JARQ 57 (1), 13-20 (2023) https://www.jircas.go.jp

Evaluation of the Relationship Between Growth Parameters for Spring-sown Onion Cultivation in Tohoku, Japan

Chisato YAMAGUCHI, Takehiko YAMAMOTO*, Daisuke YAMAUCHI and Takato MURO

Tohoku Agricultural Research Center, National Agriculture and Food Research Organization, Morioka, Japan

Abstract

Onion is one of the most productive vegetables in Japan, and onion growth models have been developed to predict its yield. However, onion growth is complex, and the selection of simple parameters is required to estimate bulb weight. This study utilized a 2-year dataset from a sequential growth study of spring-sown onions in the northeastern region of Japan to evaluate the correlation among growth parameters and to determine suitable parameters for estimating the dry weight of bulbs *via* multiple regression analysis. The results indicated that when bulb dry weight was the objective variable, the coefficients of determination of the single regression equation with plant height and leaf area as explanatory variables were 0.553 and 0.508, respectively, and the leaf parameter explained more than 50% of variance in bulb dry weight. Furthermore, the coefficient of determination was 0.912 when the leaf sheath basal diameter (ball width of the bulb) was used as an explanatory variable to explain the bulb dry weight. This indicates that there is a gap between the top and bulb growth. This study revealed the important parameters for predicting onion yield and demonstrated the switch in onion development from tops to bulbs.

Discipline: Crop Science

Additional key words: bulb development, growth parameters, leaf sheath basal diameter, spring-sown onion cultivation

Introduction

Onion (*Allium cepa* L.) is an important crop worldwide. In Japan, it is the third most produced vegetable, after potato and cabbage (e-Stat 2018), and accounted for 25,600 ha of the cultivation area and approximately 1.2 million tons of annual production in 2017 (FAOSTAT). Hokkaido is the largest production prefecture in Japan, followed by Saga and Hyogo, which account for 64.7%, 10.5%, and 8.4% of the total shipping volume, respectively (e-Stat 2018). The period from June to July is the lean season in the domestic onion market and when the import volume increases. The cultivation method of spring-sown onions was developed in the Tohoku region to supply onions during this season, and its cultivation area is progressively increasing (Yamasaki et al. 2017, Muro et al. 2020).

Yield instability is a problem in the emerging regions of onion cultivation. In the Tohoku region, such instability occurs due to various climatic and soil differences. For farmers with less experience in onion cultivation, it is difficult to obtain a constant yield of 5 t per 10 a and to identify the reason for the yield decrease. To date, only post-harvest analysis has been conducted, which does not help in identifying the cause of the onion yield decline. To elucidate the cause of the yield decrease in onions, analysis of the growth process is necessary. However, there are a number of parameters involved in growth evaluation, and it is difficult to analyze all of them in the field, which is a major reason the less-experienced farmers have a poor understanding of the accurate state and volume of onion growth and could miss the opportunity to recognize early symptoms of poor growth. Therefore, finding an index for onion growth that can be evaluated by each farmer at the field level will contribute to the stable production of onions in

*Corresponding author: tyamamt13@affrc. go. jp

Received 2 February 2022; accepted 9 May 2022.

emerging production areas.

Previous studies on onion production have been conducted under various conditions, such as fertilizer application (Usuki et al. 2015; Suesada et al. 2018; Usuki & Muro 2018; Usuki et al. 2019; Kudo et al. 2020, 2021), irrigation (Nakano & Okada 2012, Abdelkhalik et al. 2019), cropping type (Kinoshita et al. 2018; Ikeda et al. 2019, 2020), and alternate cultivation methods (Brewster 2008; Katayama & Yamasaki 2014, 2015). Usuki et al. (2019) reported that the number of expanded leaves can be accurately estimated from the accumulated daily air temperature data, suggesting that the onion growth stage can be estimated from the air temperature. The ratio of the diameter of the neck to that of the basal leaf sheath has been used for the assessment of onion bulbing (Brewster 2008). These techniques are useful for evaluating the onion growth stages.

