Evaluation of the Displacement Value as a Method to Detect Reduced Corn Wet-Milling Quality

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ABSTRACT

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A procedure based on the resistance and capacitance (RC) properties of corn to calculate a displacement value (DV) was evaluated for detection of corn that had reduced wet-milling quality. In 1991 and 1992, three hybrids were dried at air temperatures between ambient and 115°C in batch dryers. Additional samples, obtained from commercial elevators in 1992, had been dried with air temperatures ranging from 52 to 136°C. A baseline reference relationship was developed between $\log_{10}$-resistance and capacitance with data from ambient-dried samples. A DV was defined as the horizontal distance along the capacitance axis from a sample RC data point to the baseline reference. RC properties of samples dried at air temperatures >50°C were compared to the baseline and the DV determined. Selected drying treatments were wet-milled by a laboratory-scale procedure to verify milling quality and correlation with DV. The effects attributed to hybrid and harvest moisture content on the RC properties of ambient-dried samples were small, allowing the baseline reference to be applied to a wide range of corn samples. In 1992, the baseline shifted upward from the 1991 baseline by 0.5 units on the $\log_{10}$-resistance axis. DV increased significantly at drying air temperatures >50°C for batch-dried samples. While DV correlated with drying temperature in batch-dried samples ($r = 0.66$), it did not correlate with starch yield or recovery of commercial samples ($r \leq 0.10$). Although the specific causes could not be determined, the shift in the baseline indicates the method would be difficult to implement on a practical scale. Although not indicated by DV, starch recovery decreased significantly for samples batch-dried at air temperatures ≥70°C. All samples dried at 115–136°C had significantly lower starch recoveries.

Wet milling is the process by which corn is separated into fractions rich in starch, protein, fiber, and oil. Wet milling of corn has increased every year except one since 1960, increasing from 155 million bushels (4% of the total corn crop) in 1960 to 1,173 million bushels (12.4% of the total crop) in 1992. Growth in the wet-milling industry was especially rapid during the 1970's because of breakthroughs in the production of and subsequent increased use of high-fructose corn syrup (Leath and Hill 1987; R. M. Weinzierl 1993, *personal communication*). Dry milling is the process that separates corn into endosperm, germ, and fiber fractions. Dry milling has seen some limited growth in use of corn, primarily because of increased consumption of breakfast foods and other dry-milling products in the 1970's (Leath and Hill 1987). Consumption of corn by dry milling was 292 million bushels, 3% of the total production of 9,480 million bushels in 1992 (Weinzierl 1993). Production of fuel-grade ethanol, initiated in the late 1970's as a result of rising gasoline prices, is expected to double to 2.2 billion gallons by the year 2000 because of incentives created by the 1990 Clean Air Act (Anonymous 1991). Most of the ethanol currently produced uses starch from the wet-milling process, accounting for consumption of 230 million bushels in 1992, compared to 175 million bushels consumed for ethanol production by the dry-milling industry (Weinzierl 1993).

United States Grain Standards were adopted in 1916 as a method for establishing a uniform criteria for marketing and grading corn. Although harvest and postharvest technology and uses of corn have changed tremendously since 1916, there has been little change in these standards. As a result, standard corn grades do not indicate whether corn has been dried under conditions that result in poor wet-milling or dry-milling characteristics, but are only a collection of readily measured physical attributes. Most corn that is wet-milled is Standard Grade No. 2, defined as having a minimum test weight of 54 lb/bu and a maximum of 3% broken corn and foreign material, 5% damaged kernels, and 0.2% heat-damaged kernels (Watson 1987). Artificial drying at high temperatures is known to induce stress cracks and reduce germ quality, starch recovery, starch quality, flaking grit yield, and storage life of corn. This damage can result in poor characteristics for wet milling, dry milling, handling, and storage (Freeman 1973, Brooker et al 1974). Increased stress cracking increases the amount of fines and broken corn during handling, which in turn increases susceptibility to mold and insect damage during storage. In the dry-milling industry, high-temperature drying reduces grit yields because of increased stress cracks and reduces germ recovery and grit quality due to poorer germ-endosperm separation (Paulsen and Hill 1985). For the wet-milling industry, high-temperature drying makes corn difficult to steep by altering the characteristics of the protein matrix in the endosperm and increasing the time for adequate steeping. Inadequate steeping results in poor starch-gluten separation, reducing starch yield and quality while increasing the yields and decreasing the purity of lower valued protein products (Watson and Hirata 1962). An excellent review of methods developed to detect corn wet-milling quality is provided in Weller et al (1988).

The effects of artificial drying of corn on wet-milling characteristics have been well documented in studies conducted over the past 30 to 40 years. However, unless the damage induced by drying is so severe that it is visible with brown discoloration, it is not readily detectable. Currently, there is no method available that is rapid enough for commercial use in detecting corn exposed to conditions that cause poor wet-milling quality. In the wet-milling process, corn containing a lower percentage of starch may allow higher recovery of starch than corn with a higher starch percentage that has been damaged by improper drying. This damaged corn will cause more processing problems and reduce capacity of the milling plant. High starch recovery could be viewed as perhaps only one attribute of high quality corn; high quality corn may also require less time to steep, give more efficient germ separation, reduce gluten filtration requirements, and bring other advantages to the wet-milling process that the industry has not assessed in dollar amounts.

