Important Cabbage Head Traits and Their Relationships at Five Points in Development

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ABSTRACT. We set out to document events and relationships among key traits throughout cabbage head formation, particularly in early stages, in order to help develop and implement efficient strategies to increase crop yield and quality. Head traits used as indicators of horticultural maturity and crop quality were documented at five stages of development in 3 commercial fresh market/slaw and processing cabbage cultivars grown in 2001 and 2002 at The Ohio State University, Ohio Agricultural and Development Center in Wooster, Ohio. Seedlings containing 2-4 true leaves were planted in June of both years. Trait measurement began 35 days prior to the estimated market maturity date for each cultivar and continued weekly for five weeks. Harvest timing affected

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all head traits evaluated. Head weight, diameter, volume, and density and core volume generally increased with harvest date, while the ratio of head polar to equatorial diameter and the percent of head volume occupied by the core decreased. A strong curvilinear relationship between head mean diameter and head weight was found. Developmental changes in head density, in contrast to weight and size, were found to be largely independent of thermal time. Information gained in this study adds to our understanding of cabbage crop development. It also strongly suggests that accurate assessments of developmental stage during the scheduling of harvest are required to maximize head quality. The results also indicate that head growth and maturation should be viewed as separate and distinct concepts in discussions of head development.

KEYWORDS. *Brassica oleracea*, development, head density, quality, size, shape

INTRODUCTION

In head cabbage (*Brassica oleracea* L. Capitata group), the formation of true leaves is followed by a three-stage developmental sequence culminating in horticultural maturity: frame development, cupping and head initiation, and head development (Rubatzky and Yamaguchi, 1997). While head development is a continuum, major head traits and their relationships have been more thoroughly studied at stages associated with market readiness. Cabbage heads are considered to be horticulturally mature once they have reached a minimum size, weight and/or density. Density is a measure of solidity and the most frequently employed indicator of maturity for specific cultivar, environment and market combinations (Day, 1986; Isenberg et al., 1975; Reid, 1992; Swaider and Ware, 2002; Wien and Wurr, 1997). Minimal head density values are cultivar- and market-specific, but generally exceed 0.70 $g \cdot cm^{-3}$ (Day, 1986, Isenberg et al., 1975; Kleinhenz and Wszelaki, 2003; Stofella and Fleming, 1990). Nevertheless, head development or enlargement may continue after horticultural maturity has been reached, a critical fact since environmental, labor and equipment, or market factors may postpone harvest (Kleinhenz, 2003). With head development ongoing, harvest timing is likely to affect head size, weight, shape, density and other traits important to crop yield and quality. Hara and Sonoda (1979) reported a sigmoidal increase in the dry weight of head leaves 60-120 days after planting. Isenberg et al. (1975) recorded increases in weight and density over a 20-30 day period beginning approximately 100 days after planting and found that the changes were cultivar dependent. Although not well documented, and studied principally at horticultural maturity, major head traits and their relationships are thought to change throughout development (de Moel and Evaraarts, 1990; Wszelaki and Kleinhenz, 2003). What remains unknown about events and relationships among key traits early in head formation restricts our fundamental understanding of cabbage crop development and lowers our ability to develop and implement efficient strategies to increase crop yield and quality. Therefore, our goal was to document key cabbage head traits, and relationships among them, beginning early in head formation.

MATERIALS AND METHODS

A factorial set of treatments (3 cultivars and 5 harvest dates) was established in a randomized complete block design with four replications at the Ohio Agricultural Research and Development Center in Wooster, Ohio (latitude 40° 47′ N, longitude 81° 55′ W). One processing ('Transam') and two fresh market ('Bravo' and 'Bronco') cultivars of commercial importance were started in the greenhouse. Hardened seedlings with 2 to 4 true leaves were planted to the field 28 June 2001 and 20 June 2002 in single-row plots established with a cone-type transplanter. Soil type in each year was a Wooster silt loam (Fine-loamy, Mixed, Mesic Typic Fragiudalf). No preplant fertilizer application was made in 2001. This decision was based on a lack of equipment availability in time for planting, a history of moderate to heavy fertilizer applications to the site, and soil tests that indicated no major nutrient deficiencies. In 2002, 56N-49P-93K $kg \cdot ha^{-1}$ was applied to the field and incorporated one month prior to planting, to more closely follow standard commercial practices. A soybean-winter wheat rotation immediately preceded cabbage in both years. In 2001, rows were 6 m long with 1.2 m between rows and 28 cm between transplants. In 2002, rows were 4.8 m long, with between and within row spacing the same as in 2001. Standard pest management strategies, based on scouting, thresholds and application of labeled pesticides, were employed. Rainfall and irrigation maintained adequate soil moisture.

