Non-destructive Field Method of Determining Harvest Maturity of 'Bartlett' Pear

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Summary

Two design improvements for field use of a handheld non-destructive firmness instrument called a durometer were developed and evaluated. The improvements were designed to help the operator apply the correct amount of force when pressing the probe against the fruit surface and to control the tip speed during measurement. The force control design change improved the precision of the measurement under manual operation and was statistically significant (α=0.05) for two of four operators. We were unable to show a benefit for tip speed control in our study. The design for tip speed control proved difficult to use. An improved design that is more user friendly may be able to show the expected improvement in performance. Durometer measurements, using probe force and tip speed control, were compared to an automated penetrometer measurement and to non-destructive acoustic and impact firmness measurements on 'Bartlett' pears harvested on four dates over a one-month period. The destructive penetrometer measurement was able to detect significant differences (α=0.05) in firmness levels between all harvest dates, while the non-destructive methods were unable to detect significant differences between the fruit harvested on some of the dates. These results may indicate that the tissue strength properties measured by the penetrometer may be more sensitive to physical changes in the fruit at harvest than the non-destructive measurements of the elastic properties of the fruit tissue. Additional research is required to verify that the differences detected by the penetrometer are important indicators of postharvest quality and to investigate the effect of the skin on the sensitivity of the non-destructive measurements.

Background

Assessment of fruit firmness is an important tool to measure pear maturity at harvest or firmness during fruit ripening. Currently, destructive methods of firmness measurement (often called the Magness-Taylor pressure test) are conducted in the field using the UC Firmness Tester, based on the Ametek or Effegi penetrometers, (Magness and Taylor, 1925). Although it has been used by horticulturalists and growers for nearly a century, the method is poor in repeatability and destructive so that it is not appropriate as a technique to be used on-line and cannot be used to monitor the same fruit over time. Further, since the Magness-Taylor fruit firmness test is a destructive measure of the tissue failure properties, it is not consistent with modern on-line firmness measurements available in the packing shed, which are sensing the non-destructive elastic properties of the fruit tissues.

The pear industry was the driving interest in the original development of instrumental measurements of fruit firmness (Magness, and Taylor 1925; Allen, 1929). Today, impact-based non-destructive firmness devices for on-line fruit firmness evaluation are commercially available. These on-line non-destructive firmness devices allow post-harvest management of fruit firmness in the packing-shed. There has been grower interest in the development of a hand-held non-destructive firmness instrument that could be readily comparable with the classification of fruits by on-line firmness devices in the packing-shed. A prototype hand-held impact tester was designed (by Chen and Sarig) and later modified in various phases (by Slaughter, Thompson and Sarig) with funding from the California Pear Advisory Board and the preliminary prototype was tested on pears during three seasons. However, subsequent efforts for manufacture and commercial availability of a hand-held impact tester has proven to be elusive.

Prior to the development of the Magness-Taylor penetrometer, Murneek (1921) investigated the use of a spherical indenter as a means of determining the maturity of pears. While not developed into a field portable instrument at that time (which is the main reason that the Magness-Taylor penetrometer became the eventual industry standard) spherical indention has both theoretical and practical advantages over the Magness-Taylor firmness test for fruit maturity determination. First, the Magness-Taylor penetrometer is always destructive, requiring both removal of the skin (to improve measurement consistency) and failure of the flesh. In contrast, spherical indention is done with the skin intact, and when the deformation is limited, it will not cause flesh failure or damage to the fruit. If done non-destructively, spherical indention opens the possibility of monitoring fruit firmness during maturation while on the tree. Second, from a scientific point of view, the Magness-Taylor firmness test is essentially a puncture test that combines both compressive and shear forces in variable proportions preventing the direct determination of flesh elastic properties like the modulus of elasticity, which are necessary for good agreement with modern on-line non-destructive firmness measurements.

Indention (both spherical and other shapes) has evolved into the development of two official standards for the measurement of material properties. First, the American Society for Testing and Materials (ASTM) has established a standard method (ASTM D2240) based upon a device called a durometer. When equipped with an ASTM type ‘A’ pointed tip, the ‘A’ durometer is used to determine the common Shore hardness scale of “rubber or rubber–like” materials. Spherical durometer tips, like the ASTM ‘E’ tip are suitable for fruit firmness measurements. Second, the American Society of Agricultural and Biological Engineers (ASABE) has established a standard method of compression tests in fruits (ASAE, S368.4, Dec00) based on the Hertz elastic contact theory. This method allows for the determination of the elastic tissue property, modulus of elasticity, for a non-destructive deformation by a spherical indenter.

