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A Survey of Fruit Firmness in Highbush Blueberry and Species-introgressed Blueberry Cultivars

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Abstract. **Eighty-seven highbush blueberry and species-introgressed blueberry cultivars were evaluated for fruit firmness in the 1998–2000 growing seasons with a FirmTech 1 automated firmness tester. Significant differences were observed among cultivars. An average firmness of 136.1 g·mm^{-1} of deflection (g·mm^{-1} dfl) was observed across all studied cultivars, and a range of 80.4 g·mm^{-1} dfl (‘Herbert’) to 189.0 g·mm^{-1} dfl (‘Pearl River’). Species ancestry was not consistently related to firmness; however, cultivars with higher firmness values often possessed a higher percentage of *Vaccinium darrowi* Camp and *V. ashei* Reade ancestry. Conversely, cultivars with softer than average fruit often possessed a higher percentage of lowbush (*V. angustifolium* Ait.) ancestry. This information may help to identify sources of breeding material for increased firmness in highbush blueberry hybrids.**

In blueberry, softening that occurs at ripening is associated with the enzymatic digestion of cell wall components such as pectin, cellulose and hemicellulose (Proctor and Miesle, 1991). Total water soluble pectin, which comprises much of the middle lamella, was shown by Proctor and Peng (1989) to decrease steadily as blueberries ripen from green to blue. This degradation of the cell wall and middle lamella is directly responsible for the loss of firmness in ripening fruits (Eskin, 1979). Ripening is also accompanied by changes in coloration, decreases in acidity and increases in sugars (Kushman and Ballinger, 1968). Once initial ripeness has been achieved, a further process of “overripe softening” occurs which is accompanied by further decreases in acidity and increases in sugars. Both the innate firmness and post-ripeness softening are critical factors in the final quality of fresh blueberries.

Fruit firmness is an important economic trait in blueberry. Currently, labor accounts for ≈50% of the production cost of hand-harvested fresh-market fruit (Paul Macrie, N.J. blueberry grower, personal communication). Reductions in available farm labor, as well as increases in the minimum wage, have resulted in increased need for mechanical harvesting (Ballington et al., 1990). Firm fruit withstands both mechanical harvesting and subsequent shipping better than soft fruit (Ballington et al., 1984). Fruit of firmer cultivars can also be left on the bush longer (hanging potential) than fruit of soft cultivars, allowing more flexibility in timing of harvests. In addition to these production concerns, consumers perceive firm blueberries to be of higher quality. This perception (or the lack of it) can affect blueberry marketability and consumer demand.

Fruit firmness has been evaluated in both cultivated and species material. Ballington et al. (1984) evaluated 11 species, including *V. corymbosum* and *V. ashei*, and found that *V. darrowi*, *V. tenellum* Ait., *V. myrtsinites* Lam., and particularly *V. stamineum* L., are among the more firm-fruited species. In a comparison of 13 *V. ashei* and 15 *V. corymbosum* cultivars, *V. ashei* types were shown to be significantly firmer (Makus and Morris, 1987). Conversely, *Vaccinium angustifolium* has been shown to be less firm than *V. corymbosum* (Ballington et al., 1984).

Firmness is an exceedingly important characteristic when evaluating for cultivar release. Parental phenotype in blueberry often determines progeny firmness characteristics (Edwards et al., 1974). *Vaccinium angustifolium*, for instance, was shown by Finn and Luby (1992) to produce soft-fruited progeny. Several cultivars released in the past two decades have displayed greater firmness than earlier cultivars. ‘Duke’ (Draper et al., 1987), ‘Sierra’ [U.S. Dept. of Agriculture (USDA), 1988], ‘Nelson’ (USDA, 1988), and ‘Reveille’ (Ballington et al., 1990) all displayed superior firmness. Cultivars also differ in their ability to retain firmness after initial ripening. In recent years, automated firmness testers have allowed for objective measurement of fruit firmness (Mitcham et al., 1998).

