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Quantifying Phenology and Maturity in Crisphead Lettuce

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SUMMARY. The *Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie* (BBCH) identification key was adapted for crisphead lettuce (*Lactuca sativa*) to facilitate identification of phenological stages and decisions regarding field operations from seeding to harvest maturity. The original system described leaf development based on leaf count from stage 11 (1 leaf) to stage 19 (9 leaf), and head development based on percentage of expected head size reached at maturity from stage 41 to 49. The new coding leaf development stages range from 11 to 29, corresponding to the 1-leaf to 19-leaf stages. The head development stages also ranged from 41 to 49, but phenological stages near commercial maturity from 43 to 49 are now described as a function of head firmness. The important maturity traits of crisphead lettuce include head size and density. Head volume can be estimated from three diameters by using Currence's equation, which takes into account head geometry. The firmness index obtained by hand compression gave a more precise estimate of head density than the density estimate derived from Currence's equation or the sphere equation. Crisphead lettuce development stages and maturity traits can be easily quantified in the field for use in planning field operations and for experimental purposes.

The *Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie* (BBCH) scale was developed to standardize the coding of phenological stages of mono- and dicotyledonous plant species (Lancashire et al., 1991). This scale can be used for defining

phenotypic characters that are highly heritable and expressed in all environments; for determining the timing of cultural practices such as pesticide and fertilizer applications; and for planning the crop harvesting schedule. The BBCH scale is a unified system that aptly describes the phenological

stages of most crops and weeds, although some specific stages such as those related to vegetable harvesting are not precisely delineated (Lancashire et al., 1991).

In the BBCH system, for leafy vegetables that form heads, a scale of 00 to 09 is used to describe the germination phase; a scale of 10 to 19 is then used for the leaf development phase (up to 9 true-leaf stage), and the scale values jump to 41 to 49 for the development of harvestable vegetative parts, which corresponds to the head formation phase. In the field, we often observe counts above 10 leaves before principal phenological phase 4 [i.e., the beginning of head formation (code 41)] is reached. The head formation stages are described based on percentage of expected head size reached, which can be highly variable and therefore difficult to evaluate with precision. Furthermore, growers are using not only head size, but also head firmness, to define commercial maturity.

After heading initiation, crisphead lettuce leaves continue to grow, overlapping onto each other to form a head of increasing density and size. At harvest time, maturity is evaluated on the basis of density and size (Garrett et al., 1969; Goddard et al., 1972). Crisphead lettuce must reach a desirable density to meet market requirements and to minimize handling damage. Although head density is more relevant than firmness in determining optimal maturity, estimating firmness by hand compression on a 1 to 5 scale (Kader et al., 1973) is easier and faster to perform in the field than calculating head density from measured weight and volume. Furthermore, evaluating head firmness by hand compression gives a simultaneous indication of head size. However, the assessment of firmness rating requires a well-trained evaluator. An alternative method consists of calculating

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The use of trade names does not imply endorsement of the products named or criticism of similar ones not named.

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
2.54	inch(es)	cm	0.3937
16.3871	inch ³	cm ³	0.0610
1.1209	lb/acre	kg·ha ⁻¹	0.8922
28.3495	oz	g	0.0353
1.7300	oz/inch ³	g·cm ⁻³	0.5780
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

head density from head weight and volume. Volume can be estimated from diameter, assuming the crisphead lettuce head is a sphere. However, a crisphead lettuce head is not uniform and more than one diameter may be necessary for an accurate estimation of volume. An equation that takes into account the departure of the shape from a sphere (Currence et al., 1944) has been successfully used for fruit such as muskmelon (*Cucumis melo*) (Jenni et al., 1997) and pepper (*Capsicum annuum*) (Ngouajio et al., 2003). Currence's equation uses two different values of a K component depending on whether the shape is more elongated or more flat, a variation found in crisphead lettuce heads.

The relation between actual head density and head firmness determined by hand compression has never been compared. Garrett et al. (1969) studied the relationship between head density and firmness based on the change in head height caused by a load increment. Schofield et al. (2000) compared firmness measured by a force-deformation method and by the hand compression method, but did not relate them to head density. In this article, we examine the relationship between head density measured by water displacement with head firmness determined by hand compression, as well as head density calculated from head weight and volume based on the polar and equatorial diameters. We also evaluate the precision of each of these approaches.

