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Onion Plant Size Measurements as Predictors for Onion Bulb Size

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Abstract: Onion is a biennial plant that produces a bulb. The larger the onion bulb, the more valuable it becomes. Therefore, it is important to study bulb weight and plant size components affecting it. For this study, four New Mexico State Univ. breeding lines and two commercial cultivars, 'Rumba' and 'Stockton Early Yellow', were selected. These breeding lines and cultivars were evaluated for plant height, leaf number and sheath diameter, at five different dates two weeks apart throughout the growing season, and for bulb weight upon harvest. The experiment was designed as a randomized complete block design with three blocks each containing four replications. Plant size components were all positively correlated with each other and with bulb weight with correlation coefficients above 0.50. NMSU breeding lines also exhibited greater average bulb weights than commercial cultivars. Sheath diameter proved to be the best predictor of bulb size, showing strong positive correlations with bulb weight at around 12 weeks after transplanting, and positive correlations are observed as early as 6–8 weeks after transplanting.

Keywords: *Allium cepa*; average bulb weight; leaf number; plant height; sheath diameter

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1. Introduction

Onion is a biennial plant that produces a bulb which serves as an overwintering, vegetative structure [1]. To sustain cell division in the meristematic tissue, the onion bulb undergoes a transition, turning it from a sink organ to a source organ [2]. This transition also includes going from dormancy dependent on factors within the onion bulb (endo-dormancy) to dormancy dependent on external environmental factors (eco-dormancy) [2]. Initiation of bulbing is dependent on day length and temperature [3]. Leaf-bearing blades are constantly produced in the onion plant, but with the start of bulbing, leaf blade formation is inhibited, causing the formation of bladeless sheaths [3]. Afterward, all the leaf sheaths of living leaves experience cell enlargement and cause the swelling of the bulb [3]. Within the bulb, lateral buds are also produced, bringing the number of distinct leaves included in the bulb to three [3]. Eventually, older leaf blades and some outer leaf sheaths die, and the neck area softens, resulting in "bulb maturity" [3]. As the onion plant nears maturity and prepares to go into dormancy, fewer new leaves are produced [3]. Onion leaves arise alternatively from the basal plate, with younger leaves being on the inside of the stem [1]. Plant size components, leaf number, plant height and sheath diameter, determine bulb size in onion plants, which are key characteristics of these plants [1]. In onions, sheaths are a grouping of tubular leaves that form a pseudostem right above the bulb [2,3]. Moreover, onion plant size components can often be used to predict bulb size; the greater the number of leaves, the greater the plant height will be, and the larger the sheath diameter becomes, the larger the bulb size becomes [1,3]. The larger the onion bulb, the more valuable it becomes [4]. Therefore, it is important to study bulb weight and plant size components affecting it. Previous studies have indicated that a positive correlation exists between plant height and leaf number, between plant height and bulb yield and between leaf number and cured bulb weight [5–7]. Onion bulb size and weight can be drastically reduced if the plant is subject to biotic and abiotic stresses. Onion thrips infestation can result in up to 50% yield loss [8–11]. In a previous study, four NMSU breeding lines (prefix NMSU 12-), which were originally selected for reduced Iris yellow spot disease symptom expression, were subjected to heavy thrips presence and showed potential tolerance to thrips feeding damage when compared to two commercial cultivars ('Rumba' and 'Stockton Early Yellow') [12–16]. It was demonstrated that onion plants of NMSU breeding lines had fewer early season thrips and usually produced larger bulbs, and that thrips feeding causes reduced photosynthetic area and smaller bulb production [8,16]. However, more studies are required to determine which measure of plant size is the best predictor of bulb size and whether bulb size can be reliably predicted early in a plant's growth based on plant size measurements. In this study, plant height, leaf number, sheath diameter and average bulb weight of those four NMSU breeding lines were measured and compared with two commercial cultivars. The correlations between these components were also determined. We hypothesized that plant size components were all positively correlated with each other and with bulb weight. Moreover, we expected plants of the NMSU breeding lines to have a greater plant size and average bulb weight than plants from the two commercial cultivars. The results of this study may help reduce the time needed to breed onions for larger bulbs, as plant selections could potentially occur before bulb harvest.

2. Materials and Methods

2.1. Plant Material and Field Design

Four NMSU breeding lines and two commercial cultivars were used in this study [16]. 'Rumba' was the commercial cultivar in the first year of the study, while 'Stockton Early Yellow' was used in the second and the third year of the study because seeds of 'Rumba' were no longer produced. All entries were intermediate-day onions and were measured for plant height, leaf number, sheath diameter and bulb weight. The methods used in this study were identical to methods used in a previous study, as seeds were sown in the greenhouse in January, and in March, plants, which were at 4–5 leaf stage, were transplanted into the field [16]. Onions were irrigated as necessary and were grown using recommended standard cultural practices for onion production in southern New Mexico. All plants were subject to biotic stress from onion thrips and *Iris yellow spot virus*, and no insecticides were used. [16,17]. The positioning of the replications was identical to the previous study [16]. Several plants exhibited different sizes than other plants in those plots, as some plants were transplanted at a later date to due to poor stand establishment [16].