In a preliminary laboratory study of ‘Bartlett’ pears, we compared the relationships between firmness determined by spherical indention and firmness determined by both non-destructive impact (using a bench top Sinclair iQ firmness tester) and the traditional the Magness-Taylor firmness test. We observed that the firmness values for spherical indention were well correlated with both impact and Magness-Taylor measurements and that the level of correlation was related to the depth of indention, with small indentions being better correlated ($r^2 = 0.94$) with the non-destructive firmness measurement and larger indentions being better correlated ($r^2 = 0.97$) with the Magness-Taylor measurements.

The durometer, figure 1, is a portable hand-held device that is used to measure the resistance to indention by use of a calibrated spring. Durometers are widely available from a number of manufacturers and range in price from about $500 to $1,200 depending upon the type of tip and display (e.g., digital display versus needle gage type display).

Figure 1.

Being hand-operated, the current design of the durometer is subject to the same measurement precision issues that the Magness-Taylor firmness test has with fruit viscoelasticity. Viscoelasticity combines both the fluid properties and solid properties of the fruit and the viscoelastic nature of fruit tissue causes firmness measurement to be a function of three components: force, deformation, and time, where the time component is directly affected by the loading rate or rate of penetration applied by the operator during the firmness test. Like the Magness-Taylor penetrometer, the durometer tip is currently pressed into the fruit manually. Studies have shown that the viscoelastic nature of fruit requires that the speed of operation of the measurement be held constant from fruit to fruit and person to person in a manual measurement like the Magness-Taylor firmness test to maximize the precision of the test (Blanpied et al., 1978).

We believe that a simple mechanical modification to the current durometer design can be made to automate the probe tip motion during indention. This modified design will allow the operator to hold the durometer steady against the fruit during measurement, improving the precision by automating the loading rate. We believe that the accuracy will also be improved because the subjective decision of when to stop pressing the tip into the fruit will be eliminated. We believe that since this device is widely available from a number of commercial sources, that an improved design based upon a simple mechanical modification is more likely to become commercially available in the near future than a hand-held impact-type firmness sensor. Our preliminary results with a non-destructive spherical indenter used to simulate a durometer show excellent correlation to non-destructive impact firmness measurements on ‘Bartlett’ pears.

Objectives:

The goal of this project is to create a handheld non-destructive firmness instrument for field use by making a simple mechanical design changes to the current durometer that will 1) provide visual feedback to the operators to help them apply the correct amount of force when measuring pear firmness and 2) to automate the motion of the durometer tip to provide a consistent tip velocity under manual operation.

Plans and Procedures:

Two new durometer probe designs were developed and constructed to allow more precise manual operation. The first design change incorporated an exterior sleeve that fit over the barrel of the existing durometer probe. A spring was placed between the sleeve and the barrel and a red reference force line was marked on the barrel. The red line is hidden by the sleeve until the operator applies a force equivalent to 1-kilogram mass (2.2 lbs) to the sleeve when pressing the foot of the barrel of the durometer against the fruit. The redesigned durometer probe was mounted on a commercially available digital durometer display (model Rex DD3). In practice, the operator would press the tip of the durometer against the surface of the pear, increasing the applied force until the red line appeared. The measurement was terminated when the red line appeared and the maximum value displayed was recorded.

The second design change incorporated a mechanical locking mechanism that will allow the tip to be locked in the retracted position. A simple push button release mechanism located on the side of the probe allowed the durometer's internal spring to automatically push the probe tip into the fruit. The tip of the durometer probe was machined to match the diameter and curvature of the 5/16-inch Magness-Taylor penetrometer tip currently used for measuring pear firmness at harvest. The external sleeve with the reference spring was incorporated into the same mechanism as the tip lock to provide both design changes into a single probe. The redesigned durometer probe was mounted on a commercially available digital durometer display (model Rex DD3). In practice, the operator would press the probe tip against a hard surface until the display showed a reading of 100% and the tip automatically locked in the retracted position. Then the operator would press the tip of the durometer against the surface of the pear, increasing the applied force until the red line appeared indicating that the correct force was being applied. The operator would then press the release button and the durometer tip would be released into the fruit.