Contrarily, a quantitative method for evaluating onion growth in the field has not been well established. Most quantitative assessments of onion growth have focused on the harvesting stage (Katayama & Yamasaki 2015, Asai et al. 2018, Ikeda & Hosono 2021). Few studies have evaluated onion growth during the cultivation stage (from transplantation to harvesting). Different growth parameters, such as plant height, leaf number, fresh weight, and bulb diameter of onion plants, express onion growth differently. Measurement of all of these parameters at the field level is difficult and labor-intensive. Moreover, it is unclear which parameters are the most important, and the parameters used to quantitatively assess onion growth vary among researchers, complicating the situation for farmers. Dry matter weight is a basic indicator of growth; however, it requires time and equipment for drying. Therefore, it is important to elucidate the relationship among growth parameters and propose a practical method for assessing onion growth status. The objective of this study was to propose an alternative, simple, and easy method for assessing onion growth at the field level.

This study aimed to select a simple indicator that best reflects onion yield and develop a scheme that can readily and practically assess onion growth at the field level. We investigated the effectiveness of measuring leaf sheath basal diameter (LSBD), which is considered to meet the needs of farmers for a simple and rapid growth assessment method with only a single measurement.

Materials and methods

1. Plant material

Two commercially available onion cultivars were used in this study. "Momiji No. 3" (Shippo Co., Kagawa, Japan) and "Totana" (Bejo Japan Co., Ltd.) are relatively early maturing cultivars. Seeds were sown in plug trays with 288 cells (20 mm × 20 mm × 40 mm) filled with nursery soil (K-200, Yanmar Co., Osaka, Japan) mixed with 2% fertilizer (Micro Long Total 280, Jcam Agri Co., Tokyo, Japan) and cultivated for 2 months in an unheated greenhouse at the NARO Tohoku Agricultural Research Center in Iwate, Morioka, Japan (39°44.9′N, 141°7.9′E), before transplanting.

2. Field trials

Field trials were conducted at the NARO Tohoku Agricultural Research Center. "Momiji No. 3" and "Totana" seeds were both sown in greenhouses on February 16, 2018, and February 13, 2019. The seedlings were transplanted on May 7, 2018, and April 17, 2019, respectively, to a field that was fertilized with nitrogen, phosphate, and potassium at levels of $N:P_2O_5:K_2O$ = 15:30:15 kg/10 a (base fertilizer only). The seedlings were cultivated under ambient temperature (−0.1 to 40.0 °C) and day length (13.55 to 15.00 h), and the field was designed with 12-cm plant spacing, 150-cm row spacing with four lines in each row (each with 24-cm line spacing), and a planting density of 22,222 plants/10 a. Onion plants were sampled every other week, and various growth studies were conducted. Harvesting was conducted 1 week after half of the onion tops had fallen over. Pest and disease control during the growing season was performed in accordance with the practices for spring-sown onion cultivation in the Tohoku region (Yamasaki et al. 2017). Local weather information was obtained from the Kuriyagawa Meteorological Observing Station inside the Tohoku Agricultural Research Center. The temperature and precipitation during the cultivation period are presented in Table 1.

3. Growth parameter measurement

Plant height, leaf blade length, leaf blade width, leaf sheath length, leaf sheath middle diameter (LSMD), leaf sheath basal diameter (LSBD, ball width after bulbing), and fresh and dry weights of the leaf blades and bulbs were measured. Plant height was measured from the bottom of the bulb to the tip of the longest leaf blade; the leaf sheath length, between the bulb and green leaf; and LSMD, at the border between the leaf sheath and bulb. A diagram of the measurement positions is presented in Figure 1. The maximum, minimum, mean, median, and standard deviation of the measured values of each parameter are listed in Table 2.

Table 1. Temperature and precipitation during the growth period of spring-sown onion