Plots were harvested weekly beginning 35 days prior to and at horticultural maturity (H1, H2, H3, H4, and H5, respectively), with horticultural maturity (H5) serving as the control. In 2001, H1 was set when heads reached 10 cm in diameter. In the same year, H5 corresponded strongly with published days to maturity (Kleinhenz and Wszelaki, 2003; Wszelaki and Kleinhenz, 2003) information for the cultivars used. Therefore, in 2002, H1 was set at 35 d prior to published days to maturity. At harvest, all heads were collected from the center 4.8 m (2001) or 3 m (2002) of each plot. Heads were trimmed (3-4 wrapper leaves removed) prior to further evaluation. Individual head weights were taken using an electronic scale (FV-60KWP, A and D Co., Ltd., Tokyo, Japan or CW11-2EO, OHAUS, NJ). Heads were split longitudinally and core height and base width, and head polar (radial) and equatorial (transverse) diameters measured. Head and core volumes were calculated as previously reported (Kleinhenz and Wszelaki, 2003) using the formula for sphere and cone volume, respectively. Growing degree-days (GDD) were calculated using upper and lower threshold temperatures (21 and 0°C, respectively) selected based on work detailing cabbage metabolism and growth response to temperature (Criddle et al., 1997; Hara and Sonoda, 1982). Two formulae were used to calculate GDD, which were then summed over the course of development (planting to harvest) for each cultivar and year. If the daily maximum temperature (T_{max}) fell below the upper threshold, then GDD = $(T_{min} + T_{max})/2) - B$, where T_{min} = daily minimum temperature and B = the base temperature (0°C). If T_{max} exceeded 21°C, then an intermediate cutoff method (University of California, 2003) was employed, where GDD = $[(T_{min} + 21)/2) - B] - [(T_{max} - 21) * 2]$. Using this cutoff method, GDD = 0 when $T_{max} \geq$ 30 C. Temperatures ≥ 30 C are reported as stressful to cabbage (Criddle et al., 1997; Rubatzky and Yamaguchi, 1997). Data were analyzed with the General Linear Model procedure of SAS for Windows v.8 (Statistical Analysis System, Cary, NC) and with the Regression Wizard of SigmaPlot 2000 for Windows v. 6.0 (SPSS Inc., Chicago, IL).

RESULTS

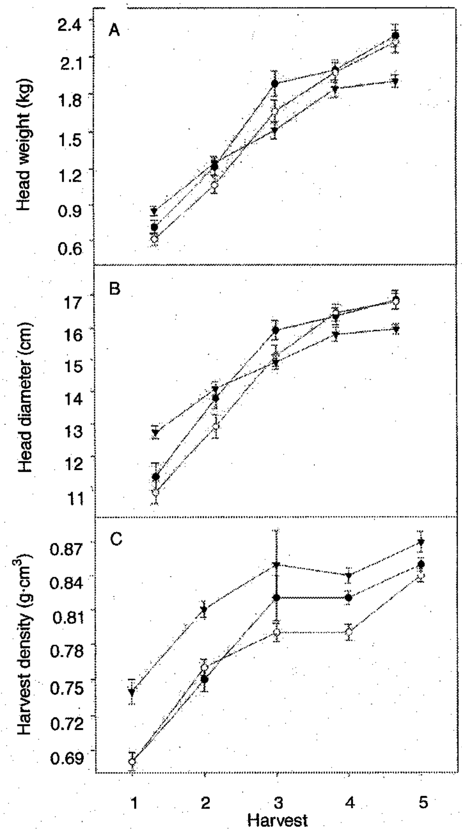
Year (Y), cultivar (C), harvest date (HD) and their interactions affected all head traits evaluated (Table 1). Although significant, the HD × C and HD × Y interactions resulted from changes in magnitude, not direction. Differences between H1 and the H5 ranged from 100-800% for head weight, 20-100% for mean diameter, 7-30% for density, and 4-230% for core volume, with differences greater in 2002 than in 2001 (data not shown). Head weight, diameter and density generally increased with harvest date, although the rate of increase varied with cultivar and was greatest between H1 and H3 (Figure 1). Percent dry matter of heads was recorded in 2002 only, and showed no apparent relationship to plant developmental stage (data not shown). In plotting treatment means for head weight × mean diameter, a linear relationship between the two was apparent, although the slope of the lines differed between relatively early (H1 and H2) and late (H3-H5) stages of development (data not shown). However, when plotted on an individual head basis, the head weight × mean diam-

TABLE 1. Analysis of Variance for the influence of year, cultivar and harvest date on physical characteristics of heads from three cabbage cultivars in June of 2001 and 2002.