The USDA–Agricultural Research Service (ARS) blueberry breeding program at the Philip E. Marucci Center for Blueberry and Cranberry Research and Extension at Rutgers Univ. has an extensive collection of highbush blueberry cultivars. We felt the first step in breeding for improved firmness was to assay the collection for firmness of ripe fruit prior to softening. This study was done to measure the firmness of a large number of blueberry cultivars and to examine firmness in relation to ancestry and release date.

Materials and Methods

Fruit samples of 87 blueberry cultivars were assayed across three growing seasons, 1998 to 2000, from demonstration plots planted in 1995 at the Philip E. Marucci Center for Blueberry and Cranberry Research and Extension at Rutgers Univ., Chatsworth, N.J. The bushes were grown in USDA plant hardiness zone 6, on soils that are mostly Atsion sand containing 3% to 15% organic matter. Cultural practices in the plots (3 cm deep × 0.75 m wide) included clean cultivation, surface mulching with cranberry leaves, and the use of solid-set irrigation for irrigation and frost protection. In these plots, northern-adapted highbush cultivars were represented by five plants per cultivar (among these were ‘Legacy’, ‘Sierra’, and ‘Ozarkblue’, all of which have some *V. darrowi* ancestry). All other cultivars, including North Carolina-adapted highbush, southern highbush (*V. corymbosum* introgressed with *V. darrowi*), half-highs (*V. angustifolium* x *V. corymbosum* hybrids), processing types (*V. ashei* x *V. constablaei* Gray), and rabbiteye hybrids (*V. ashei* x *V. corymbosum*), were represented by two plants (except as noted in Table 1). The cultivars were evaluated weekly for overall ripeness, and ripe fruit was sampled a single time when the crop on that cultivar was 15% to 25% ripe. Fruit was sampled equally from the available bushes, and care was taken to ensure that the fruit collected was undamaged and at peak quality. Thirty-five to forty berries were collected from each cultivar in 1998 and 60–70 berries were collected in 1999 and 2000. After collection, the samples were refrigerated at 5 °C until the next day, then brought to 21 °C before being evaluated. A FirmTech 1 firmness tester (BioWorks, Stillwater, Okla.), which measured the force-deformation responses of compressed berries in terms of g·mm^{-1} of deflection (g·mm^{-1} dfl), was used to assess firmness. The testing unit was set to a minimum deflection threshold of 15 g and a maximum compression force of 200 g. In 1998, each sample size was 25 berries and in 1999 and 2000 sample size was 50. To minimize structural effects, berries were positioned so they would be compressed equatorially. The FirmTech 1 tester reported average firmness in each experimental sample as well as standard deviation, minimum and maximum values. Additionally, firmness values for individual berries were stored to spreadsheet files that were accessed for statistical analyses.

A square root transformation was applied to equalize the variances within the data before statistical analysis. Data were analyzed as a two-factor general linear mixed model using the Proc Mixed model of the Statistical Analysis System (SAS Institute, Cary, N.C.), with cultivars as a fixed factor, and years as a random factor. Means comparisons were per-

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formed with the Tukey–Kramer adjusted P test ($P \leq 0.05$).

Results and Discussion

For firmness, year was not a significant effect; however, there was a significant interaction of year × cultivar ($F = 8.18$, $P \leq 0.0001$). Yearly averages for 1998 and 1999 were closely comparable at 141.7 and 140.4 g·mm^{-1} dfl, respectively, whereas the 2000 average was somewhat lower at 131.1 g·mm^{-1} dfl (Table 1). The lower firmness in 2000 may be linked to weather differences, in that, among the 3 years, the 2000 growing season had average to above average rainfall, while both the 1998 and 1999 seasons had rainfall considerably below average. Drier conditions may have led to the formation of thicker cuticles on fruit. Cuticle and epidermal thickness may have played a role in measured fruit firmness. Shrinking and swelling of berries in response to turgor changes may also have caused the fruit to soften. The effect of weather on blueberry firmness is poorly understood; however, Ballinger et al. (1973) found both year and harvest date effects could be significant.