	Year	Apr.	May			Jun.			Jul.			Aug.		
		L	E	M	L	E	M	L	E	M	L	E	M	L
Average daily temperature (°C)	2018	12.7	12.6	14.5	16.8	19.2	15.2	22.3	22.2	24.0	25.6	22.3	21.7	23.6
	2019	10.3	13.6	16.2	18.0	18.3	17.3	19.3	20.1	21.2	25.2	27.0	25.6	22.5
Maximum daily temperature (°C)	2018	18.7	17.5	20.3	24.0	25.2	19.1	27.4	26.8	28.2	31.0	27.7	27.2	27.2
	2019	16.4	20.4	23.4	25.3	24.5	22.5	24.0	25.4	26.0	29.3	33.0	30.2	26.6
Minimum daily temperature (°C)	2018	6.0	8.2	8.6	9.6	13.4	11.6	18.0	18.2	19.8	21.2	17.9	16.0	20.6
	2019	3.4	6.5	9.6	9.8	11.5	11.8	15.6	15.4	17.5	22.0	21.9	21.9	19.0
Daily precipitation (mm)	2018	0.0	0.0	132.5	25.0	28.5	25.0	72.0	90.5	21.0	4.5	38.0	88.5	76.5
	2019	39.5	27.5	1.0	65.0	2.5	37.5	94.0	5.0	51.0	5.5	13.5	91.5	44.5

E, M, and L are the early, middle, and late stages of the month, respectively.

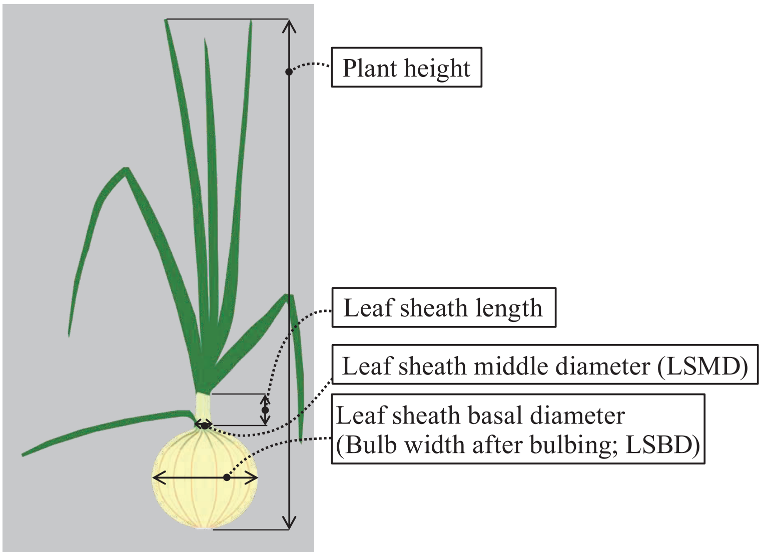

Fig. 1. Measurement position in the spring-sown onion growth survey
The positions of the onions measured as growth parameters are shown. The plant height was measured from the bottom of the bulb to the tip of the longest leaf. The leaf sheath length was measured between the bulb and green leaves. The leaf sheath mid-diameter was measured at the border between the leaf sheath and bulb.

Table 2. Number of samples, minimum, maximum, average, median, and standard deviation for each spring-sown onion growth parameter survey dataset used in the analysis

	Plant height (mm)	Leaf blade length (mm)	Leaf blade width (mm)	Leaf sheath length (mm)	LSMD[z] (mm)	LSBD[x] (mm)	Bulb Fw (g)	Bulb Dw (g)	Leaf blade Fw (g)	Leaf blade Dw (g)	Leaf blade area (cm^2)
Number of samples	347	297	281	355	355	355	353	355	354	351	297
Minimum	141	107	5.31	17	3.55	7.12	0.72	0.014	0.61	0.065	7.83
Maximum	1,216	930	41.20	267	24.16	130.92	721.58	53.09	167.96	12.28	1,209.48
Average	624.3	453.2	19.99	118.12	11.28	46.75	144.18	10.39	45.53	3.31	359.07
Median	698.0	447.0	20.38	108.86	11.21	28.82	33.15	2.28	36.61	2.94	277.44
Standard deviation	291.5	221.3	9.49	67.91	4.32	35.84	185.38	12.78	41.98	2.90	334.17

[z] Leaf sheath middle diameter, [x] Leaf sheath basal diameter

4. Statistical estimation of onion bulb weight

The data for 2 years (2018 & 2019) were combined and used for the analysis. Multiple regression analysis was conducted using bulb weight as the objective variable and each parameter of the growth study as the explanatory variable. The variance intensification factor (VIF) statistic was calculated to determine multicollinearity when multiple explanatory variables were used, and a value of 2.0 or higher was considered to indicate multicollinearity. The Akaike information criterion (AIC) was calculated for the multiple regression equations, and the equation with the lowest AIC was evaluated as the best equation. Partial correlation coefficients were analyzed to examine the effect of single growth parameters on yield for the 277 samples for which the values of the fresh weight parameters were available. All statistical analyses were conducted using the R software (ver. 4.0.3).