Source	Weight	---------------Head Diameter--------------- Polar (P)	Equatorial (E)	Mean	P:E ratio	Volume	Density	Core height	Core width	Core volume	Volume core/ head
Year (Y)	***	***	***	***	***	***	**	***	***	***	***
Cultivar (C)	*	***	***	***	***	***	***	***	***	***	***
Harvest date (HD)	***	***	***	***	***	***	***	***	***	***	***
Y × C	***	***	***	***	NS	***	**	*	***	*	***
Y × HD	***	***	***	***	***	***	NS	**	***	**	***
C × HD	***	***	***	***	***	***	NS	***	***	***	***

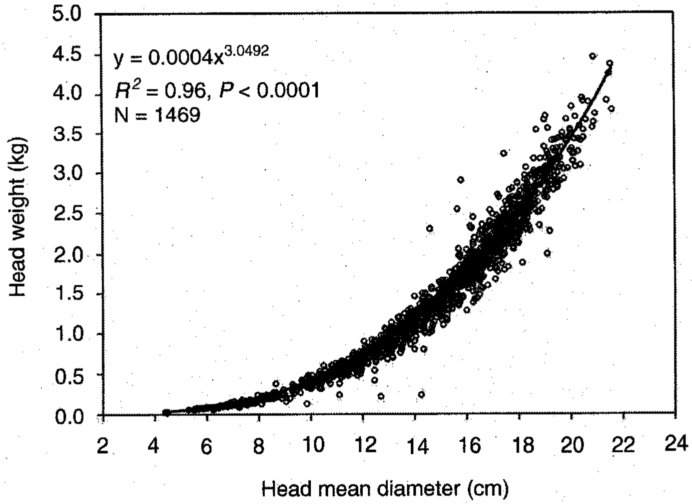
[z] NS, *, **, *** = Not significant or significant at $P \leq 0.05$, 0.01 or 0.001, respectively.

FIGURE 1. Mean head weight (A), head diameter (B) and head density (C) at 5 harvest dates on weekly intervals, beginning 35 d prior to, and ending with, horticultural maturity. 'Bravo' = ●, 'Bronco' = ○ and 'Transam' = ▼. Values are means of 8 to 16 heads from each of four replications across two years. Error bars are standard error of the means.



eter relationship was strong across all treatments ($R^2 = 0.96$, $P < 0.0001$), curvilinear and described by a power equation ($y = 0.0004 * x^{3.054}$), where y = head weight (kg) and x = mean head diameter (cm) (Figure 2). Head polar and equatorial diameter increased with harvest date, with greater gains in equatorial relative to polar diameter values between H1 and H3 (Figures 3A, 3B). Decreases in head diameter ratios resulted in noticeable changes in head shape between H1 and H3 (Figures 3C, 4). Core dimensions also changed, but more

FIGURE 2. Relationship between mean head diameter and head weight of cabbage planted in June 2001 and 2002. Relationship is across cultivars ('Bravo', 'Bronco' and 'Transam') and 5 harvest dates on weekly intervals, beginning 35 d prior to, and ending with, horticultural maturity. N = 1469.



slowly than head diameter (Figures 5A, 5B). This resulted in a decline in the percent of head volume occupied by the core during head development (Figures 5C). Thermal time as calculated was more strongly related to cabbage head growth across treatments and years than thermal time calculated with formulae lacking either an upper threshold or cutoff procedure (data not shown). Accumulated growing degree-days explained year-to-year variability in head weight and mean diameter, but not density (Figure 6).

DISCUSSION

Head Weight, Mean Diameter and Density. Increases in head weight, size and density were relatively rapid after initiation but slowed as heads reached horticultural maturity. These results are similar to those reported by de Moel and Everaarts (1990), Hara and Sonoda (1979) and Isenberg et al. (1975). Increases in density suggest that gains in head weight outpaced increases in head volume throughout much of head development, perhaps due to the expansion of internal head leaves (head fill). Although higher density may also result from increases in percent dry matter, Strandberg and White (1979) reported no

FIGURE 3. Mean polar (A) and equatorial (B) diameter, and ratio of polar:equatorial diameter (C) of cultivars at five harvest dates on weekly intervals, beginning 35 d prior to, and ending with, horticultural maturity. 'Bravo' = ●, 'Bronco' = ○ and 'Transam' = ▼. Values are means of 8 to 16 heads from each of four replications across two years. Error bars are standard error of the means.