2.2. Data Collection

Ten arbitrarily selected plants from each plot were identified with plastic labels. During the growing season, measurements were collected from each of the selected ten plants in each plot every two weeks five separate times in the first and second year and four times in the third. In 2021, data collection began at 6 WAT; no data were collected at 12 weeks after transplanting (WAT) since the field was inaccessible after rainfall. Plant height (cm) was measured by straightening all the leaves upwards in a bunch and measuring the height from the soil level to the green tip of the longest leaf. Leaf number was counted as living leaves with more than half of their area having green tissue. Sheath diameter (mm) was measured right above the bulb using a caliper. The ten individual plants were deemed ready for harvest when the tops had fallen. At harvest, individual bulbs without leaves or roots were weighed.

2.3. Data Analyses

In 2020 and 2021, several plots were omitted from the analyses. These plots included plants that were planted later, matured at different times, died before a comprehensive season's worth of data could be collected, had inadequate growth and were smaller. The method used to determine which plants and plots need to be excluded from the analyses were identical to the previous study and included calculating mean bulb weights and standard deviations of entries [16]. Plot means data were analyzed using the Proc MEANS and Proc MIXED statements in SAS (SAS 9.0; SAS Institute, Inc., Cary, NC, USA). Entries were considered fixed effects, and plot and replication locations in the field were considered random effects. Standard errors of the means were calculated PDIFF was used to determine if there are differences between NMSU breeding lines and commercial cultivars for leaf number, plant height, sheath diameter and bulb weight. Proc CORR was used to determine correlations among different measured components on an individual plant basis.

3. Results and Discussion

3.1. Plant Size Components

Onion plants of different entries exhibited differences in plant size measurements through the growing season. Leaf number per plant did not differ between NMSU breeding lines and the commercial cultivars for the most part (Table 1), but sheath diameter was greater for plants of NMSU 12-337, especially towards the end of the growing season (Table 2). All NMSU breeding lines had greater plant heights in comparison with the commercial cultivar in 2019 and 2020 (Table 3). In 2021, a greater plant height of these breeding lines was only observed at the last observation date (Table 3). These results were observed since in 2021, data collection began two weeks earlier, the maximum air temperature was lower, and precipitation was higher than the previous two years [16].

Table 1. Leaf number means measured five times, biweekly, on per plant basis for five onion entries grown at the Fabian Garcia Science Center and Leyendecker Plant Science Research Center, Las Cruces, NM, during the 2019, 2020 and 2021 growing seasons [z].

	Observation Date [y]				
	1	2	3	4	5
Entry			*2019*		
NMSU 12-236	*7.6* [x] ± 0.2 [w]	*8.6* ± 0.2	*9.8* ± 0.2	10.0 ± 0.6	*9.4* ± 0.2
NMSU 12-238	6.9 ± 0.2	8.4 ± 0.2	9.4 ± 0.2	10.1 ± 0.6	8.1 ± 0.2
NMSU 12-243	6.4 ± 0.2	8.0 ± 0.2	8.9 ± 0.2	8.9 ± 0.6	8.3 ± 0.2
NMSU 12-337	7.1 ± 0.2	8.0 ± 0.2	9.4 ± 0.2	9.8 ± 0.6	*9.9 ± 0.3*
Rumba	6.6 ± 0.2	7.8 ± 0.2	9.3 ± 0.2	8.7 ± 0.7	8.0 ± 0.3
	***	**	*	NS	***
			2020		
NMSU 12-236	5.9 ± 0.3	8.0 ± 0.3	9.4 ± 0.3	10.1 ± 0.6	*9.9* ± 0.3
NMSU 12-238	*7.2* ± 0.3	*9.2* ± 0.3	10.9 ± 0.3	9.9 ± 0.6	9.2 ± 0.3
NMSU 12-243	5.9 ± 0.3	7.7 ± 0.3	9.2 ± 0.3	*9.7* ± 0.6	8.3 ± 0.3
NMSU 12-337	5.8 ± 0.3	7.7 ± 0.3	9.1 ± 0.3	10.0 ± 0.6	*9.9* ± 0.3
Stockton Early Yellow	6.3 ± 0.3	8.1 ± 0.3	10.1 ± 0.3	10.7 ± 0.7	8.3 ± 0.3
	***	**	***	*	***
			2021		
NMSU 12-236	*3.8* ± 0.2	*4.9* ± 0.3	*5.9 ± 0.3*	-	*6.2* ± 0.3
NMSU 12-238	4.2 ± 0.2	5.5 ± 0.3	7.6 ± 0.3	-	*6.8* ± 0.3
NMSU 12-243	5.1 ± 0.2	6.6 ± 0.3	8.2 ± 0.4	-	*6.3* ± 0.3
NMSU 12-337	4.5 ± 0.2	6.1 ± 0.3	7.6 ± 0.3	-	*8.6* ± 0.3
Stockton Early Yellow	4.9 ± 0.2	6.0 ± 0.3	7.3 ± 0.4	-	5.1 ± 0.3
	***	***	***		***