Significant differences were found for cultivar firmness ($F = 5.95$, $P \leq 0.0001$). Average firmness values ranged from 80.4 g·mm^{-1} dfl ('Herbert') to 189.0 g·mm^{-1} dfl ('Pearl River') with an average of all cultivars 136.7 g·mm^{-1} dfl (Table 1). Because of the very large number of pairwise comparisons made among cultivars, and the relatively conservative nature of the Tukey–Kramer test, 14 statistical groupings were resolved and considerable overlap existed between groups. The firmest group contained 'Pearl River', 'Misty' (186.7 g·mm^{-1} dfl), 'Bladen' (184.7 g·mm^{-1} dfl), 'Cooper' (174.5 g·mm^{-1} dfl), and 'Avonblue' (172.4 g·mm^{-1} dfl) as well as 44 other cultivars, and ranged as low as 129.0 g·mm^{-1} dfl ('Ornablue'). The softest group contained 'Herbert' (80.4 g·mm^{-1} dfl), 'Atlantic' (98.8 g·mm^{-1} dfl), and 20 additional cultivars, and ranged as high as 129.0 g·mm^{-1} dfl ('Ornablue'). Despite the lack of statistical separation among cultivars the casual observer can normally recognize firmness differences of 10–20 g·mm^{-1} dfl (personal observation). In our evaluations, firmness of 130–140 g·mm^{-1} dfl is considered average, and typical of several widely grown cultivars such as 'Bluecrop', 'Elliott', and 'Croatan'. Firmness of 150–160 g·mm^{-1} dfl is very good and typical of cultivars such as 'Duke', 'Burlington', 'Ozarkblue', 'Reka', 'Star', and 'Brigitta Blue'. Values above 160 are considered superior.

Differences in climate, soils, cultural practices, and other environmental factors may cause firmness of some cultivars to vary from region to region. For instance, studies conducted in North Carolina have shown that 'Reveille' is consistently firmer than 'Bladen', and 'Croatan' is, on average, much softer than

Table 1. Fruit firmness values of highbush blueberry (*Vaccinium corymbosum*) and species-introgressed blueberry cultivars, 1998–2000.