The objectives of this study were to adapt the BBCH scale for crisphead lettuce by incorporating a potential leaf count up to 19 and by providing a standardized description

of the head formation phase based on head firmness; to select a non-destructive method for head volume measurements that uses the sphere equation, Currence's equation, and one to three head diameters; and to relate head density measurements made by water displacement with those derived by the hand compression method as well as with head density derived from the aforementioned equations for volume. This methodology will be easy to use in the field and will support the development of a bioclimatic model to predict maturity for planning seeding and harvesting schedules.

Materials and methods

QUANTIFYING PHENOLOGY. The crisphead lettuce variety Ithaca (Coop Uniforce, Sherrington, Quebec, Canada) was direct seeded in nine fields on three commercial farm sites (Table 1). Plots consisted of double-row beds, 6 inches high and 36 to 40 inches wide depending on the site and current farm practices. Crisphead lettuce plants were staggered in double rows spaced 12 inches and manually weeded and thinned to obtain a within-row spacing of 12 to 14 inches depending on the site. This resulted in population densities ranging from 59,900 to 61,900 plants/ha. All plots were overhead irrigated immediately after sowing. Nitrogen (N) fertilization was applied in accordance with commercial recommendations (Center de référence en agriculture et en agroalimentaire du Québec, 2003): preplant N was applied at a rate of 80 kg·ha⁻¹. Potassium and phosphorous were applied according to soil tests and recommendations for each soil type. Pest and disease control was

carried out according to standard procedures (Ontario Ministry of Agriculture, Food and Rural Affairs, 2004).

RELATIONSHIP BETWEEN HEAD FIRMNESS AND DENSITY. Twenty-four-day-old plants of crisphead lettuce varieties Ithaca 989, Emperor, Onondaga, and Summertime were transplanted on 28 June 2002 to a well-decomposed muck soil in Saint-Blaise, Quebec. Bed size, weed control, fertilizer application, and irrigation were similar to the experiment described above. Plots containing 80 plants of each variety were arranged in a complete randomized block design with four replicates and were surrounded by guard rows. When 80% of the plants of the variety Ithaca reached an acceptable firmness index of 3 (Kader et al., 1973), 15 plants per plot were randomly harvested and promptly delivered to the storage facilities of Agriculture and Agri-Food Canada in Saint-Jean-sur-Richelieu, where they were stored at 6 °C for less than 6 h. The wrapper leaves were removed, leaving the first tightly held leaf attached. Similar to the procedure by Radovich and Kleinhertz (2004), each head was placed in a plastic bag, which was tied after removing the excess air, and the "observed" volume was measured by immersion in a container (9 inches wide × 12 inches long × 16 inches deep) equipped with a weir and filled with water at full capacity. The displaced water was collected into a graduated cylinder and weighed with a scale with readability at 0.01 g (PB3002; Mettler Toledo, Columbus, OH). Weighing displaced water (1 g = 1 cm³) allowed the measurement of the head volume. Additional measurements taken on the 240

Table 1. Soil type, location, seeding dates, and planting dates of 'Ithaca' crisphead lettuce fields for identification of phenological stages in 2004.

Site	Soil identification	Location in Quebec, Canada	Latitude and longitude	Seeding date	Harvest date
1	Typic Humic Mesisol (euic, mild subaquic)	Saint-Blaise	lat. 45°11'N long. 73°20'W	20 May 9 June 30 June	23 July 4 Aug. 24 Aug.
2	Terrie Humic Mesisol (euic, mild subaquic, clayey)	Saint-Patrice-de-Sherrington	lat. 45°10'N long. 73°31'W	25 May 25 June 14 July	24 July 18 Aug. 13 Sept.
3	Limno Humic Mesisol (euic, mild subaquic, coprogenous)	Sainte-Clotilde	lat. 45°09'N long. 73°41'W	3 June 18 June 7 July	28 July 10 Aug. 3 Sept.

heads included fresh weight, polar diameter, and two perpendicular equatorial diameters measured with a 40-cm Mantax caliper (Haglof, Langsele, Sweden).

In addition, head volumes were estimated using the following sphere equation:

$$V_s = \pi(D_{e1} + D_{e2} + D_p)/162$$

where V_s is the head volume estimated from the sphere equation (cubic centimeters), D_{e1} is the first equatorial diameter (centimeters), D_{e2} is the second perpendicular equatorial diameter (centimeters) and D_p is the polar diameter (centimeters).