[z] Seeds were sown in a greenhouse in January and plants were transplanted to the field in March. The experiment was designed as a RCBD with three blocks, with each containing four replications. Standard cultural practices for growing onions were used, using drip irrigation. [y] The observation dates were 8, 10, 12, 14 and 16 weeks after transplanting in 2019, 8, 10, 12, 15 and 17 in 2020 and 6, 8, 10 and 14 weeks after transplanting in 2021. No data collection took place at the 4th observation date in 2021. [x] In each plot, ten plants were chosen arbitrarily to undergo living leaf count, with the same ten plants revisited biweekly for living leaf count. Proc Means statement in SAS Studio was used for plot means calculation. Proc MIXED with fixed effects was utilized for means calculation, not considering random effects. Values in italics signify that an entry mean differed from the commercial cultivar. [w] Standard error of the mean. NS, *, **, *** Nonsignificant at $p = 0.05$, significant at $p = 0.05$, significant at $p = 0.01$, and significant at $p = 0.001$, respectively. Test was conducted at $\alpha = 0.05$.

Table 2. Sheath diameter (mm) means measured five times, biweekly, on per plant basis for five onion entries grown at the Fabian Garcia Science Center and Leyendecker Plant Science Research Center, Las Cruces, NM, during the 2019, 2020 and 2021 growing seasons ^{z}.

	Observation Date ^{y}				
	1	**2**	**3**	**4**	**5**
Entry			*2019*		
NMSU 12-236	*11.4* ^{x} ± 0.4 ^{w}	15.2 ± 0.5	18.2 ± 0.5	17.2 ± 0.6	14.3 ± 0.7
NMSU 12-238	10.0 ± 0.4	15.1 ± 0.5	19.3 ± 0.5	18.2 ± 0.6	13.3 ± 0.7
NMSU 12-243	9.6 ± 0.4	14.7 ± 0.5	19.2 ± 0.5	18.3 ± 0.6	14.1 ± 0.7
NMSU 12-337	*11.6* ± 0.5	*16.7* ± 0.5	*20.3* ± 0.5	*21.0* ± 0.6	*19.0* ± 0.8
Rumba	10.4 ± 0.5	14.8 ± 0.6	17.1 ± 0.6	16.8 ± 0.7	13.1 ± 0.9
	**	*	***	***	***
			2020		
NMSU 12-236	6.9 ± 0.7	10.3 ± 1.0	13.8 ± 0.9	15.1 ± 0.5	13.9 ± 0.6
NMSU 12-238	10.0 ± 0.8	14.4 ± 1.0	18.0 ± 0.9	17.0 ± 0.6	13.6 ± 0.7
NMSU 12-243	7.1 ± 0.7	11.5 ± 1.0	15.0 ± 0.9	16.2 ± 0.5	13.2 ± 0.6
NMSU 12-337	7.2 ± 0.7	11.6 ± 1.0	16.3 ± 0.9	*17.9* ± 0.5	*16.8* ± 0.6
Stockton Early Yellow	9.1 ± 0.7	12.9 ± 1.0	15.5 ± 0.9	15.2 ± 0.5	12.2 ± 0.6
	**	**	**	***	***
			2021		
NMSU 12-236	*3.4* ± 0.4	*5.1* ± 0.6	*6.8* ± 0.9	-	8.8 ± 0.6
NMSU 12-238	3.7 ± 0.4	6.4 ± 0.6	10.4 ± 0.9	-	10.3 ± 0.6
NMSU 12-243	5.2 ± 0.4	8.6 ± 0.7	11.4 ± 0.9	-	10.9 ± 0.6
NMSU 12-337	4.9 ± 0.4	8.4 ± 0.6	12.5 ± 0.8	-	*14.7* ± 0.6
Stockton Early Yellow	5.1 ± 0.4	8.0 ± 0.6	11.3 ± 0.9	-	9.6 ± 0.6
	***	***	***		***

^{z} Seeds were sown in a greenhouse in January and plants were transplanted to the field in March. The experiment was designed as a RCBD with three blocks, with each containing four replications. Standard cultural practices for growing onions were used, using drip irrigation. ^{y} The observation dates were 8, 10, 12, 14 and 16 weeks after transplanting in 2019, 8, 10, 12, 15 and 17 in 2020 and 6, 8, 10, and 14 weeks after transplanting in 2021. No data collection took place at the 4th observation date in 2021. ^{x} In each plot, ten plants were chosen arbitrarily to undergo sheath diameter measurement, with the same ten plants revisited biweekly for sheath diameter measurement. Proc Means statement in SAS Studio was used for plot means calculation. Proc MIXED with fixed effects was utilized for means calculation, not considering random effects. Values in italics signify that an entry mean differed from the commercial cultivar. ^{w} Standard error of the mean. *, **, *** significant at $p = 0.05$, significant at $p = 0.01$, and significant at $p = 0.001$, respectively. Test was conducted at $\alpha = 0.05$.