		Year of	Firmness (g·mm^{-1} of deflection)					
Cultivar	Type[z]	release	Avg	1998	1999	2000	Min.	Max.
Herbert	HB	1952	80.4 a[y]	79.1	91.5	73.4	53.4	118.0
Atlantic	HB	1939	98.8 ab	89.2	109.9	100.1	71.0	141.1
Cabot	HB	1920	103.1 a–d	112.1	---	93.7	67.9	146.7
Concord	HB	1928	103.7 a–c	97.6	109.8	106.1	71.9	145.4
Murphy	HB	1950	105.0 a–d	96.2	---	114.1	81.6	139.4
Dixi	HB	1936	107.8 a–d	104.6	109.9	111.5	75.5	163.4
Wareham	HB	1936	108.3 a–d	107.7	121.6	98.4	67.9	150.7
Olympia	HB	1933	112.3 a–e	126.8	100.0	112.9	81.3	150.1
Northland	HB	1967	113.3 a–f	105.6	121.2	114.7	89.8	147.5
Hardyblue	HB	---	113.8 a–f	124.7	110.4	108.5	79.6	153.7
Wolcott	HB	1950	114.9 a–f	107.3	129.8	110.5	83.5	158.4
St. Cloud	HH	1990	115.3 a–i	---	115.0	113.2	88.7	148.6
Ivanhoe	HB	1951	115.8 a–f	131.3	106.1	114.2	79.6	176.5
Friendship	HH	1992	118.5 a–n	---	122.1	107.1[x]	79.7	135.1
Pioneer	HB	1920	119.4 a–g	107.7	134.8	118.5	87.0	168.3
Georgiagem	SHB	1987	119.9 a–h	127.1	128.8	106.4	89.8	159.2
Heerma	HB	1983	120.6 a–k	---	129.9	111.8	72.7	183.3
Patriot	HB	1976	121.5 a–i	121.3	126.0	118.6	95.5	165.0
Bluejay	HB	1978	121.5 a–i	123.8	122.8	118.7	88.5	164.1
Sampson	SHB	1998	122.2 b–i	138.0	107.0	125.5	86.3	199.2
Jersey	HB	1928	123.8 b–j	130.0	112.8	131.0	86.3	164.2
Weymouth	HB	1936	124.1 b–j	124.8	117.2	133.1	76.6	170.9
Stanley	HB	1930	124.1 b–j	123.6	121.3	129.2	91.5	167.5
Elizabeth	HB	1966	125.2 b–l	110.3	137.6	116.8	87.6	157.9
June	HB	1930	125.6 b–k	121.1	135.9	121.2	85.8	159.0
Blueray	HB	1955	125.9 b–k	110.3	135.9	135.4	83.4	193.8
Bluetta	HB	1967	127.2 b–k	143.3	119.8	122.3	76.2	168.3
Harding	HB	1912	127.5 b–l	---	126.5	126.6	86.9	176.5
Little Giant	PRO	1995	127.8 b–l	111.8	127.6	146.7	95.1	168.4
Sunrise	HB	1988	128.4 b–l	128.4	137.7	121.6	93.4	182.8
Lateblue	HB	1967	128.6 b–l	130.4	156.3	103.6	96.1	179.9
Puru	HB	1989	128.7 b–l	146.6	113.9	128.2	92.5	163.7
Ornablue	ORN	1969	129.0 a–n	---	141.5	117.2	107.5	159.5
Blue Ridge	SHB	1987	129.4 b–n	131.0	---	126.1	87.2	172.3
Pender	HB	1998	129.5 b–l	130.4	126.5	134.0	90.4	190.3
Angola	HB	1951	130.0 b–l	132.9	154.1	107.9	89.9	170.6
Ama	HB	1983	130.2 b–n	---	125.1	131.0	65.3	174.0
Berkeley	HB	1949	130.3 b–l	111.5	152.6	129.8	88.8	199.4
Morrow	HB	1964	131.0 b–l	147.1	127.8	120.8	89.6	171.9
Darrow	HB	1965	131.1 b–l	138.9	139.4	117.7	93.5	182.2
Cape Fear	SHB	1987	131.5 b–n	141.3	---	120.9	65.7	174.3
Bluechip	HB	1979	132.0 b–l	133.5	143.4	123.3	57.8	193.6
Katherine	HB	1920	132.1 b–n	---	160.3	103.7	97.1	174.1
Spartan	HB	1977	132.4 b–l	148.0	127.9	124.8	87.2	190.4
Bluecrop	HB	1952	133.3 b–m	155.1	139.1	109.6	96.6	172.1
Croatan	HB	1954	133.4 b–m	134.5	142.2	126.9	91.8	168.6
Nelson	HB	1988	133.6 b–m	141.8	146.0	114.4	95.2	185.8

Continued on next page

in our determinations (C.M. Mainland, personal communication). Similar differences can be found in a study by Perkins-Veazie et al. (1995). It should be noted, however, that we sought to determine "innate" firmness (i.e., after color development, but prior to any significant subsequent softening), and some differences between our determinations and those of others may represent sampling technique or degree of post-ripeness softening.

The regression of cultivar fruit firmness on release date was highly significant ($P \leq 0.001$) with r^2 = 0.20. This r^2 value is quite low; however, the large number of cultivars sampled allowed significance to be discerned. The relationship between firmness and release date is represented by the equation:

$$\text{Firmness}_{\text{g/mm dfl}} = 0.36 \text{ year} - 578.05.$$

Thus, the average gain per decade was only 3.6 g·mm^{-1} dfl. Many of the least-firm cultivars are pure *V. cormybosum* and the seven softest cultivars were among those released before 1953. That the newer cultivars overall tend to be firmer, may be attributable, at least partially, to the diversification of highbush germplasm through the incorporation of firmer species material into *V. corymbosum*. However, it may also be due to repeated cycles of selection for firmness. With the advent of mechanical harvesting and the now worldwide distribution of blueberries, breeders have placed continued emphasis on producing firm-fruited cultivars.