A method that involved measuring electrical properties of corn kernels to determine the extent of damage from drying was introduced by Holaday (1964). In this method, the electrical properties of the corn in question were compared to a standard relationship developed from undamaged corn. In theory, values of the electri-

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cal properties of dryer-damaged corn would deviate from those of undamaged corn; the deviation being termed the displacement value (DV).

The objectives of this project were to: 1) develop a relationship between log-resistance and capacitance (RC) for ambient-dried corn samples, and 2) investigate the deviation of damaged corn, as measured by the displacement value (DV), from the RC relationship that would make it possible to rapidly identify corn that has reduced wet-milling quality.

METHODS

Batch Drying Methods

Batch dryers were used to dry corn from two crop years. Each year, three hybrids were selected having a range of relative endosperm hardness (soft, medium-hard, and hard). The batch-dried corn provided an initial evaluation of the resistance-capacitance (RC) method to determine whether additional testing on corn from a wider range of sources was warranted. The batch-dried corn also served as a comparison of RC properties for samples obtained from sources with unknown drying conditions. Temperature of the drying air was used as a measure of drying condition for all treatments. The drying operations were conducted and samples were stored for several weeks at 4°C to reduce moisture variations within the samples.

In 1991, three hybrids of yellow dent corn (FR27 × FRMo17, FR618 × FR600, FR1087 × LH123) were harvested at two moisture ranges, 23–29 and 18–21% wb. (Unless noted, moisture is reported as wet basis.) The corn was placed in plastic bags and kept in cold storage (2°C.) until placed in the dryer. Before drying, the samples were allowed to warm at room temperature for several hours. Using a steam-heated tray dryer (Proctor and Schwartz, Philadelphia), batch drying was conducted at five air temperatures (ambient, 50, 70, 90, and 115°C). Ambient-dried samples were dried to a 10–20% moisture range for use in the baseline equation. Ambient air conditions ranged from 45 to 65% rh and 27–31°C. Corn was arranged on trays ~5–7.5 cm deep. Air flowed through each tray at ~2.5–5.1 m/sec. The relative humidity of drying air entering the corn was <10% for temperatures above ambient conditions.

In 1992, three yellow dent corn hybrids (FR1141 × FR36, FR618 × FR600, FR618 × LH123) were harvested at 25–30% moisture. The samples were dried at temperatures similar to those used in 1991 in small laboratory batch dryers used in work by Baker (1989) and by Gunasekaran and Paulsen (1985). All samples were dried to 14–15% moisture, including the ambient-dried samples. Air velocities past the layers of corn were ~0.25-0.53 m/sec. Air temperatures varied 10–15°C over the surface of the trays when drying at 70–115°C, so treatments represent a range of temperature, not single values. An additional set of samples was dried using the tray dryer at temperatures of 50, 70, 90, and 115°C. This dryer did not have the temperature variations observed in the laboratory dryers.

Commercial Drying Methods

After finding some success in detecting poor wet-milling quality in batch-dried corn with the RC method, commercially dried samples were collected to provide sources of test material in addition to those provided by the limited number of hybrids subjected to batch drying. Commercial samples were dried with full-scale equipment and various dryer configurations and temperatures. All of the corn was collected in late 1992 and was regular dent corn, except for the corn obtained from an elevator that dried only very hard endosperm dent corn. Samples were collected from seven large-scale facilities located in east-central and north-central Illinois. There is no information on how the commercially obtained samples were handled prior to being delivered to the elevator. There was limited information available on how the corn was dried at the elevator, except for the drying air temperature and dryer configuration (cross, countercurrent, or concurrent air flows). Drying temperatures used by the elevators ranged from 55 to 136°C. The most commonly used drying air temperature at the elevators visited was 99°C.

Resistance and Capacitance Measurement Methods

Capacitance and resistance of a 250-g sample were measured with a Motomco 919 automatic moisture meter (Dickey-john Corp., Auburn, IL) and a meter based on work by Whitten and Holaday (1957), respectively. Before measurement of resistance and capacitance properties, all samples were warmed to room temperature overnight. Corn was screened over a 12/64-in. round-hole screen on a Gamet reciprocating shaker, then hand-inspected to remove foreign material. In 1991, two to three measurements of resistance and capacitance were taken on each sample replicate; ~5 min were required for each sample. Because variation in repeated measurement was small, one set of measurements was conducted on each 250-g sample in 1992, and three to five replicates were tested from each drying treatment. The moisture meter was used to measure capacitance in both crop years. While capacitance of a corn sample is a function of frequency, the frequency used to measure capacitance was not a variable in this study and was held constant at 60 Hz by the moisture meter. The Motomco 919 has a "Data A" feature that is directly related to the capacitance of the sample. The relationship is (Data A value) × 0.013, with capacitance given in picofarads.