The two durometer changes were compared to the standard durometer using a set of eight rubber samples with firmnesses comparable to the firmness of pears at harvest. Four operators were asked to measure the firmness of each sample eight times, four times on each side of the sample. After the tests the operators were asked to describe their opinion on the ease of use of the two design changes.

Fifty 'Bartlett' pears were harvested from the California River pear district on each of four dates: June 24th, June 29th, July 8th and July 15th. The fruit were transported to the UC Davis campus for analysis. In order to allow assessment of each method independent of operator effects, all measurements were automated. Durometer measurements were made using a commercial durometer stand that automatically controls both probe speed and foot force applied to the fruit. Non-destructive acoustic and impact firmness measurements were taken at four locations around the circumference of the fruit using an Aweta bench top instrument. Since the durometer measurement is non-destructive for firm pears (deformations of less than 1/50th of an inch for fruit above 10 lbs. penetrometer firmness), the durometer measurements were conducted next, before the penetrometer measurements were conducted. Four 'E' durometer measurements (using foot force and probe speed control) were made, equally spaced along the circumference of the fruit at the widest part of the pear. After the durometer measurements were made, small sections of the peel were removed at four locations around the circumference of the fruit about 0.5 inches from the location where the durometer measurements were made and automated penetrometer measurements were made using an FTA instrument. The penetrometer measurements were taken using a probe speed of 5 mm/s (0.2 inches/s) to a probe depth of 7.9 mm (0.3 inches).

Results

Two durometer attachments were designed and fabricated at UC Davis for this study, figure 2. The first device (shown on the right side of figure 2) was designed to attach to a standard Rex durometer probe and provide a simple means for the operator to control the force with which the foot of the durometer is pressed against the fruit during measurement. This device consists of an internal cylinder that clamps onto the durometer probe, replacing the foot on a standard 'E' Rex durometer.

Figure 2. Force control adapter (right) and force and tip speed controlled probe (left) for a handheld durometer.

The force control mechanism, mounted on a Rex 'E' durometer is shown in figure 3. In this photograph, the operator has exposed the red force control line, indicating that 9.8 N (2.2. lbs) of force has been applied by the foot of the durometer against the surface of the pear.

The second device designed in 2008 incorporates both force control and tip speed control features (shown on the left side of figure 2). The red button shown on the probe on the left side of figure 2 is the tip release button.

The difference in precision (expressed as the coefficient of variation for the four measurements on each side of the sample) between the 'E' tip durometer with and without probe force control is shown in Table 1.