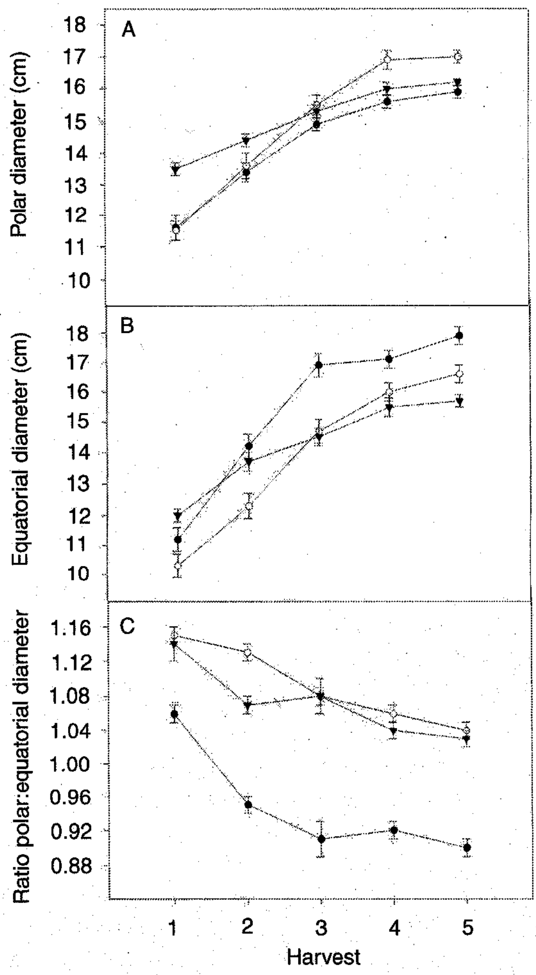
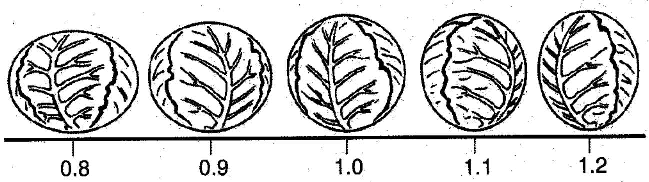


FIGURE 4. Idealized cabbage head shapes corresponding to polar:equatorial diameter ratios of 0.8, 0.9, 1.0, 1.1 and 1.2.



increase in the percent dry matter of heads as they matured. Although previously proposed (North, 1957), the relationship between head diameter and weight has only recently been described in cabbage at horticultural maturity (Kleinhenz and Wszelaki, 2003; Wszelaki and Kleinhenz, 2003). However, work described here is the first to document similar relationships across a wide range of developmental stage and head size.

Head Polar and Equatorial Diameter and Shape. Interestingly, head expansion was greatest in the equatorial direction, as indicated by a decrease in the ratio of polar:equatorial diameter during development. This phenomenon is not explained by a slowing of stem growth, since the most pronounced period of preferential equatorial expansion (H1 to H3) coincides with the period of most rapid stem elongation. Rather, it is likely that asymmetric head expansion resulted from rapid extension of older head leaves, attached at near right angles to the core, combined with thickening of the petiole of newer leaves arising more vertically from the stem. These concurrent events would result in head growth occurring primarily perpendicular to the core, and would explain preferential equatorial expansion of heads, which was evident as a change in head shape.

Core Characteristics. Like other key traits, core height and base width changed most rapidly between H1 and H3. Although stem elongation slowed between H3 and H5 in this study, Hara and Sonoda (1979) reported only a slight decrease in the number of leaves produced late in head development. This suggests that internode length decreases markedly in later stages of head maturation and that the continuous production of leaves, though with minimal expansion, contributes to head fill. Overall, changes in core traits were less pronounced than in other traits, particularly mean head diameter. This is also evident in the decreased percent of head volume occupied by the core.