Several correlations were detected between different plant size components. Leaf number and sheath diameter, as well as plant height and sheath diameter, were positively correlated with each other through the growing season of each year (Figures 1 and 2).

In 2019, NMSU 12-236 exhibited a sharp decrease in correlation between leaf number and sheath diameter by 12 WAT (from about 0.7 to 0.3) (Figure 1). This may have been caused by plants of this entry maturing earlier and hence starting to lose leaves at that time [18]. NMSU 12-236 did not exhibit the same drop in correlation coefficient in 2020 and 2021, perhaps because several plants were smaller than others in the beginning of the growing season. This allowed a continued production of larger plants and more leaves by 12 WAT. Also, the fact that data collection began earlier in 2021 may have affected these results (Figure 1).

In 2019 and 2021 the correlation between sheath diameter and leaf number was not different between plants of the commercial cultivar and breeding lines in most cases (Figure 1). In 2019, the correlation between plant height and sheath diameter of NMSU 12-236 remained high through the growing season (about 0.7) but was reduced greatly in 2020 (from 0.93 to 0.66). This perhaps was seen because the last observation date in 2020 was at 17 WAT, as opposed to 16 WAT in 2019, which may have allowed more plants to mature and lose green leaves (Figure 2). NMSU 12-337 exhibited an increase in correlation, from 0.64 at 6 WAT to 0.78 at 14 WAT, which is perhaps because plants of this breeding line take longer to mature and had more large, living leaves at 14 WAT (Figure 2) [18].

Table 3. Plant height (cm) means measured five times, biweekly, on per plant basis for five onion entries grown at the Fabian Garcia Science Center and Leyendecker Plant Science Research Center, Las Cruces, NM, during the 2019, 2020 and 2021 growing seasons [z].

	Observation Date [y]				
	1	**2**	**3**	**4**	**5**
Entry			*2019*		
NMSU 12-236	*52.3* [x] ± 1.6 [w]	*66.7* ± 1.7	*72.3* ± 1.5	*72.6* ± 1.2	*65.0* ± 1.4
NMSU 12-238	*48.8* ± 1.6	*67.8* ± 1.7	*78.1* ± 1.5	*77.5* ± 1.2	*65.4* ± 1.4
NMSU 12-243	*50.1* ± 1.6	*68.2* ± 1.7	*77.8* ± 1.5	*77.3* ± 1.2	*67.1* ± 1.4
NMSU 12-337	*55.2* ± 1.8	*71.6* ± 2.0	*77.8* ± 1.7	*78.3* ± 1.3	*74.9* ± 1.6
Rumba	46.4 ± 1.9	58.1 ± 2.1	63.4 ± 1.8	61.3 ± 1.4	48.8 ± 1.7
	**	***	***	***	***
			2020		
NMSU 12-236	*24.3* ± 3.1	35.8 ± 3.4	47.6 ± 3.1	51.1 ± 2.2	*47.1* ± 1.7
NMSU 12-238	39.3 ± 3.2	*54.7* ± 3.5	*65.3* ± 3.2	*65.1* ± 2.3	*54.7* ± 1.7
NMSU 12-243	*28.4* ± 3.1	42.3 ± 3.4	54.2 ± 3.1	*56.1* ± 2.2	*48.3* ± 1.7
NMSU 12-337	*27.3* ± 3.1	40.7 ± 3.4	54.2 ± 3.1	*57.5* ± 2.2	*53.3* ± 1.7
Stockton Early Yellow	31.1 ± 3.1	39.9 ± 3.4	47.2 ± 3.1	46.7 ± 2.2	33.2 ± 1.7
	**	***	***	***	***
			2021		
NMSU 12-236	*12.4* ± 1.6	*18.0* ± 2.4	*25.3* ± 2.4	-	29.0 ± 1.7
NMSU 12-238	16.5 ± 1.6	27.4 ± 2.4	40.5 ± 2.4	-	*37.5* ± 1.7
NMSU 12-243	22.8 ± 1.7	36.7 ± 2.5	46.2 ± 2.5	-	*36.3* ± 1.8
NMSU 12-337	22.4 ± 1.6	34.2 ± 2.3	46.0 ± 2.3	-	*49.0* ± 1.6
Stockton Early Yellow	22.0 ± 1.7	33.2 ± 2.5	41.0 ± 2.5	-	25.8 ± 1.8
	***	***	***		***

[z] Seeds were sown in a greenhouse in January and plants were transplanted to the field in March. The experiment was designed as a RCBD with three blocks, with each containing four replications. Standard cultural practices for growing onions were used, using drip irrigation. [y] The observation dates were 8, 10, 12, 14 and 16 weeks after transplanting in 2019, 8, 10, 12, 15 and 17 in 2020 and 6, 8, 10, and 14 weeks after transplanting in 2021. No data collection took place at the 4th observation date in 2021. [x] In each plot, ten plants were chosen arbitrarily to undergo plant height measurement, with the same ten plants revisited biweekly for plant height measurement. Proc Means statement in SAS Studio was used for plot means calculation. Proc MIXED with fixed effects was utilized for means calculation, not considering random effects. Values in italics signify that an entry mean differed from the commercial cultivar. [w] Standard error of the mean. **, *** significant at $p = 0.01$, and significant at $p = 0.001$, respectively. Test was conducted at $\alpha = 0.05$.