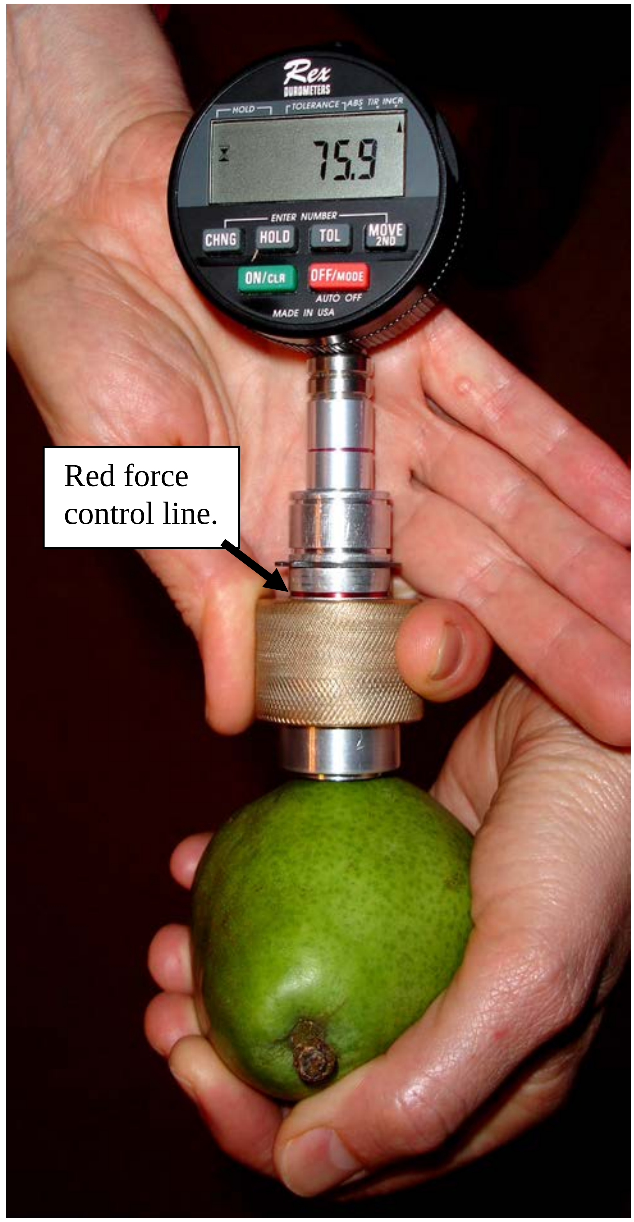

Figure 3. Force control mechanism mounted on an 'E' durometer. The operator slides the outer ring toward the fruit until the red force control line appears.

An improvement in precision was obtained for all operators when the force control mechanism was used, however the level of improvement was only statistically significant for two of the operators. The operators' precision with the standard durometer was better than expected. The operators' opinion of the red force control line was generally favorable because it eliminated the ambiguity in determining when to stop pressing the probe against the fruit.

Table 1. Effect of force control on durometer precision when measuring rubber samples.

		Coefficient of Variation (%)			
Durometer	N	Operator 1	Operator 2	Operator 3	Operator 4
Standard	16	2.4a*	3.1a	2.9a	5.1a
With Force Control	16	1.6b	1.7b	2.5a	4.4a

*Treatments with the same letter are not significantly different (α=0.05)

No significant benefits were observed for the durometer design using probe force and tip speed controls over the durometer using only force control. The operators commented that the locking mechanism increased the weight of the durometer (which they disliked) and that it was difficult to push the tip release button while holding the outer ring steady at the red force control line and read the display at the same time. In addition, since the tip is initially retracted when using tip speed control the digital gage's maximum reading mode must be disabled and the operator is required to observe the minimum value displayed while holding the outer ring at the red force control line. Some operators felt that this made the durometer more difficult to use and may have negated some of the benefit of tip speed control. In addition, we did not observe any benefit in precision to increasing the durometer probe size from the 0.2 inch diameter of the 'E' tip to the 0.3 inch diameter of the Magness-Taylor tip. While the research literature has shown that loading rate must be controlled in order to maximize the precision of a mechanical firmness measurement, additional design changes for both the loading rate control and the display features are required in order to provide a design that is more user friendly and able to provide the improved precision expected.

The relationship between the average penetrometer and average 'E' durometer firmness scores for the 50 fruit harvested on each of the four test dates is shown in figure 4. On average, 'E' durometer values changed about 0.5% for every 1 lb. change in penetrometer firmness. The 'E' tip durometer was a non-destructive measurement when measuring pears at harvest with durometer values above 75 for all harvest dates. These durometer scores mean that the 'E' tip deformed the pear less than 0.025 inches, allowing the measurement to be non-destructive. The relationships between the average Aweta acoustic and impact firmness scores and the average penetrometer values for the 50 fruit harvested on each of the four test dates are shown in figure 5. On average, one unit and three fourths of a unit of change in the acoustic and impact firmness scores, respectively, were observed for every 1 lb. change in penetrometer firmness.

The average coefficient of variation (CV = standard deviation/mean) across all four harvest dates for the four measurements taken on each fruit with each of the firmness methods were compared, Table 2. Results show that the average CV values for the durometer and penetrometer were very similar with values of 4.8% and 4.2%, respectively. These results indicate that when probe force and speed control are used, the precision of the durometer measurement on an individual fruit is comparable to the precision of an automated penetrometer measurement. The acoustic and impact firmness methods had better precision than the durometer or penetrometer.

Table 2. Comparison of the average precision of four methods of measuring firmness.