Effect of Thermal Time. Variation in the influence of harvest date on head traits was greater between years than among cultivars, suggesting that, in this study, environment had a greater influence on treatment differences than did genetics. Environmental differences between years included higher air temperatures in 2002 compared to 2001 (data not shown), and a lack of fertilizer

FIGURE 5. Mean core length (A), base width (B) and percent head volume occupied by the core (C) of cultivars at five harvest dates on weekly intervals, beginning 35 d prior to, and ending with, horticultural maturity. 'Bravo' = ●, 'Bronco' = ○ and 'Transam' = ▼. Values are means of 8 to 16 heads from each of four replications across two years. Error bars are standard error of the means.

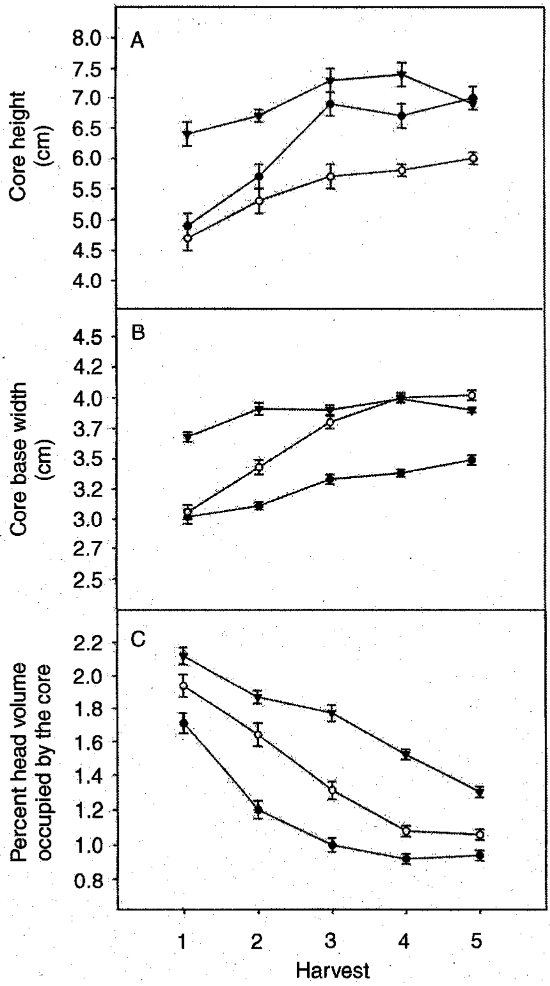
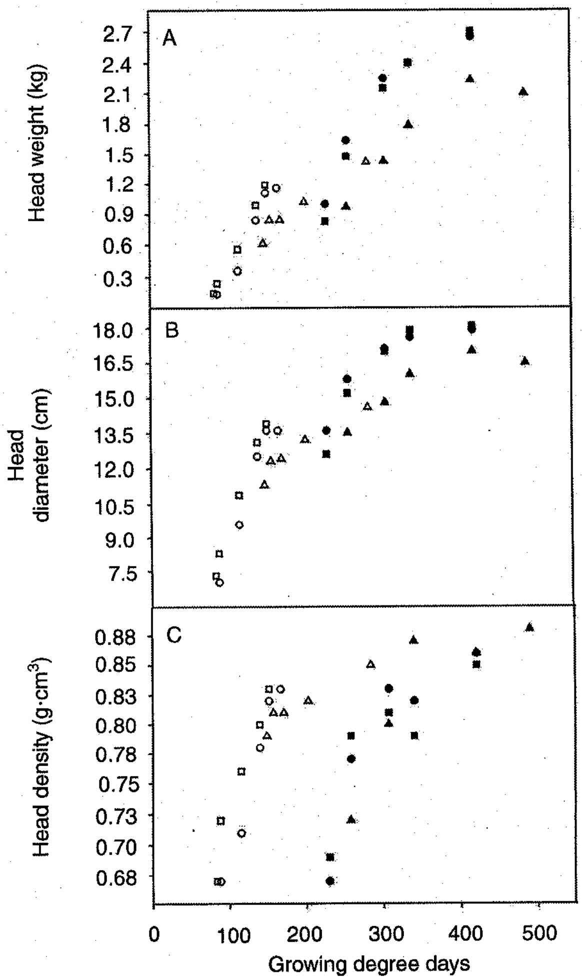