Plant height and leaf number were positively correlated in most cases and was higher in the beginning of the growing season (Figure 3), as similarly observed by other research in other crops [19]. In 2019, NMSU 12-236 had a marked weakening in correlation between plant height and leaf number as well (from 0.74 to 0.1), and the same was observed in 2020 (from 0.87 to 0.29) (Figure 3). One possible reason for the decreasing correlation between plant height and leaf number toward the end of the growing season is that plant height was measured by straightening all the leaves upwards in a bunch and measuring the height from soil to the green tip of the longest leaf, and only living leaves were counted. Therefore, as plants near maturity, they exhibit reduced height and fewer leaves (Table 1) [18]. This is because as a plant nears dormancy, the older leaves start to break at the tip, some leaves die to form the dry outer scale tissue for the bulb and none are replaced by new leaves as no new leaves are produced [3,20].

Figure 1. Correlations between sheath diameter and leaf number through the growing season and for entries on a per plant basis in (**A**) 2019, (**B**) 2020 and (**C**) 2021, at $p < 0.001$ significance level.

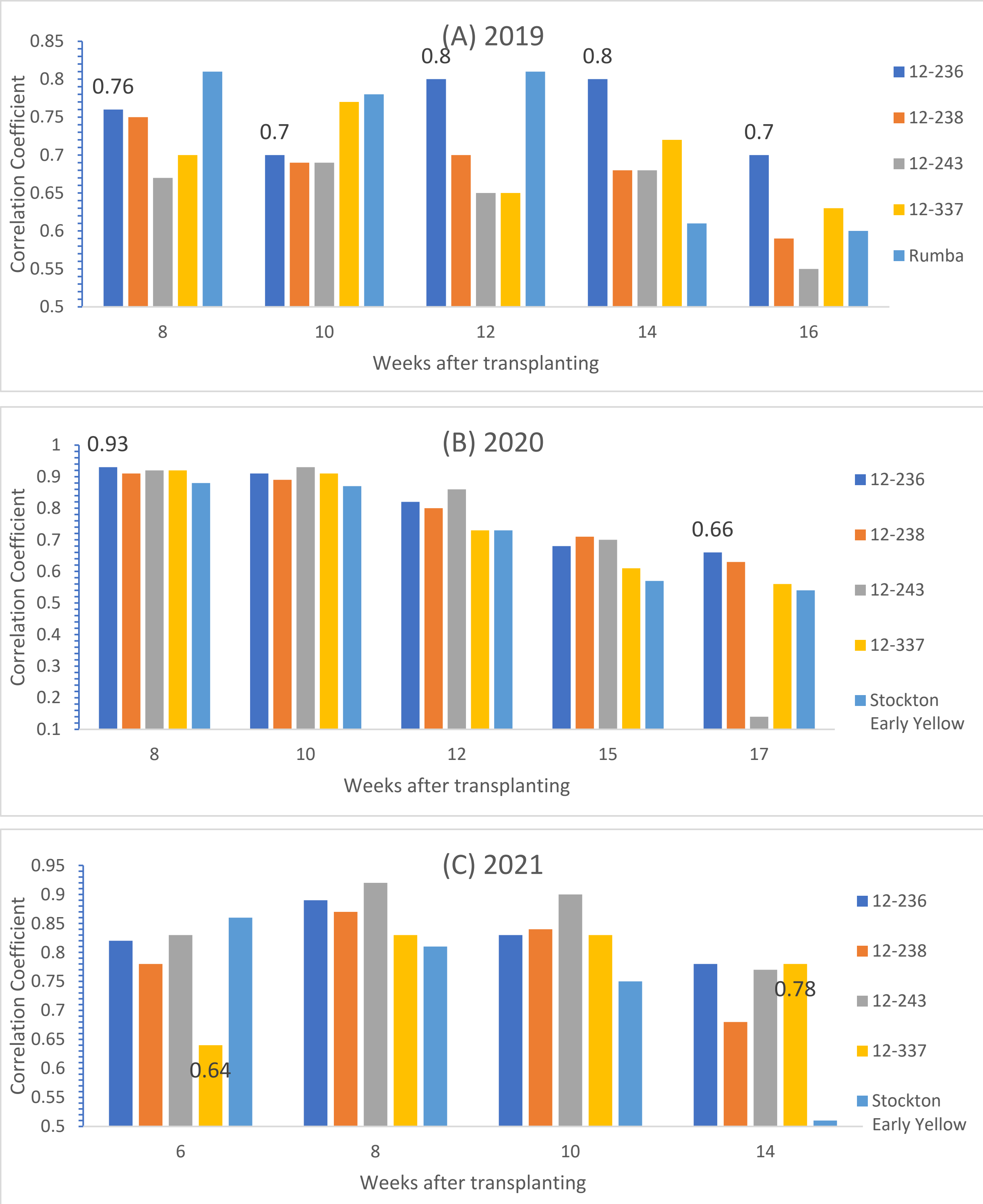

Figure 2. Correlations between sheath diameter and plant height through the growing season and for entries on per plant basis in (**A**) 2019, (**B**) 2020 and (**C**) 2021, at $p < 0.001$ significance level.