All of the cultivars we labeled as southern highbush have some *V. darrowi* ancestry in their pedigree, and some possess additional germplasm such as *V. ashei*. This ancestry is a common factor in some of the most firm cultivars. In particular, 'Misty', 'Bladen', and 'Reveille', which were among the firmest-fruited cultivars, all contain *V. ashei* and a trace of *V. tennellum* in their background, as well as *V. darrowi*. The southern highbush cultivars with the lowest firmness values were 'Cape Fear' (131.5 g·mm^{-1} dfl), 'Blue Ridge' (129.4 g·mm^{-1} dfl), 'Sampson' (122.2 g·mm^{-1} dfl), and 'Georgiagem' (119.9 g·mm^{-1} dfl). 'Cape Fear', 'Blue Ridge', and 'Sampson' possess *V. angustifolium* in their ancestry (15.7%, 15.6%, and 11%, respectively) and 'Georgiagem' has 'Ashworth' as a great-grandparent (Ehlenfeldt, 1994). Darrow et al. (1960) reported that 'Ashworth' produced soft fruit and they believed 'Ashworth' may contain significant lowbush germplasm.

Other cultivars that possess significant amounts of *V. angustifolium* ancestry, specifically the "half-highs" (≈15% to 50% *V. angustifolium*), seem to show a propensity for producing softer fruit. Of the three half-highs evaluated, two had values in the 110–120 g·mm^{-1} dfl range. 'Polaris' (151.1 g·mm^{-1} dfl) was a notable exception, however, being nearly as firm as 'Duke' (154.4 g·mm^{-1} dfl). Even some cultivars with less lowbush ancestry than the half-highs seem to produce less-firm berries. 'Bluetta', 'June', and 'Northland' all possess 25% *V. angustifolium* ancestry, (Hancock, et al., 1982) and exhibited lower than average firmness values (Table 1).

Fruit firmness of a number of rabbiteye

Table 1. Continued.

Cultivar	Type[z]	Year of release	Firmness (g·mm^{-1} of deflection) Avg	1998	1999	2000	Min.	Max.
Toro	HB	1987	133.7 b–m	136.5	137.5	129.4	100.8	186.2
Elliott	HB	1973	135.4 b–n	136.2[x]	149.9	120.6	99.0	175.4
Chanticleer	HB	1997	135.5 b–n	139.6	130.9	140.3	92.6	180.6
Bonus	HB	---	135.8 b–n	127.7	132.8[x]	146.0	77.0	201.3
Rubel	HB	1912	136.3 b–n	117.7	165.8	129.3	104.1	185.2
Rancocas	HB	1926	136.3 b–n	131.3	142.1	137.9	75.8	176.6
Collins	HB	1959	138.1 b–n	157.9	130.6	129.6	89.1	200.0
Jubilee	SHB	1994	138.1 b–n	162.3	118.3	137.3	97.0	186.4
Bluegold	HB	1989	138.6 b–n	147.2[x]	143.5	130.4	95.7	199.4
Pemberton	HB	1939	140.1 b–n	141.9	154.6	126.1	99.6	173.9
Bounty	HB	1987	142.1 b–n	163.3	---	121.7	102.5	189.6
Sharpblue	SHB	1976	143.3 b–n	152.0	146.3	133.6	107.0	191.9
Earliblue	HB	1952	143.4 b–n	173.9	130.4	124.3	96.4	205.0
Magnolia	SHB	1994	146.1 c–n	114.2	163.8	165.3	98.7	197.9
Legacy	HB	1994	146.6 c–n	149.2	145.5	132.2	108.2	183.8
Nui	HB	1989	148.3 c–n	156.6	150.4	145.6	94.6	194.2
O'Neal	SHB	1987	148.6 c–n	143.7	155.4	148.8	116.0	191.4
Polaris	HH	1996	151.1 c–n	---	146.5	154.5	99.8	202.7
Sierra	HB	1988	151.2 c–n	173.5	148.9[x]	130.7	89.4	215.1
Meader	HB	1971	151.9 d–n	164.5	147.2	146.8	109.8	210.5
Ozarkblue	SHB	1996	153.2 d–n	147.4	169.9	144.3	119.3	214.7
Gulfcoast	SHB	1987	153.5 d–n	160.3	148.7	155.1	91.9	217.0
Burlington	HB	1939	153.5 d–n	182.8	152.8	131.0	103.2	215.0
Reka	HB	1989	153.8 d–n	154.6	145.1	163.7	116.2	210.1
Summit	SHB	1998	154.0 c–n	---	170.4	136.3	111.7	182.0
Chandler	HB	1994	154.0 d–n	170.2	152.2	144.7	109.2	236.3
Coville	HB	1949	154.2 d–n	148.2	175.8	142.3	100.9	221.7
Duke	HB	1987	154.4 d–n	173.1	152.6	140.5	106.3	199.3
Star	SHB	1996	155.9 d–n	181.3[x]	145.3	158.5	116.7	217.9
Scammel	HB	1931	156.4 c–n	---	160.6	150.1	121.9	194.2
Brigitta Blue	HB	1977	159.7 e–n	188.0	150.2	145.9	99.3	230.9
Bluehaven	HB	1967	161.4 f–n	173.5	161.8	151.7	112.3	223.8
Harrison	HB	1974	164.9 g–n	156.7	184.0	158.7	110.6	244.5
Marimba	SHB	1992	169.0 h–n	175.6	164.8	169.1	116.6	223.2
Reveille	SHB	1990	169.3 i–n	185.9	174.7	150.5	124.6	220.5
Avonblue	SHB	1977	172.2 j–n	195.0	161.0	163.8	113.3	240.4
Cooper	SHB	1987	174.5 k–n	184.5	184.2	157.6	132.6	223.1
Bladen	SHB	1990	184.7 l–n	193.9	184.0	---	137.7	243.7
Misty	SHB	1989	186.7 n	188.8	208.3	162.7	145.3	255.9
Pearl River	SHB/RE	1994	189.0 mn	225.0	196.7	176.5	125.6	292.
Average[w]			136.7	141.7	140.4	131.1		

