of V-shaping on the number of heads, yield, and quality of broccoli in Fields 2–4.

| Field | Plot     | Fresh weight of a marketable head (g) | Number of heads (per 10 a) | Number of marketable heads (per 10 a) | Marketable yield (kg/10 a) | Heads (%) |
|-------|----------|---------------------------------------|---------------------------|---------------------------------------|---------------------------|-----------|
|       |          |                                        |                           |                                       |                           |           |
| 2     | Control  | 364                                    | 3,125                     | 3,047                                 | 1,108                     | Marketable |
|       | V-shaped | 284 (78)†                             | 5,313 (170)               | 5,156 (169)                           | 1,463 (132)               | 97.5      |
| 3     | Control  | 229                                    | 4,082                     | 4,082                                 | 934                       | 100.0     |
|       | V-shaped | 203 (89)                              | 8,164 (200)               | 6,594 (162)                           | 1,394 (149)               | 80.8      |
| 4     | Control  | 283                                    | 2,734                     | 2,656                                 | 751                       | 97.1      |
|       | V-shaped | 248 (88)                              | 3,984 (146)               | 3,125 (118)                           | 778 (104)                 | 78.4      |

* Percentage (%) of the number of heads or fresh weight of the plot to that of the control in the same field.

Table 4. Days after transplanting (DAT) to the mean date of harvest in the control and V-shaped plots, its effective heat unit summation (EHUS), and the increase of EHUS by V-shaping in four experimental fields.

| Field | Control | DAT (day) | A: EHUS (°C day) | V-shaped | DAT (day) | B: EHUS (°C day) | B-A: Increase of EHUS by V-shaping (°C day) |
|-------|---------|-----------|-----------------|----------|-----------|-----------------|---------------------------------------------|
|       |         |           |                 |          |           |                 |                                             |
| 1z°   | 63      | 1,125     |                 | 92       | 1,376     |                 | 251                                         |
| 2     | 59      | 1,097     |                 | 93       | 1,402     |                 | 305                                         |
| 3     | 50      | 930       |                 | 79       | 1,234     |                 | 304                                         |
| 4     | 70      | 1,223     |                 | 130      | 1,546     |                 | 323                                         |
| Average† | 61 ± 4 | 1,094 ± 61|                 | 99 ± 11  | 1,390 ± 64|                 | 296 ± 16                                    |

* The data of V-shaped in Field 1 are those of the 11th leaf stage plot in Exp. 2. Data are mean values of replicates (n = 3 in Field 1, n = 2 in Fields 2–4).
† The values were mean data of four fields ± SE (n=4).

Table 5. Results of the two-way analysis of variance of V-shaping (V), field (F), and their interactions (V × F) on the number of marketable heads (per 10 a), marketable yield (kg/10 a), and EHUS (°C day).

| Source | Number of marketable heads | Marketable yield | EHUS |
|--------|---------------------------|------------------|------|
| V      | ***                       | ***              | ***  |
| F      | ***                       | ***              | ***  |
| V × F  | ***                       | **               | NS (P = 0.89) |

* ***: P < 0.001, **: P < 0.01, *: P < 0.05, NS: not significant.

2. Characteristics of V-shaping cultivation

Although the period of harvest in the V-shaped plot was later than that in the control, V-shaping cultivation enabled the harvesting of two heads of 12 cm in diameter from one plant while retaining the standard planting density and resulted in a 61% increase at most in the number of marketable heads (Table 2). By delaying harvest, the risk of encountering a low temperature increased; however, it may be useful to disperse or extend the period of harvest and shipment. The FW of a marketable head decreased by 11–27% in the V-shaped plots in each field (Tables 2 and 3), mainly because of the thinner stems rather than the heads in the control plots. However, in Japan, since the standard of shipment is decided by the diameter of heads (Takahashi et al., 2018), the stem being thinner does not matter for shipment if the head diameter is at least 12 cm.

Second to cold injury, the major problem leading to the reduction of head quality was the inferior shape of heads (Table 2). One reason for the inferior shape was the physical contact of leaves to heads. The density of plants was virtually increased in the V-shaped plots. Planting density may need to be decreased, or leaves should be cut as necessary. Another case of inferior shape was flat dome or loose head. Sato (2015) suggested that N = 40 kg/10 a is optimum for harvesting two heads, but the amount of fertilizer used in Exp. 2 was only N = 30 kg/10 a without manure compost. A reduced amount of fertilizer may reduce the volume of florets, resulting in a flat dome or loose head. The marketable yields were higher in the V-shaped plot in Fields 2 and 3, where manure compost had been inputted, than those in any V-shaped plot in Fields 1 and 4 (Tables 2 and 3). Although the amount of chemical fertilizer used in Field 3 was only N = 10 kg/10 a, cattle manure compost was applied at as much as 8 t/10 a (Table 1), which seemed a large quantity of fertilizer altogether. Since the period of cultivation extends and the
amount of harvest increases in V-shaping cultivation, a long-term fertilizer effect and a large amount of fertilizer by compost may be important. Therefore, planting density and the amount of fertilizer need to be further investigated.