FIGURE 6. Relationship between growing degree-days (GDD) and head weight (A), head diameter (B) and head density (C) of cabbage planted in June 2001 and 2002. Treatment means of 'Bravo', 'Bronco' and 'Transam' are represented by circles, squares, and triangles, respectively. Filled and open symbols represent 2001 and 2002, respectively. If the daily maximum temperature (T_{max}) fell below the upper threshold (21°C), then GDD = (T_{min} + T_{max})/2) – B, where T_{min} = daily minimum temperature and B = the base temperature (0°C). If T_{max} exceeded 21°C, then GDD = [(T_{min} + 21)/2) – B] – [(T_{max} – 21) * 2].



applications in 2001. Despite the absence of fertilizer applications in 2001, heads produced in that year met or exceeded characteristic size and weight values for the cultivars (Kleinhenz and Wszelaki, 2003, Wszelaki and Kleinhenz, 2003), and were larger and slightly denser than heads grown with fertilizer in 2002. Therefore, temperature appears to be the factor contributing most to the variation in growth observed between years. Because growth rate is influenced by temperature, plant development is frequently discussed relative to thermal time (Allen, 1976). Growing degree-day accumulation, adjusted for the negative effect of high temperatures on cabbage growth, explains much of the year-to-year variation in head weight and mean diameter (Figure 6). However, head density, a primary indicator of horticultural maturity, appeared to be influenced less by thermal time. These observations may be significant since they suggest that air temperatures, while influencing the terminal size and weight of mature heads, have a minimal effect on the rate of head maturation. While changes in density may be "genetically hardwired" (i.e., largely dependent on chronological time), photoperiod or other environmental factors may also be involved (Wurr et al., 1996). Based on the results of this and previous work (de Moel and Everaarts, 1990; Hara and Sonoda, 1979; Isenberg et al., 1975; Wurr et al., 1996) we propose that major aspects of cabbage head development follow a sigmoidal pattern as a function of time. However, although changes in head size and weight correlate strongly with thermal time, additional work is necessary to determine the most appropriate measure of time (e.g., chronological, photo-thermal) relative to changes in density as heads mature.

Practical Implications. Beyond increasing our basic understanding of cabbage crop development, information gained in this study may help lead to improvements in the management of cabbage yield and quality. Cabbage may be harvested at various points during the period of development studied here in order to meet the head size requirements of specific markets (Day, 1986; Senior and Whitwell, 1989) or because of labor, equipment or climatic concerns (Kleinhenz, 2003). Head weight, size, shape, density and core dimensions, as well as relationships among them, are also critical indicators of quality in the development, evaluation and selection of cabbage germplasm (Kleinhenz and Wszelaki, 2003; Stofella and Fleming, 1990; Wszelaki and Kleinhenz, 2003). For example, the relationship between head size and weight reported here is noteworthy because it suggests an ability to predict head weight (and, therefore, crop yield) across a wider range of head size and maturity than previously reported (Kleinhenz, 2003). Also, head shape was observed to flatten during development. Since optimal head shape for most markets is represented by a polar:equatorial diameter ratio of 1.0 (round), changes in head shape during development may affect the relative marketability of heads harvested at different maturities. They may also affect the efficacy of tools designed to assist in the prediction of yield, which assume a constant head shape (Kleinhenz, 2003). Finally, the relationship between head and core volume is a key indicator of crop quality, since the core is removed prior to fresh-market consumption or processing. As heads develop, a decrease in the percent head volume occupied by the core results in more usable product available to processors and consumers.

This study documents the status of a comprehensive list of cabbage head traits at five points in head development ending with horticultural maturity. Although fertilizer applications and plant spacing employed in this study deviate slightly from standard production practices, the lack of an environmental influence on the direction of the HD effect indicates that similar trends would be found in commercial settings. Head weight, volume, density and core size increased, while head polar:equatorial diameter ratio and head volume occupied by the core decreased as heads developed and expanded. The rate of change in all traits slowed with time, a trend more pronounced beginning approximately two weeks prior to expected horticultural maturity. Early in development, head expansion was greater in the equatorial than in the polar direction and this was attributed to the elongation of leaves in a direction perpendicular to the stem and the thickening of petioles in leaves arising more parallel to the stem. Head weight increased at a greater rate than head volume, perhaps due to thickening of older leaves and a marked shortening of internodes in the production of new leaves. The economically important relationships between head size and weight, polar and equatorial diameter, and core and head volume were also affected by harvest date, and strongly suggest that accurate assessments of developmental stage are required to establish harvest schedules intended to maximize head quality. With head density apparently unrelated to thermal time, it may be appropriate to view head growth and maturation as separate and distinct concepts in discussions of head development. It also underscores the need to determine the genetic and/or environmental factors that influence head density.

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