Firmness Method	N	Average CV/Fruit (%)
Penetrometer	200	4.8a
‘E’ Durometer	200	4.2a
Acoustic Firmness	200	3.2b
Impact Firmness	200	2.8b

*Methods with the same letter are not significantly different (α=0.05)

The changes in average firmness by harvest date for each of the three non-destructive methods in comparison to the standard penetrometer measurement are shown in figures 6, 7 and 8. The solid vertical bars in each figure represent the fruit to fruit variability (+/- 1 standard deviation) in penetrometer readings and the broken vertical bars represent the variability (+/- 1 standard deviation) of the non-destructive method for the 50 fruit studied at each harvest date. The vertical scales of the non-destructive measurements in figures 6, 7 and 8 were selected using the relationships found in figures 4 and 5 so that the sensitivities of the measurements could be compared. The results show that the change in penetrometer firmness was the most linear with harvest date of the four methods, followed by the durometer, the impact firmness, and then the acoustic firmness measurement. These results also show that the fruit to fruit variability in firmness relative to the change in firmness over time was lowest for the penetrometer, followed by impact firmness, acoustic firmness, and then the durometer measurements. These results appear to indicate that while the precision of measurement on an individual fruit for the non-destructive methods is comparable to (for the durometer) or superior to (for the Aweta measurements) the penetrometer, the penetrometer appears to be better able to distinguish differences in firmness between fruit harvested on different dates.

An analysis of variance of the average firmness of each measurement method on each harvest date was conducted and a Fisher’s protected least significant difference test applied to the mean values, Table 3. These results show that the average penetrometer values for the 50 fruit at each harvest date were significantly different. The least significant difference value for the average penetrometer measurement of 50 fruit was 0.33 lbs and the decrease in firmness was about 2 lbs. per week during the study, indicating that the penetrometer would be capable of distinguishing firmness changes in 50-fruit batches every two days. Both Aweta methods were able to distinguish firmness changes during the first three weeks of the study but were unable to distinguish the fruit harvested in the last week from that harvested in week 3. The least significant difference value for the average durometer score on a 50-fruit batch was about 1%. The durometer was able to distinguish fruit harvested in the first two weeks from fruit harvested in the last two weeks, but could not distinguish fruit in week 1 from that of week 2 nor could it distinguish fruit harvested in week 3 from that harvested in week 4. The apparent conflict between the improved precision of measurement within a fruit for the non-destructive methods shown in Table 2, and the improved ability to distinguish between fruit from different harvest dates of the destructive penetrometer measurement may indicate that maximum tissue strength (as measured by the penetrometer) is a better indicator of physical change in the fruit at harvest than non-destructive measurements of the elastic properties. Additional research is needed to verify that the differences detected by the penetrometer are good indices of postharvest quality or storage life of ‘Bartlett’ pears.

Table 3. Comparison of firmness changes with harvest date for four firmness methods.

Harvest Date	N	Penetrometer (lbs.)	Durometer (%)	Acoustic	Impact
June 24	50	24.3a*	90.9a	48.2a	84.4a
June 29	50	23.0b	90.2a	45.2b	83.1b
July 8	50	20.5c	87.6b	42.6c	80.1c
July 15	50	18.3d	87.3b	41.8c	80.2c

*Harvest dates with the same letter are not significantly different (α=0.05). The least significant difference (LSD) values were 0.33 lbs, 1%, 1.3, and 0.7 for the penetrometer, durometer, acoustic, and impact methods, respectively.

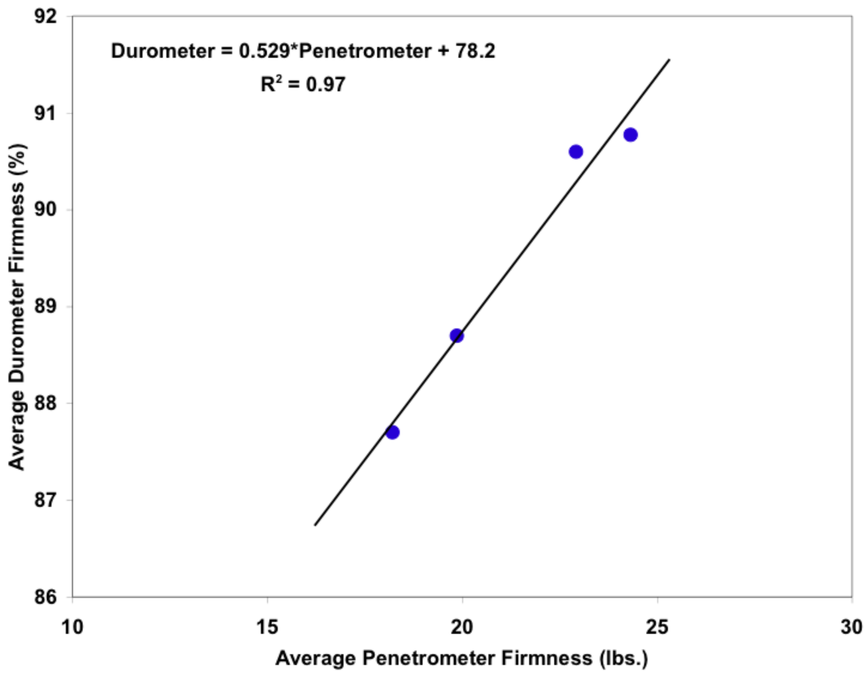

Figure 4. Relationship between the average penetrometer and 'E' durometer firmness values at each harvest date. Each point is the average of measurements on fifty fruit.