[z]HB = highbush, SHB = southern highbush, LB = lowbush, HH = half-high, ORN = ornamental, PRO = processing type, RE = rabbiteye.
[y]Means comparisons were performed using the Tukey–Kramer adjusted P test ($P \leq 0.05$).
[x]Entry for which multi-fruit datafile was lost. Statistical analysis used the single yearly average value for this entry.
[w]For comparison purposes, averages across cultivars were calculated using only those cultivars that had data for all 3 years.

cultivars was evaluated during this study. These fruit, however, were collected from potted plants located in coldframes under daily sprinkler irrigation. Due to the differences in growing conditions, the values for *V. ashei* were not included in Table 1. However, the firmness of 7–13 rabbiteye cultivars evaluated across 3 years averaged 170.6 $g \cdot mm^{-1}$ dfl; considerably higher than the average of southern highbush cultivars (151.6 $g \cdot mm^{-1}$ dfl, excluding 'Pearl River'). 'Pearl River', which is 50% *V. ashei*, was the firmest of the cultivars tested at 189.0 $g \cdot mm^{-1}$ dfl. These trends suggest that overall *V. ashei* is firmer than those cultivars derived from *V. corymbosum* and *V. darrowi*.

Introducing species germplasm into *V. corymbosum* and producing a commercially viable cultivar, although difficult and time-consuming, seems to offer breeders a method of creating offspring with significantly improved firmness. However, there are also cultivars, such as 'Duke' that are firm-fruited, retain their firmness, and seem to transmit their firmness to progeny. In the USDA program, crosses have been made which attempt to incorporate the firmness present in *V. ashei* germplasm, 'Duke', and other sources.

Firmness has the potential to affect harvest loss, storability and consumer acceptance. This study measured innate firmness; studies also need to be made to assess the abilities of different cultivars to maintain firmness after initial ripening has occurred. Ehlenfeldt (1998) noted that several cultivars, including 'Duke', G-695 (released in 2000 as 'Cara's Choice'), and G-805 (released in 2000 as 'Hannah's Choice'), appear to maintain their firmness even when left on the bush. 'Reveille', in our recent observations, should also be added to the list of cultivars with excellent on-bush firmness retention. Postharvest softening is also a factor in need of further study. Although data concerning postharvest softening of blueberry in cold storage shows variable cultivar responses, Forney et al. (1998) showed that 'Burlington' gets firmer in storage. Other factors being equal, it seems likely that firm-fruited, nonsoftening cultivars will store longer than the softer cultivars, and that any improvements in firmness will be beneficial to the industry.

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