Results

1. Onion growth

Onion plants sown in 2018 and 2019 showed similar growth rates. Figure 2 presents the growth data for Momiji No. 3 in 2018. Plant height and LSBD increased with an increase in the number of days after planting (Fig. 2A, B). LSMD and leaf blade fresh weight increased approximately 65 d after planting and decreased thereafter (Fig. 2B, D). The fresh weights of tops and bulbs exhibited the same trend after planting, which rapidly increased from 50 to 80 days after planting until harvest (Fig. 2D). Contrarily, the leaf area increased up to 60 d after planting, with no subsequent increase (Fig. 2C).

2. Relationship between growth parameters and estimation of bulb weight by growth parameters

A multiple regression analysis was conducted using bulb dry weight as the objective variable and the other growth parameters as explanatory variables (Table 3). To evaluate multicollinearity, each parameter was used as an explanatory variable on its own or in combination, such as leaf blade length and LSBD, leaf sheath length and LSMD, LSMD and LSBD, and LSBD and leaf fresh weight, with a VIF less than or equal to 2.0. When two parameters were used, the coefficient of one of the parameters was negative; however, this could not explain how negative growth was associated with yield. When

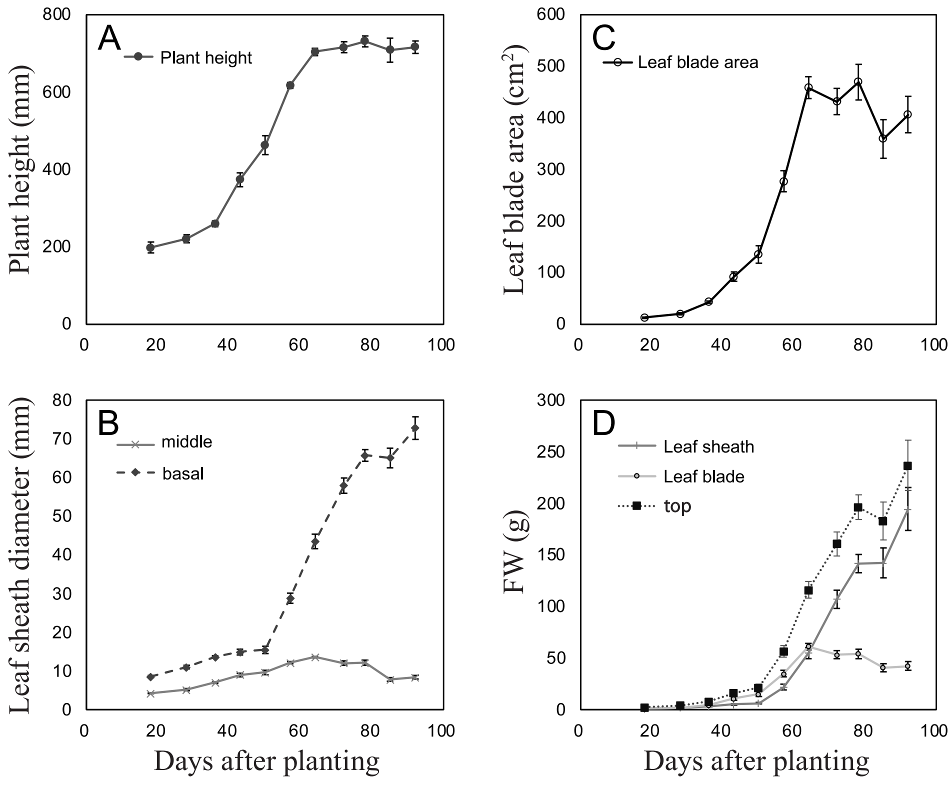

Fig. 2. Post-planting growth survey of spring-sown onions (Momiji No. 3) grown in 2018
(A) Plant height, (B) middle and basal leaf sheath diameter, (C) leaf blade area, and (D) fresh weight of the leaf sheath, leaf blade, and top. Values indicate the mean ± SE (n = 8).