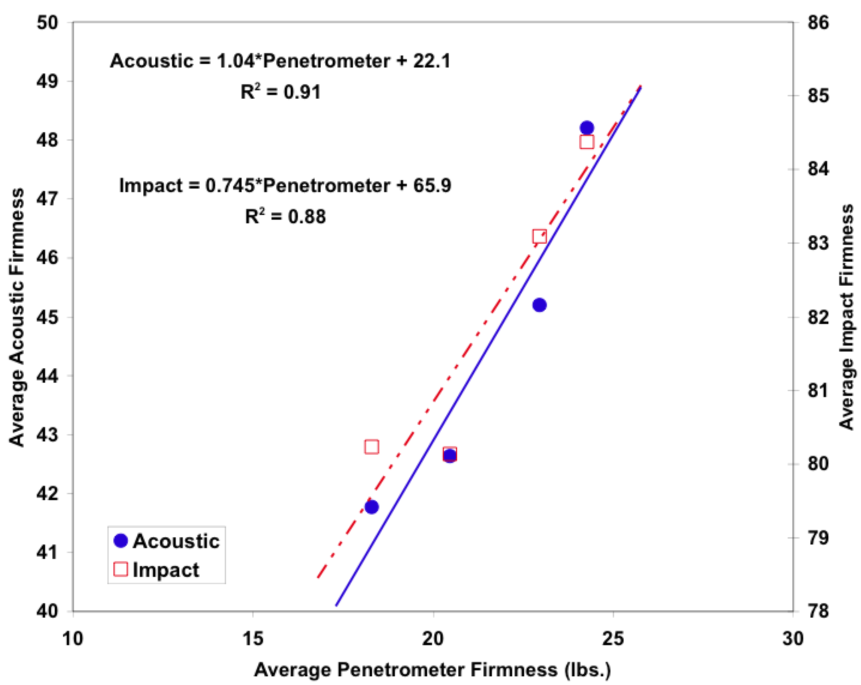

Figure 5. Relationships between the average penetrometer and acoustic and impact firmness values at each harvest date. Each point is the average of measurements on fifty fruit.

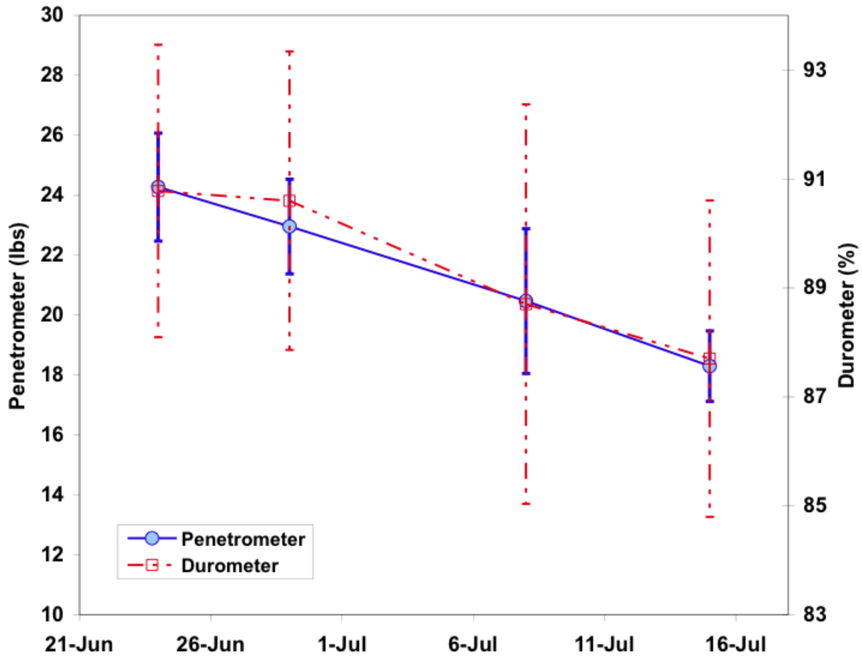

Figure 6. Chronological changes in penetrometer and durometer firmness values at four harvest dates. The vertical bars represent +/- 1 standard deviation.