Figure 3. Correlations between plant height and leaf number through the growing season and for entries on per plant basis in (**A**) 2019, (**B**) 2020 and (**C**) 2021, at $p < 0.001$ significance level.

The correlations in 2021 were not as strong initially as in previous years, perhaps because data collection began earlier when plants were smaller (Figure 3, Table 3). At the last observation dates, sheath diameters also decrease, which is due to the softening of the sheath area as plants near the end of their growth, allowing the caliper to produce smaller numbers (Table 2). Based on this research, sheath diameter is the plant component least prone to unexpected change. Sheath diameters of all plants consistently increased from the first observation date, until dormancy began (Table 2). Therefore, sheath diameter appears to be the best indicator of the plant size.

3.2. Bulb Weight

As mentioned in another study [16], plants of the NMSU breeding lines exhibited a greater average bulb weight than plants of the commercial cultivars in 2019 and 2020 (Table 4). In 2021, plants of NMSU 12-243 and 12-337 were the only entries with a greater average bulb weight (Table 4).

Table 4. Average bulb weight measured upon harvest on per plant basis for five onion entries grown at the Fabian Garcia Science Center and Leyendecker Plant Science Research Center, Las Cruces, NM, during the 2019, 2020 and 2021 growing seasons ^{z}.

	Year		
	2019	**2020**	**2021**
Entry		*Average Bulb Weight (g)*	
NMSU 12-236	*186.1* ^{y} ± 11.2 ^{x}	*174.0* ± 12.0	60.7 ± 11.3
NMSU 12-238	*207.1* ± 11.2	*234.2* ± 12.0	101.7 ± 11.3
NMSU 12-243	*198.8* ± 11.2	*201.8* ± 12.0	*160.3* ± 11.9
NMSU 12-337	*223.9* ± 11.2	*194.3* ± 12.0	*170.19* ± 10.8
Commercial Cultivar ^{w}	102.9 ± 11.2	95.4 ± 12.0	82.8 ± 11.9
	***	***	***

^{z} When 80 percent of the tops were down in a plot, it was considered mature and was harvested. ^{y} Proc MIXED statement was utilized using plot means to differentiate between entries. Entries were deemed fixed. Values signified in italics represent that an entry mean differed from the commercial cultivar. ^{x} Standard error of the mean. ^{w} In the 2019, 'Rumba' was the commercial cultivar, and in 2020 and 2021, 'Stockton Early Yellow'. *** Significant at $p = 0.001$. Test was conducted at $\alpha = 0.05$.

Larger onion plants produced larger bulbs, as plant height, sheath diameter and leaf number were positively correlated with average bulb weight (Figures 4–6). The correlations between bulb weight and sheath diameter were at their highest at 12 and 14 WAT in 2019 (from 0.65 to 0.83) and at 12 and 15 WAT in 2020 (from 0.61 to 0.79) (Figure 4). Strong positive correlations between sheath diameter and bulb weight were observed as early as 6–8 WAT (Figure 4).

In 2021, the correlations were positive through the growing season, with a slight decrease at the last observation date (14 WAT) (Figure 4). In 2019, the correlation between bulb weight and leaf number of NMSU 12-236 decreased greatly after 12 WAT (from 0.61 to 0.28), perhaps due to plants of this line maturing earlier and losing leaves (Figure 5) [18]. In 2020, the correlations remained strong for all entries through the growing season, dropping slightly at the last observation date (17 WAT) (Figure 5).

The correlations between bulb weight and leaf number were mostly at their strongest at 10 WAT in 2021, with the commercial cultivar exhibiting the weakest correlation among entries at 14 WAT (Figure 5). The correlations between bulb weight and plant height were lower at 16 WAT in 2019, perhaps due to plants maturing and losing green leaves (Figure 6). In 2020, plants of NMSU 12-337 exhibited a lower positive correlation than plants of other entries (0.44) at all observation dates except the last (0.62) (Figure 6). The reason for this observation may be that this line is maturing later and may have had smaller plants than other entries from 8 WAT to 15 WAT (Figure 6) [18]. As observed with correlations between bulb weight and leaf number, the commercial cultivar exhibited the weakest correlation (0.26) among entries at the last observation date in 2021 (Figure 6).