Currence's equation was used to take into account head geometry:

$$V_c = KD_c^2 D_p$$

where

$$K = 0.1528(D_c/D_p) + 0.4152, \text{ if } (D_c/D_p) \leq 1$$

$$K = -0.2204(D_c/D_p) + 0.7872, \text{ if } (D_c/D_p) > 1$$

and V_c is the head volume estimated from Currence's equation (cubic centimeters) K is a shape factor, D_c is the average equatorial diameter (centimeters), and D_p is the polar diameter (centimeters).

Estimated head densities were calculated from head weight and volumes derived from 1) Currence's equation, 2) the sphere equation using a) one diameter (equatorial or polar), b) two diameters (two equatorial, or one equatorial and one polar), and c) three diameters.

The firmness of the heads was ranked from 1 to 5 by a well-trained evaluator using the hand compression method (Kader et al., 1973): 1 = soft, easily compressed or spongy; 2 = fairly firm, neither soft nor firm, with good head formation; 3 = firm, compact, but may yield slightly to moderate pressure, and commercially acceptable; 4 = hard, compact, and solid; and 5 = extra-hard, overmature, and may have cracked midribs.

STATISTICAL ANALYSIS. Analyses of variance were performed using PROC GLM (SAS, version 9.1 for Windows; SAS Institute, Cary, NC). The TableCurve 2D software (version 5.01; Systat Software, San Jose, CA) was used to fit regression curves for crisphead lettuce head

density measured by water displacement as a function of firmness, as well as densities estimated by the different methods. Simple linear regression and Table Curve 2D software were used to select the simplest equation from

among 8,189 linear and nonlinear equations, based on high coefficient of determination and narrow confidence intervals and low residuals.

Results and discussion

A modified BBCH scale was developed to describe the growth of crisphead lettuce (Fig. 1 and Table 2). Similar to the original BBCH scale (Meier, 2001), the system starts with the principal developmental stages 0 (for germination) and 1 (for leaf development). The new code uses additional stages ranging from 20 (10 leaves) to 29 (19 leaves). With 'Ithaca', the variety used in this study, the average number of unfolded leaves in the week preceding beginning of heading (stage 41) was 15.7 ± 0.6 leaves and never exceeded 19 leaves (stage 29), therefore, it is unlikely that stages beyond stage 29 will be necessary. However, other crisphead varieties may produce more than 19 unfolded leaves before the beginning of heading stage (stage 41) and there would still be room to use coding between 30 and 39 for describing stages after 19 leaves.

Feller et al. (1995) described head-forming leafy vegetables, but did not include any descriptions for principal developmental stages between 1 and 4, leaving a large gap between stage 19 (9 leaves) and stage 41 (beginning of heading). During this intermediate phase, the plant continues to produce leaves until the two youngest leaves are not unfolding;

Fig. 1. Ten typical phenological stages of crisphead lettuce. The number on the right top of each picture refers to the phenological stage codes as follows: Code 10 = cotyledons are completely unfolded; Code 15 = 5 true leaves longer than 2 cm are visible; Code 20 = 10 true leaves longer than 2 cm are visible; Code 29 = 19 true leaves longer than 2 cm are visible; Code 41 = head begins to form, the two youngest leaves do not unfold; Code 43 = the head is soft, easily compressed or spongy; Code 45 = the head is well formed, fairly firm, neither soft nor firm; Code 47 = the head is firm, compact, but may yield slightly to moderate pressure; Code 49 = the head is hard, compact and solid; and Code 50 = the head is extra-hard, overmature, and may have cracked ribs, and the stem (or core) inside the head begins to elongate (1 cm = 0.3937 inch).