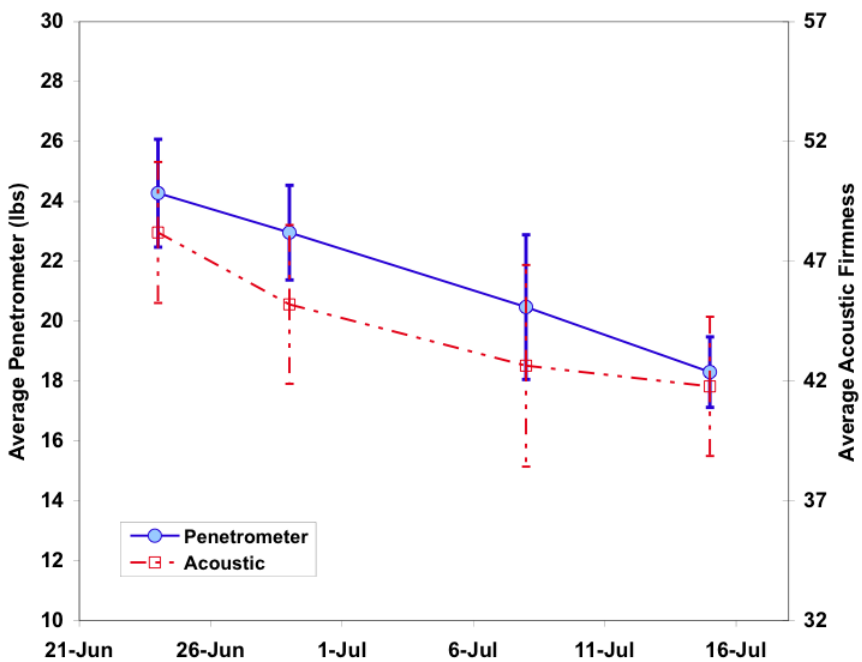

Figure 7. Chronological changes in penetrometer and acoustic firmness values at four harvest dates. The vertical bars represent +/- 1 standard deviation.

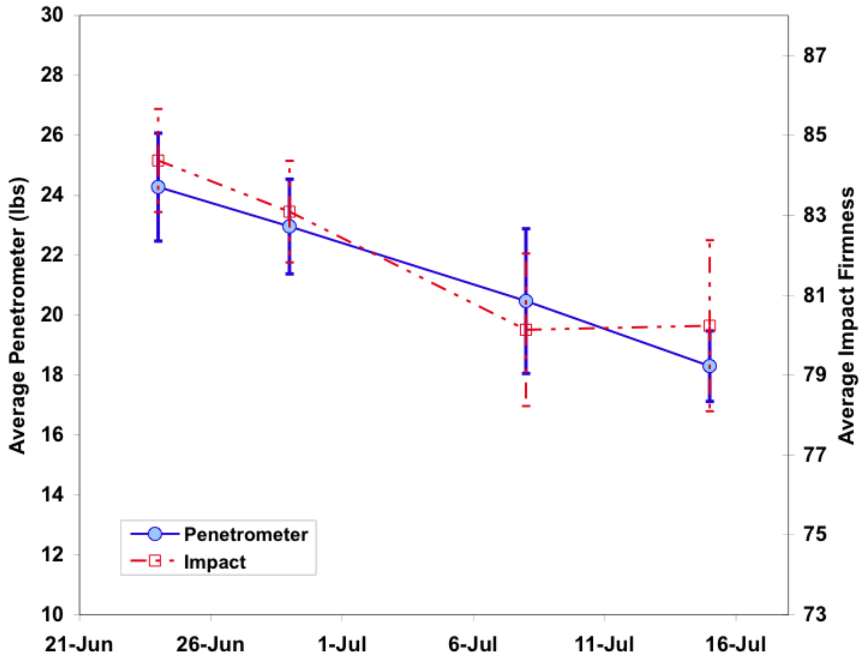

Figure 8. Chronological changes in penetrometer and impact firmness values at four harvest dates. The vertical bars represent +/- 1 standard deviation.

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