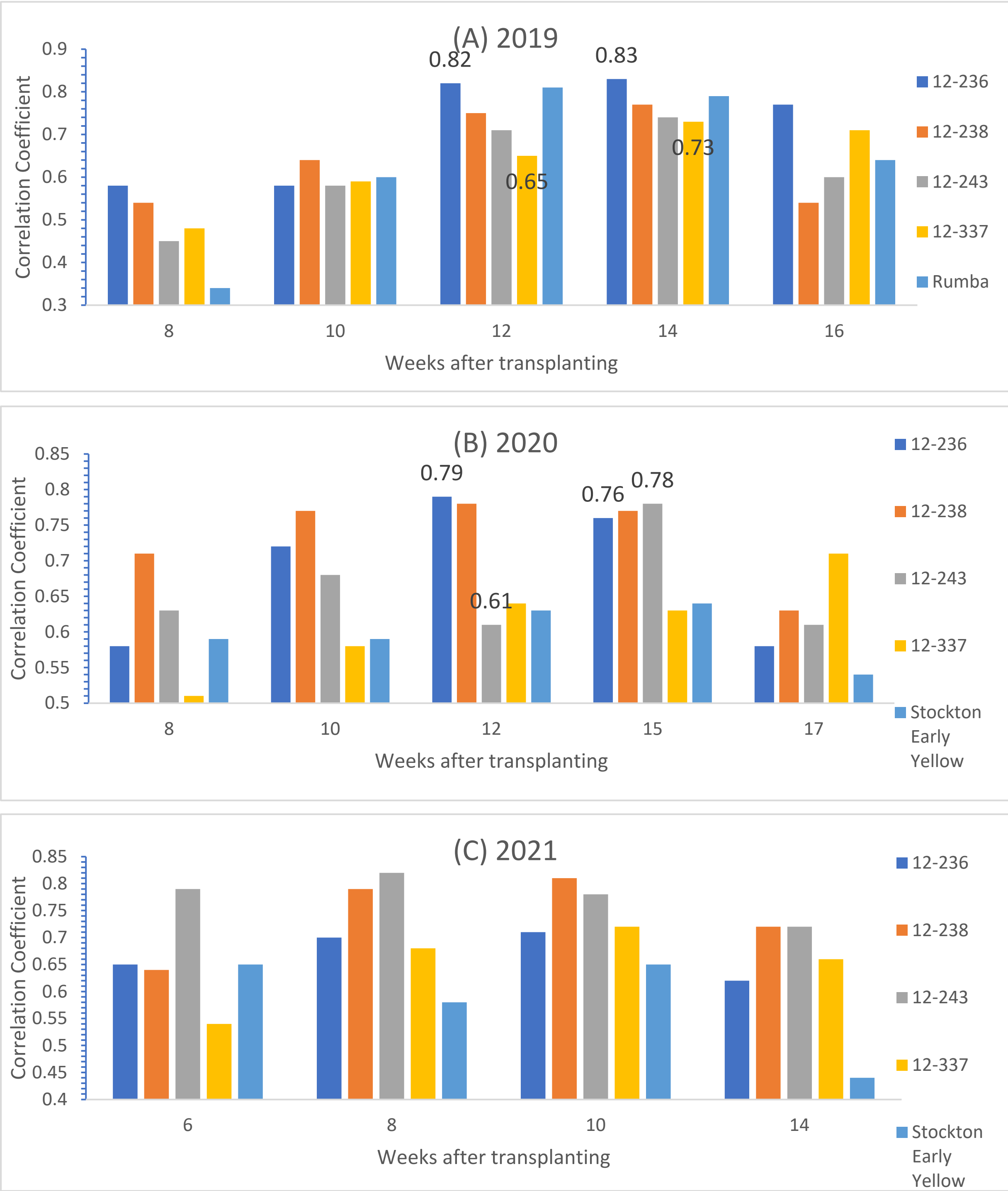

Figure 4. Correlations between sheath diameter and bulb weight through the growing season and for entries on per plant basis in (**A**) 2019, (**B**) 2020 and (**C**) 2021, at $p < 0.001$ significance level.

Figure 5. Correlations between bulb weight and leaf number through the growing season and for entries on per plant basis in (**A**) 2019, (**B**) 2020 and (**C**) 2021, at $p < 0.001$ significance level.

Figure 6. Correlations between bulb weight and plant height through the growing season and for entries on per plant basis in (**A**) 2019, (**B**) 2020 and (**C**) 2021, at $p < 0.001$ significance level.

3.3. Conclusions

All measures of plant size were positively correlated with each other. Plant size measurements were also positively correlated with average bulb weight indicating that bigger plants will produce larger bulbs. Because plant height and leaf number are subject to unexpected changes through the growing season, sheath diameter may be the most reliable measure of plant size. The strongest correlations between bulb weight and sheath diameter were observed at 12 weeks after transplanting, and strong positive correlations were observed as early as 6–8 WAT. Therefore, if the goal of a breeding program were to develop cultivars that produce larger bulbs, that goal may be achieved by focusing the breeding effort on plant size components, specifically sheath diameter. For future studies, we suggest examining this relationship more closely by measuring plant size components, specifically sheath diameter, and basing selections for larger bulb weights upon these measurements.