Table 3. Multiple regression analysis of the objective variable (spring-sown onion bulb dry weight) and explanatory variables (each growth parameter)

No.	Parameter		regression equation	AIC	RMSE	R^2
Number of parameters: 2						
(1)	LSBD[x]	Leaf blade length	Bulb Dw = 0.378 × LSBD***–0.0113 × Leaf blade length***–2.16***	667	3.042	0.932
(2)	LSMD	Leaf sheath length	Bulb Dw = –0.822 × LSMD***+0.190 × Leaf sheath length***–2.78**	1,315	6.323	0.755
(3)	LSBD	LSMD[z]	Bulb Dw = 0.360 × LSBD***–0.353 × LSMD***–2.45***	903	3.538	0.923
(4)	LSBD	Leaf blade Fw	Bulb Dw = 0.373 × LSBD***–0.0421 × Leaf blade Fw***–5.16***	900	3.537	0.922
Number of parameters: 1						
(5)	Plant height		Bulb Dw = 0.0328 × Plant height***–10.1***	1,514	8.547	0.553
(6)	Leaf blade length		Bulb Dw = 0.0269 × Leaf blade length***–3.23*	1,376	10.071	0.259
(7)	Leaf blade width		Bulb Dw = 0.963 × Leaf blade width***–9.78***	1,139	7.535	0.594
(8)	Leaf sheath length		Bulb Dw = 0.158 × Leaf sheath length***–8.29***	1,378	6.921	0.706
(9)	LSMD		Bulb Dw = 0.997 × LSMD***–0.855***	1,769	12.017	0.114
(10)	LSBD		Bulb Dw = 0.341 × LSBD***–5.53***	950	3.790	0.912
(11)	Leaf blade Fw		Bulb Dw = 0.176 × Leaf blade Fw***+2.31**	1,658	10.340	0.337
(12)	Leaf blade Dw		Bulb Dw = 3.08 × Leaf blade Dw***+0.284	1,561	9.185	0.485
(13)	Leaf blade area		Bulb Dw = 0.0250 × Leaf blade area***–0.00159	1,254	8.205	0.508

[z] Leaf sheath middle diameter
[x] Leaf sheath basal diameter
**Significantly different at $P < 0.01$ by Student's *T*-test
***Significantly different at $P < 0.001$ by Student's *T*-test
Data show the totals for Momiji No.3 and Totana.

each parameter was used alone in the regression analysis, the AICs were larger across the board than when two parameters were used. However, when LSBD was used as an explanatory variable, the AIC was the lowest among the cases where each parameter was used as an explanatory variable, with a coefficient of determination of 0.912, which was considered to explain the target variable well.

The coefficient of determination of the simple regression equation obtained from the dry weight of bulbs was estimated using Table 3, Equation (10), which had a low AIC, and the measured value was 0.912, indicating that the LSBD explained approximately 90% of the dry weight of the bulbs (Fig. 3). The coefficients of determination of the simple regression equation obtained from the measured values and the estimated dry weight of bulbs based on plant height (Table 3, Equation (5)) and leaf area (Table 3, Equation (13)), which are frequently measured in growth studies, were 0.553 and 0.508, respectively, indicating that both parameters explained less than 60% of the dry weight of bulbs.

To select the growth factor most influencing yield, we determined the partial correlation between the growth parameters and the fresh weight of the bulb, which is directly related to yield (Table 4). A considerable overlap was observed between fresh weight (Fw) and dry weight (Dw); therefore, from the viewpoint of selecting a simple indicator, we used only the Fw value for the leaf blade weight. Partial correlation with bulb fresh weight showed significant negative partial correlations with leaf blade length and significant positive partial correlations with the leaf sheath length and LSBD. In particular, the partial correlation of LSBD with bulb fresh weight was more than twice that of the leaf sheath length, indicating that leaf sheath, especially LSBD growth, is related to bulb weight.

Discussion

1. For 2 years, the yields of the two onion cultivars were generally acceptable

The mean bulb weights of the in-field trials conducted in this study were approximately 195 g (17.4 g dry weight) for Momiji No. 3 and 360 g (28.4 g dry weight) for Totana in 2018 as well as 540 g (33.0 g dry weight) for Momiji No. 3 and 575 g (34.2 g dry weight) for Totana in 2019. These results were comparable to those reported in previous studies (Kudo et al. 2020, 2021, Ikeda et al. 2021) and the standard yields of commercial growers. Therefore, these data can be, at least partially, generalized and reflect standard onion production practices.