3. Applicability to various fields (Exps. 2, 3)

Hereafter, “Field 1” refers to the result of the V-shaped plot at the 11th leaf stage in Exp. 2 unless otherwise specified. Field 2 was only 7 km distant from Field 1 because Field 2 was expected to reproduce the results of Field 1, with minor differences in the cultivation methods and weather conditions (Supplemental Table 1; Supplemental Fig. 1). Fields 3 and 4 were selected as the representative fields in western Japan, which were about 400 and 350 km west-southwest of Field 1, respectively. Experiments in this study were conducted only in a year, however, the reliable properties concerning the V-shaping cultivation were revealed based on the multi-locational experiment, Exp. 3.

The number of marketable heads in the V-shaped plots in Fields 1–3 increased by more than 60%, whereas those in Field 4 increased only slightly (Tables 2 and 3). As we succeeded to increased yields of broccoli greatly by V-shaping in Fields 1, 2, and Field 3, where cultivation conditions of the listed items in Table 1 (planting density, the use of covering material, soil type, etc.) were largely different, the applicability of V-shaping to various fields seems high.

In terms of the date of transplanting, it was delayed by 6–9 days in Field 4 compared to those in the other fields (Table 1). Considering the EHUS, the growth when the temperature is high on one day can be equivalent to that when the temperature is low across several days (Ebata, 1990). In other words, a few days delay of transplanting in summer could cause a large delay in harvest in winter. In fact, the difference in DAT between Field 4 and the other fields expanded by 7–20 days in the control plots and 37–51 days in the V-shaped plots (Table 4). As a result, the heads in the V-shaped plot in Field 4 had been exposed to severe cold and stopped growing or caused quality degradation before harvesting them all. Furthermore, Field 4 had more rainfall during the experiments than the average value for 30 years (Supplemental Table 1) and the drainage at the field was poor because of the low rate of sand and the high rate of clay (Table 1), which resulted in flooding repeatedly after rainfall. Excessive soil moisture is known to hinder the growth of broccoli (Gutezeit, 2004; Nakano et al., 2017). Therefore, it is assumed that the growth in Field 4 was delayed or even stopped for a while by flooding, resulting in the increase of EHUS (Table 4). Thus, the reasons for the slight increase in the number of marketable heads in the V-shaped plot in Field 4 seem to be the delay of transplanting and flooding.

Cultivation conditions, such as the soil property, the use of covering material, the amount of fertilization and sunshine duration, were different among the four fields (Table 1; Supplemental Table 1). Thus, the EHUSs seem to be differently estimated according to the field (Tables 4 and 5). However, the interaction effect of V-shaping and field was not detected in the EHUS (Table 5). This means that the increase in EHUS by V-shaping was not significantly different according to the field. In fact, the increases in EHUS in the V-shaped plots were almost the same value: around 300°C day regardless of the field (Table 4). Therefore, the delay of the harvesting period equivalent to about 300°C day must be counted before starting the V-shaping cultivation. The transplanting date should also be advanced as necessary.

Cold injury, occurring at below 0°C, deteriorates the quality of broccoli (Tan et al., 1999); in fact, the degradation of head quality by cold injury was increased in the V-shaped plots in Field 1 (11th, 13th, and 15th leaf stage) in late-December (Table 2; Fig. 3f–h) and in Field 4 from late-January onward (Table 3; Fig. 4c-2). These timings corresponded to the severe cold period when the daily minimum temperature fell greatly below 0°C (~3 to ~7°C) (Supplemental Fig. 1). Although it is difficult to suggest the exact temperature causing cold injury in this study, a minimum temperature of 0°C can be the approximate lowest limit to avoid cold injury. It suggests that V-shaping cultivation seems to be applicable to warm areas where the minimum temperature does not become as cold in winter. Even in cooler areas, V-shaping cultivation can be applied by starting early to finish harvesting before the arrival of severe cold.

We only investigated V-shaping cultivation to harvest in autumn and winter seasons in this study; however, the cultivar ‘Yumehibiki’ itself has been demonstrated to be applicable to the spring season (Takahashi et al., 2018). Therefore, V-shaping cultivation with ‘Yumehibiki’ is likely to be applicable to other seasons such as spring or early-summer. However, the PA or IPA can differ according to the season and the additional examinations to clear the appropriate stage for V-shaping in other seasons are necessary.

We only used ‘Yumehibiki’, which is characterized by large lateral heads (Takahashi et al., 2018), but we have already seen the applicability of V-shaping methods in several cultivars which can produce axillary branches vigorously (data not shown). Selecting proper cultivars according to the season or area is also important for practical application.

We concluded that it is possible to increase the number of marketable heads of 12 cm in diameter by more than 60% in broad areas, using the ‘Yumehibiki’ cultivar planted at a practical density (> 3,000 plants per 10 a) by V-shaping at the 7th to 11th leaf stage allowing an approximate 300°C day increase in EHUS for harvesting before the minimum temperature falls below approximately 0°C. Because the period of harvest in the
V-shaping plot was delayed inevitably, transplanting early seems better to avoid cold injury. In addition, improving the drainage of the field seems important not to hinder the growth, and input of manure compost (a long-term fertilizer effect and a large amount of fertilizer) may improve the quality and yield of heads. More studies are necessary to determine the amount of fertilizer, planting density, and evaluation of profit in relation to labor invested in V-shaping for practical purposes; nonetheless, the possibility of harvesting two heads by V-shaping was shown in this study.

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