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References

1. Lancaster, J.E.; Triggs, C.M.; De Ruiter, J.M.; Gandar, P.W. Bulbing in onions: Photoperiod and temperature requirements and prediction of bulb size and maturity. *Ann. Bot.* **1996**, *78*, 423–430. Available online: http://www.jstor.org/stable/42764759 (accessed on 15 June 2022). [CrossRef]
2. Chope, G.A.; Cools, K.; Hammond, J.P.; Thompson, A.J.; Terry, L.A. Physiological, biochemical and transcriptional analysis of onion bulbs during storage. *Ann. Bot.* **2012**, *109*, 819–831. [CrossRef] [PubMed]
3. Abdalla, A.; Mann, L. Bulb development in the onion (*Allium cepa* L.) and the effect of storage temperature on bulb rest. *Hilgardia* **1963**, *35*, 85–112. [CrossRef]
4. Shock, C.C.; Feibert, E.B.; Riviera, A.; Saunders, L.D. Response of onion yield, grade, and financial return to plant population and irrigation system. *HortScience* **2015**, *50*, 1312–1318. [CrossRef]
5. Heath, O.V.S.; Hollies, M.A. Studies in the physiology of the onion plant: VI. A sensitive morphological test for bulbing and its use in detecting bulb development in sterile culture. *J. Exp. Bot.* **1965**, *16*, 128–144. Available online: http://www.jstor.org/stable/23686773 (accessed on 15 June 2022). [CrossRef]
6. Liaqat, A.; Waqar Hassan, M.; Jamil, M.; Iqbal, J.; Yaqoob, M.; Akram, M.; Ahmed, I.; Hussain, A. Effect of nursery bulb size and planting density on thrips population, plant height and yield of onion ('Phulkara' Variety) in Bahawalpur, Pakistan. *Pakistan J. Life Soc. Sci.* **2016**, *14*, 96–193.
7. Gulumbe, A.A.; Abubakar, L.; Sokoto, B.M.; Aliero, A.A. Correlation studies for bulb yield and yield contributing traits among onion (*Allium cepa* L.) genotypes. *Asian Res. J. Agric.* **2018**, *9*, 1–6. [CrossRef]
8. Cranshaw, W.S. Thrips. In *Compendium of Onion and Garlic Diseases and Pests*, 2nd ed.; Schwartz, H.F., Mohan, S.K., Eds.; APS Press: Minneapolis, MN, USA, 2008; pp. 89–91.
9. Diaz-Montano, J.; Fuchs, M.; Nault, B.A.; Shelton, A.M. Evaluation of onion cultivars for resistance to onion thrips (*Thysanoptera: Thripidae*) and Iris yellow spot virus. *J. Econ. Èntomol.* **2010**, *103*, 925–937. [CrossRef] [PubMed]
10. Fournier, F.; Boivin, G.; Stewart, R.K. Effect of *Thrips tabaci (Thysanoptera: Thripidae)* on yellow onion yields and economic thresholds for its management. *J. Econ. Èntomol.* **1995**, *88*, 1401–1407. [CrossRef]
11. Cramer, C.; Mandal, S.; Sharma, S.; Nourbakhsh, S.; Goldman, I.; Guzman, I. Recent advances in onion genetic improvement. *Agronomy* **2021**, *11*, 482. [CrossRef]
12. Cramer, C.S.; Singh, N.; Kamal, N.; Pappu, H.R. Screening onion plant introduction accessions for tolerance to onion thrips and Iris yellow spot. *HortScience* **2014**, *49*, 1253–1261. [CrossRef]
13. Cramer, C.S.; Kamal, N.; Singh, N. Evaluating Iris yellow spot disease incidence and severity in onion germplasm of varying leaf characteristics. *HortScience* **2017**, *52*, 527–532. [CrossRef]
14. Singh, N.; Cramer, C.S. Improved tolerance for onion thrips and Iris yellow spot in onion plant introductions after two selection cycles. *Horticulturae* **2019**, *5*, 18. [CrossRef]
15. Kamal, N.; Nourbakhsh, S.S.; Cramer, C.S. Reduced Iris yellow spot symptoms through selection within onion breeding lines. *Horticulturae* **2021**, *7*, 12. [CrossRef]
16. Nourbakhsh, S.S.; Cramer, C.S. Onion germplasm possesses lower early season thrips numbers. *Horticulturae* **2022**, *8*, 123. [CrossRef]

17. Walker, S.J. *Bulb Onion Culture and Management for Southern New Mexico*; New Mexico State University: Las Cruces, NM, USA, 2009; pp. 1–16.
18. Nourbakhsh, S.S. Thrips Tolerance in Onions: An Examination of Thrips Population Response to Different Plant Size and Foliage Characteristics, and Their Effects on Bulb Weight. Master's. Thesis, New Mexico State University, Las Cruces, NM, USA, 2021.
19. Cross, H.Z.; Zuber, M.S. Interrelationships among plant height, number of leaves, and flowering dates in maize. *Agron. J.* **1973**, *65*, 71–74. [CrossRef]
20. Bachie, O.; Santiago, L.; McGiffen, M. Physiological responses of onion varieties to varying photoperiod and temperature regimes. *Agriculture* **2019**, *9*, 214. [CrossRef]