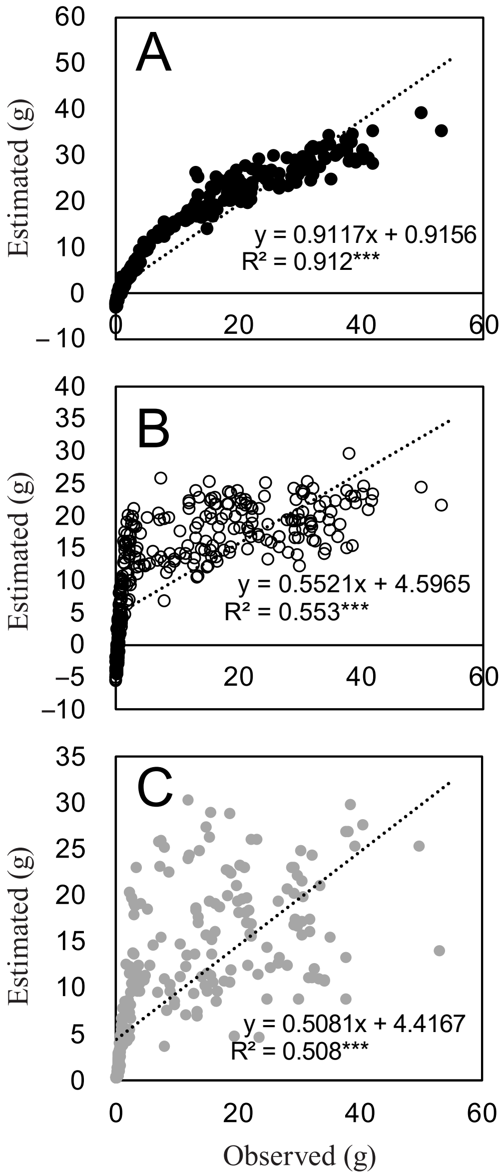

Fig. 3. Comparison of estimated and measured spring-sown onion bulb dry weight

The estimated bulb dry weight, calculated using the equation in Table 3, was plotted against the measured bulb dry weight. (A) Estimated value calculated using formula (10) mentioned in Table 3 (used parameter: leaf sheath basal diameter), (B) estimated value calculated using formula (5) mentioned in Table 3 (used parameter: plant height), and (C) estimated value calculated using formula (13) mentioned in Table 3 (used parameter: leaf blade area). The data show the total values for Momiji No.3 and Totana.

In this study, both evaluated species, "Momiji No. 3" and "Totana," showed similar growth and analytical results; therefore, we focused mainly on the former. The results for each parameter were not largely different among cultivars, except at the end of the growth period (the time to plant tops falling over). Therefore, the results might be applicable to various onion species (cultivars) and should be examined using more varieties.

Table 4. Partial correlation between spring-sown onion bulb fresh weight and growth parameters

Correlation coefficient	Bulb fresh weigth
Plant height	0.00
Leaf blade length	–0.31 ***
Leaf blade width	–0.17
Leaf sheath length	0.37 ***
LSMD[x]	0.16
LSBD[y]	0.76 ***
Leaf blade Fw	0.09
Leaf blade area	–0.05

[x] Leaf sheath middle diameter
[y] Leaf sheath basal diameter
Control variables were growth parameters other than explanatory variables.
***: $P < 0.1\%$
Data show the totals for Momiji No.3 and Totana.

2. Plant height and leaf area are correlated with bulb weight to some extent

Plant height and leaf area have been reported to be growth indicators (Brewster 2008). Leaf area influences photosynthesis, which significantly affects the weight and yield of onion bulbs (Brewster 2008). In this study, the coefficients of determination of the simple regression equations with bulb dry weight as the objective variable and plant height and leaf area as explanatory variables were 0.553 and 0.508, respectively, indicating that plant height and leaf area explained more than 50% of variance in bulb dry weight (Fig. 3). Contrarily, the coefficient of determination was as high as 0.912 when the leaf sheath base diameter was used as an explanatory variable, explaining bulb dry weight better than plant height or leaf area, highlighting a slight correlation between top and bulb growth (Fig. 3).