this marks the stage described as the beginning of heading. Meier (2001) proposed a three-digit system to allow the inclusion of a “mesostage” for the species, whereby up to 19 leaves are counted along the main stem. With this system, 1 leaf would be coded 101 and 19 leaves would be coded 119, typically followed by stage 410 (i.e., the beginning of heading). By contrast, a two-digit system is adopted in the present study to avoid large numerical gaps between the principal developmental stages. The system for beets uses developmental stages 11 (1 leaf) to 19 (9 leaf) and includes principal developmental stage 3 describing rosette growth as a function of percentage of soil cover. This approach could be used for crisphead lettuce, but the percentage of soil cover is more difficult to describe precisely than leaf count. Here, we propose that the leaf development stage after the completely unfolded cotyledon (stage 10) be described using a scale from stage 11 (1 leaf) to stage 29 (19 leaves), which would permit precise and rapid description of the stages (Fig. 1 and Table 2). The phenological stages can be graphically represented as a function of time, and differences between multiple seedings can be easily observed (Fig. 2). For crop management purposes, we identified 10 useful phenological stages (Fig. 1). These include Code 10, cotyledons are completely unfolded; Code 15, five true leaves longer than 2 cm are visible; Code 20, ten true leaves longer than 2 cm are visible; Code 29, 19 true leaves longer than 2 cm are visible; Code 41, head begins to form, the two youngest leaves do not unfold; Code 43, the head is soft, easily compressed, or spongy; Code 45, the head is well formed, fairly firm, and neither soft nor firm; Code 47, the head is firm, compact, but may yield slightly to moderate pressure; Code 49, the head is hard, compact, and solid; and Code 50, the head is extra-hard, overmature, and may have cracked ribs, and the stem (or core) inside the head begins to elongate.

The four varieties used in the density and firmness evaluation test showed a variation in head size, weight, shape, and firmness. ‘Ithaca’ was firmer and heavier than ‘Emperor’ and ‘Summertime’ and larger than ‘Emperor’ and ‘Onondaga’ (Table 3).

Table 2. Phenological stages of crisphead lettuce using a modified BBCH scale (0 = dry seed stage, 50 = beginning of inflorescence emergence)^a.

Code	Head firmness score (1–5 scale) ^b	Description ^c
Principal developmental stage 0: Germination		
00	—	Dry seed
05	—	Radicle emerged from seed
08	—	Hypocotyl with cotyledons growing toward soil surface
09	—	Emergence: cotyledons break through soil surface
Principal developmental stage 1 and 2: Leaf development		
10	—	Cotyledons completely unfolded
11	—	First true leaf longer than 2 cm
12	—	2 true leaves longer than 2 cm
13	—	3 true leaves longer than 2 cm
14	—	4 true leaves longer than 2 cm
15	—	5 true leaves longer than 2 cm
16	—	6 true leaves longer than 2 cm
17	—	7 true leaves longer than 2 cm
18	—	8 true leaves longer than 2 cm
19	—	9 true leaves longer than 2 cm
20	—	10 true leaves longer than 2 cm
21	—	11 true leaves longer than 2 cm
22	—	12 true leaves longer than 2 cm
23	—	13 true leaves longer than 2 cm
24	—	14 true leaves longer than 2 cm
25	—	15 true leaves longer than 2 cm
26	—	16 true leaves longer than 2 cm
27	—	17 true leaves longer than 2 cm
28	—	18 true leaves longer than 2 cm
29	—	19 true leaves longer than 2 cm
Principal developmental stage 4: Head development		
41	—	Head begins to form: the two youngest leaves do not unfold
43	1	Soft head, easily compressed or spongy
45	2	Good head formation, i.e., fairly firm head, neither soft nor firm
47	3	Firm, compact head, but may yield slightly to moderate pressure
49	4	Hard, compact and solid head
Principal developmental stage 5: Inflorescence emergence		
50	5	Extra-hard, overmature, and may have cracked ribs, and stem (or core) inside the head begins to elongate

^aSee Feller et al., (1995) or Meier (2001) for the description of stages 51 to 99 (harvested seeds).

^bFirmness was evaluated by hand compression on a 1 to 5 scale: 1 = soft, easily compressed or spongy; 2 = fairly firm, neither soft nor firm, good head formation; 3 = firm, compact, but may yield slightly to moderate pressure, commercially acceptable; 4 = hard, compact and solid; and 5 = extra-hard, overmature, and may have cracked midribs.

^c1 cm = 0.3937 inch.

Fig. 2. Phenological stages of ‘Ithaca’ crisphead lettuce based on a modified BBCH scale from 0 to 50 in eight sequential seedings grown on organic soils, from seeding to commercial maturity, during the 2004 growing season.

Table 3. Effect of four crisphead lettuce varieties on head characteristics grown on organic soils.