3. Differences between top and bulb growth

The difference between the growth of the top parts and bulbs was indicated by the difference between the increase in leaf area and bulb weight. The increase in leaf area preceded that in fresh weight. First, the leaf area increased up to 60 d after planting and remained nearly constant until harvest (Fig. 2C). This coincided with the cessation of leaf blade growth (Fig. 2D), indicating that nutritional growth ceased approximately 60 d after planting, and photosynthetic products were transferred to the bulbs. Similarly, Brewster (2008) showed that bulb growth (dry weight) was delayed compared with leaf blade growth (dry weight) and reported that sufficient leaf growth is necessary before bulb initiation. In addition, in this study, bulb weight showed almost no or negative partial correlation across the board with the top parameters (Table 4). This was based on the seesaw relationship between bulb enlargement and leaf growth after the bulbing period. These results indicate that it is necessary to select an appropriate growth parameter as an onion growth indicator depending on the purpose.

In recent years, molecular biological approaches have been employed to elucidate the mechanisms of onion bulbing (Lee et al. 2013, Khokhar et al. 2017, Ikeda et al. 2020). Bulbing is regulated by two antagonistic flowering locus T-like (FT-like) genes: AcFT1 promotes bulb enlargement and AcFT4 suppresses bulb enlargement by upregulating AcFT1 expression (Lee et al. 2013, Khokhar et al. 2017). Onions overexpressing AcFT4 showed no bulb enlargement and continued vegetative growth in winter (Lee et al. 2013). In this study, a gap was observed between the increase in plant height or leaf area and that in bulb weight, indicating that the developmental stage of the plant must switch from top growth, including leaves, to bulb enlargement and that top growth, such as plant height and leaf area, is not directly related to bulb weight.

4. Fitting between estimated and measured values

In previous studies, the relationship between yield and top growth was examined only through growth studies at the time of harvest, and yield was studied in relation to plant height and leaf area. However, no standard has been established regarding an index that should be adopted to estimate yield. The results of the multiple regression analysis indicated that the diameter of the base of the leaf sheath is the best index for estimating bulb weight as a single growth parameter.

Although plant height and leaf area contributed to the increase in bulb dry weight, they did not contribute as much as the leaf sheath base diameter (bulb width: coefficient of determination, 0.912) (Fig. 3). The linearity of the plot was broken, particularly in the latter half of the cultivation period, and estimating the bulb weight using this formula was difficult. This may be because all the growth data during the cultivation period were used for the analysis in this study, indicating that it is possible to estimate the dry weight of bulbs from plant height and leaf area depending on the season. The estimation of the dry weight of bulbs by LSBD may be more suitable if the estimation is divided into two periods: before and after bulbing.

In this study, we focused on a growth survey method for farmers that can easily and practically assess onion growth at the field level. Thus, much attention was paid to which growth parameters could reflect the volume of onion growth the best during the cultivation period. This is a little different in purpose from that of studies that could develop a plant growth model to explain and simulate the onion growth under various conditions. However, further studies are required to achieve this goal.

Acknowledgements

The authors would like to thank Mr. Hiroki Takahashi, Mr. Masayuki Goto, Mr. Kazuhiro Hayasaka, Mr. Masato Inoue, Ms. Misaki Saito, and Ms. Yumiko Takahashi of the National Agriculture and Food Research Organization, Tohoku Agricultural Research Center, Japan for their assistance in conducting the experiments.

References

Abdelkhalik, A. et al. (2019) Effect of deficit irrigation on the productive response of drip-irrigated onion (*Allium cepa* L.) in Mediterranean conditions. *Hort. J.*, **88**, 488-498.

Asai, M. & Murakami, K. (2018) Varietal differences in the overwintering ability of onion plants growing in snow associated with soluble carbohydrate accumulation. *J. Jpn. Soc. Hortic. Sci.*, **19**, 13-19 [In Japanese].

Brewster, J. L. (2008) *In* Brewster, J. L. (ed). Crop production science on horticulture. Vol. 15. Onions and other vegetable alliums, 2nd edition. ed Brewster, J. L. CABI Publishing, Wallingford, UK.

e-Stat, Portal site of official statistics of Japan (2018). https://www.e-stat.go.jp. Accessed on July 19, 2021 [In Japanese].

FAOSTAT, Food and Agriculture Organization of the United Nations. (2017) FAOSTAT statistical database. http://apps.fao.org. Accessed on July 19, 2018.

Ikeda, H. et al. (2019) Sowing time and temperature influence bulb development in spring-sown onion (*Allium cepa* L.). *Sci. Hortic.*, **244**, 242-248.

Ikeda, H. et al. (2020) A comparative study on the growth and bulb development of several onion (*Allium cepa* L.) cultivars sown in spring in the northeast region of Japan. *Hort. J.*, **89**, 586-592.

Ikeda, J. & Hosono, T. (2021) Effect of mulching and differences in fertilizer for basal application on the yield of onion (*Allium cepa* L.) in a converted heavy clayey paddy field in the Hokuriku region of Japan. *Jpn. J. Soil Sci. Plant Nutr.*, **92**, 1-10 [In Japanese].

Katayama, K. & Yamasaki, A. (2014) Effects of early seeding and mulching on growth and yield of onion in spring seeding cropping type in upland field converted from paddy field. *Tohoku Agric. Res.*, **67**, 111-112 [In Japanese].

Katayama, K. & Yamasaki, A. (2015) Effects of phosphate local fertilization on growth and yield of onion on ridge with mulching in spring seeding cropping type in upland field converted from patty field. *Tohoku Agric. Res.*, **68**,

119-120 [In Japanese].
Khokhar, K. M. (2017) Environmental and genotypic effects on bulb development in onion–a review. *J. Hortic. Sci. Biotechnol*., **92**, 448-454.
Kinoshita, T. et al. (2018) Type of mulching film and planting date adapted to a new onion cropping type using onion sets for early winter harvesting in the northern Tohoku area of Japan. *Hort. Res.* (*Japan*). **17**, 303-309 [In Japanese].
Kudo, K. et al. (2020) Nutrient uptake characteristics of spring-planted onions in the Tohoku area of Japan. *Jpn. J. Soil Sci. Plant Nutr*., **91**, 381-384 [In Japanese].
Kudo, K. et al. (2021) Estimation of optimal fertilizer application for spring-planted onions in the Tohoku area of Japan. *Jpn. J. Soil Sci. Plant Nutr*., **92**, 263-266 [In Japanese].
Lee, R. et al. (2013) FLOWERING LOCUS T genes control onion bulb formation and flowering. *Nat. Commun*., **4**, 2884.
Muro, T. et al. (2020) The cultivation guide for spring-sown onion in Tohoku region. https://www.naro.go.jp/publicity_report/publication/files/Onion_Manual.pdf. Accessed on July 19, 2021 [In Japanese].
Nakano, Y. et al. (2012) Root system development of onion as affected by water table levels and their changes. *Root Res*., **21**, 63-71 [In Japanese].
Suesada, T. et al. (2018) Effect of seeding time and phosphate fertilizer using the method of local application below the seeds on yield in direct-sown seeds of onions (*Allium cepa* L.) in central Japan. *J. Jpn. Soc. Hortic. Sci*., **17**, 49-54 [In Japanese].
Usuki, K. et al. (2015) Effect of placement and amount of applied phosphatic fertilizer on the early growth of direct-sown onions (*Allium cepa* L.) on andosols. *J. Jpn. Soc. Hortic. Sci*., **14**, 157-161 [In Japanese].
Usuki, K. et al. (2018) Effect of timing of nitrogen and potassium application in combination with local application of calcium superphosphate on the growth and yield of direct-seeded onions (*Allium cepa* L.). *J. Jpn. Soc. Hortic. Sci*., **17**, 405-413 [In Japanese].
Usuki, K. et al. (2019) Consideration of methods to estimate the leaf number of direct seeding onions (*Allium cepa* L.) using air temperature. *J. Jpn. Soc. Hortic. Sci*., **18**, 17-23 [In Japanese].
Yamasaki, A. (2017) New spring-sowing cropping type of onion in Tohoku region. *JATAFF J*., **5**, 18-22 [In Japanese].