Variety	Head firmness score (1–5 scale) ^z	Head wt (g) ^y	Equatorial: polar diam (ratio)	Head vol (cm ³) ^x	Head density (g·cm ⁻³) ^w
Ithaca	3.8 a ^v	550 a	0.97 b	1579 a	0.35 a
Emperor	3.2 c	335 c	0.98 b	1160 c	0.27 c
Onondaga	3.8 ab	470 b	1.02 ab	1380 b	0.34 a
Summertime	3.7 b	435 b	1.04 a	1475 ab	0.30 b
P value from ANOVA	<0.0001	<0.0001	0.0051	<0.0001	<0.0001

^xFirmness was evaluated by hand compression on a 1 to 5 scale: 1 = soft, easily compressed or spongy; 2 = fairly firm, neither soft nor firm, good head formation; 3 = firm, compact, but may yield slightly to moderate pressure, commercially acceptable; 4 = hard, compact and solid; and 5 = extra-hard, overmature, and may have cracked midribs.

^y1 g = 0.0353 oz.

^zHead volume was measured by water displacement; 1 cm³ = 0.0610 inch³.

^wHead density was calculated from head weight and volume by water displacement; 1 g·cm⁻³ = 0.5780 oz/inch³.

^vMeans within a column not followed by the same letter differ at the 0.05 level according to Fisher's protected least significant test.

Table 4. Linear regression between observed (Y) and calculated (X) volume and density of crisphead lettuce head. Observed volume and density were obtained from water displacement. Calculated volume and density were derived by using the equation from Currence et al., (1944) and the sphere equation with one to three head diameters. Based on 'Ithaca', 'Emperor', 'Onondaga', and 'Summertime' varieties grown on organic soils (n = 235).

	Head vol (cm ³) ^z		Head density (g·cm ⁻³) ^z	
	Equation ^y	R ²	Equation ^y	R ²
Currence's equation ^x	Y = 1.13X + 223	0.86	Y = 0.609X + 0.0529	0.45
Sphere equation using:				
Polar and two equatorial diameters	Y = 1.19X + 211	0.83	Y = 0.522X + 0.0803	0.45
Polar and one equatorial diameters	Y = 1.10X + 308	0.77	Y = 0.386X + 0.138	0.34
Two equatorial diameters	Y = 1.03X + 370	0.79	Y = 0.333X + 0.163	0.21
Polar diameter	Y = 0.819X + 573	0.52	Y = 0.197X + 0.222	0.21
One equatorial diameter	Y = 0.861X + 548	0.67	Y = 0.147X + 0.243	0.09

^z1 cm³ = 0.0610 inch³, 1 g·cm⁻³ = 0.5780 oz/inch³.

^yAll coefficients are significant at P < 0.001.

^xThe head volume estimated from Currence's equation [V_c (cm³)] was estimated as follows:

V_c = KD_e³D_p, where: K = 0.1528 (D_e/D_p) + 0.4152, if (D_e/D_p) ≤ 1 or K = -0.2204 (D_e/D_p) + 0.7872, if (D_e/D_p) > 1, D_e, the average equatorial diameter (cm); and D_p, the polar diameter (cm); 1 cm = 0.3937 inch.

Fig. 3. Relationship between crisphead lettuce head density calculated from head weight and volume by water displacement with (A) firmness estimated by hand compression on a 1 to 5 scale (1 = soft, easily compressed or spongy; 2 = fairly firm, neither soft nor firm, good head formation; 3 = firm, compact, but may yield slightly to moderate pressure, commercially acceptable; 4 = hard, compact and solid; and 5 = extra-hard, overmature, and may have cracked midribs) and (B) density using the equation of Currence et al., (1944) (1 g·cm⁻³ = 0.5780 oz/inch³).

'Ithaca' and 'Emperor' heads tended to be longer than they were wide, but the opposite was true for 'Summertime'. 'Emperor', a late variety, had

softer, smaller, and lighter heads than the other three varieties.

Currence's equation using three head diameters gave the best estimate

of head volume measured by water displacement (R² = 0.86, n = 235). Depending on the desired precision and the available resources, several

alternative approaches are available for estimating head volume (Table 4). The approach using one equatorial diameter explained 67% of the variation in the observed volume, whereas using the polar diameter explained only 52% of the variation. A good alternative consists in estimating volume from two equatorial diameters, as this explains 79% of the variation in the observed volume. Overall, the estimated volume based on the sphere equation or Currence's equation underestimated the actual volume as determined by water displacement.

Surprisingly, estimating head density using head firmness obtained by hand compression was more precise ($R^2 = 0.65$) than estimating head density using Currence's equation ($R^2 = 0.45$) (Fig. 3). The relationship between observed density and firmness followed a nonlinear exponential equation. The large distortion in the estimation of the observed head density below $0.3 \text{ g}\cdot\text{cm}^{-3}$ may be due to the difficulty of precisely measuring the diameter of a soft crisphead lettuce head with a caliper. Hand firmness clearly gave a more precise estimate of head density for soft heads below a firmness index of 3.5.

In conclusion, head volume can be estimated with good precision ($R^2 = 0.86$) from Currence's equation using three diameters. If resources are limited, a good compromise is to estimate head volume using the sphere equation, either with two equatorial diameters ($R^2 = 0.79$) or

one equatorial diameter ($R^2 = 0.67$). Head firmness can be used to evaluate head density with better precision than density estimated from the measurement of one to three diameters. A modified BBCH scale, estimation of head volume from one to three diameters, and head density based on a firmness index can be easily used by growers and agrologists for planning field operations and defining commercial maturity of crisphead lettuce, and by scientists for experimental and modeling purposes.

Literature cited

- Centre de référence en agriculture et en agroalimentaire du Québec. 2003. Guide de référence en fertilisation. 1st ed. Centre de référence en agriculture et en agroalimentaire du Québec, Sainte-Foy, Quebec, Canada.
- Currence, T.M., R.E. Lawson, and R.M. Brown. 1944. A rapid method for finding the volume and density of muskmelon fruits. *J. Agr. Res.* 68:427–440.
- Feller, C., H. Bleiholder, L. Buhr, H. Hack, M. Hess, R. Klose, U. Meier, R. Stauss, T. Van den Boom, and E. Weber. 1995. Phänologische entwicklungsstadien von gemüsepflanzen: I. Zwiebel-, wurzel-, knollen- und blattgemüse. *Nachrichtenblatt des Deutschen Pflanzenchutzdienstes* 47:193–206.
- Garrett, R.E., M. Zahara, and F. Zink. 1969. A method for evaluating selectors of crisphead lettuce. *Trans. Amer. Soc. Agr. Eng.* 12:564–566.
- Goddard, W.B., M. Zahara, P.A. Adrian, and D.H. Lenker. 1972. The relationship of physical properties to market acceptability of crisphead lettuce. *Trans. Amer. Soc. Agr. Eng.* 15:358–360.
- Jenni, S., K.A. Stewart, G. Bourgeois, and D.C. Cloutier. 1997. Non-destructive volume estimation for growth analysis of eastern-type muskmelon ovaries. *HortScience* 32:342–343.
- Kader, A.A., W.J. Lipton, and L.L. Morris. 1973. Systems for scoring quality of harvested lettuce. *HortScience* 8:408–409.
- Lancashire, P.D., H. Bleiholder, T. van den Boom, P. Langelüddeke, R. Stauss, E. Weber, and A. Witzemberger. 1991. A uniform decimal code for growth stages of crops and weeds. *Ann. Appl. Biol.* 119:561–601.
- Meier, U. 2001. Growth stages of mono- and dicotyledonous plants. BBCH Monograph. Federal Biological Research Centre for Agriculture and Forestry. Wissenschaftsverlag, Berlin, Germany.
- Ngouajio, M., W. Kirk, and R. Goldy. 2003. A simple model for rapid and non-destructive estimation of bell pepper fruit volume. *HortScience* 38:509–511.
- Ontario Ministry of Agriculture. Food and Rural Affairs. 2004. Vegetable production recommendations 2004-2005. Ontario Ministry of Agriculture, Food and Rural Affairs Publ. 363.
- Radovich, T.J.K. and M.D. Kleinheinz. 2004. Rapid estimation of cabbage head volume across a population varying in head shape: A test of two geometric formulae. *HortTechnology* 14:388–391.
- Schofield, R.A., J.R. DeEll, and D.P. Murr. 2000. Objective method for measuring firmness of iceberg lettuce. *HortScience* 35:894–897.