For resistance measurement, the corn sample was modeled as a single resistor (Fig. 1). Corn has dielectric properties and, thus, could be represented as a resistor and capacitor in a parallel arrangement. However, for the resistances and frequency (60 Hz) used in this method, the error in resistance measurement can be quite small, except in cases where the resistance of the corn sample exceeds 45 megohms. There were relatively few samples with resistance above this; the maximum measured resistance was 88 megohms, resulting in an error of ~15% if frequency was assumed to be negligible in the calculation of resistance. However, this method uses the $\log_{10}$ of the sample resistance (R), not the actual resistance. As a result, the error in the log(R) terms was <1%. A probe similar to one developed by Whitten and Holaday (1957) and the circuit developed by Weller (1987) was used for resistance measurement (Figs. 1 and 2). Corn samples were placed into the sample holder and pressure applied. By increasing pressure applied to the sample, the measured resistance decreased due to larger kernel-to-kernel contact area, while variability in resistance measurements was reduced. In preliminary testing, resistance measurement was sensitive to pressures <20 psig (140 kPa), but this effect decreased above this point. Resistance initially decreased after pressure was applied to the samples, but became constant after a 5-sec wait period. Therefore, a pressure of 45 psig (310

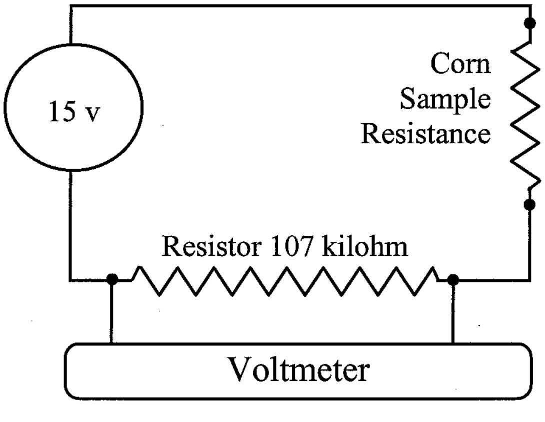

Fig. 1. Schematic of circuit and probe used to measure resistance of a 250-g sample of corn.

kPa) was applied to the sample and a voltage reading (V_m) was taken 5 sec after pressure was applied. An input voltage of 15 volts and a pressure of 45 psig (310 kPa) were used in all testing.

The resistance of the sample (R_c) was calculated as:

$$R_c = \left(\frac{V_t}{V_m} - 1\right)\frac{R_m R_v}{R_m + R_v} \tag{1}$$

where R_c is the corn sample resistance (ohms), R_m is the impedance of the voltmeter, a constant, R_v is the resistance of a precision resistor, 107 kilohm, a constant, V_m is the voltage meter reading for the sample (volts), V_t is the effective input voltage (15 volts), constant. Notice that the resistance term in Eq. 1 is a constant value because R_m and R_v are constants.

In 1991, the input voltage was controlled by a variable transformer (Powerstat, Superior Electric, Bristol, CT) and voltage measurements were taken by a digital multimeter (model 360-2, Simpson Electric, Chicago). In 1992, the input voltage was controlled by a 15 volt (DC) power supply, voltages measured using a voltmeter (model 77, John Fluke Mfg., Everett, WA). Both systems performed well and gave excellent repeatability of measurements.

The voltage source was changed in the resistance measuring equipment in 1992. The variable transformer that provided a 15 volt (AC) input voltage required frequent checking and adjustment during data collection. To alleviate this problem, a DC power supply that converted standard 120 volts (AC) to 15 volts DC, was used in 1992. Although the input voltage was routinely checked during all sample collection, the DC supply made measurement more convenient and reliable.

Baseline Equations

The resistance and capacitance data collected from ambient-dried samples dried in 1991 were used to develop a relationship, defined as the baseline reference equation, between the capacitance and $\log_{10}$ of the log(R). The data were fitted to linear, quadratic, and cubic relationships (PROC GLM, SAS Institute, Cary, NC).

At the time the baseline reference equations were developed in 1991, the relationship between log(R) and capacitance was thought to be relatively constant, and a limited amount of data from ambient-dried corn was collected in 1992. However, an adjustment was necessary based on observations from the ambient-dried corn collected in 1992 (Fig. 3). Unfortunately, a new baseline could not be created, as it had been the previous year, but it was modified by shifting the existing baseline upward by 0.5 $\log_{10}$ units of resistance. Significantly more data would have been required to create a new baseline for the second crop year.

Calculation of Displacement Value

To calculate the displacement value (DV) for a corn sample, the measured resistance (R_c) of the sample was substituted into the baseline reference equation to calculate a predicted capacitance (C'). The absolute value of the difference between the predicted and measured (C) capacitance was defined as the DV for the sample and has units of capacitance, measured in picofarads (pF). Because DV measures the horizontal distance from the baseline, DV is always a positive value. Statistical analysis of treatment means was conducted with a completely randomized experiment design. Treatment means were compared for statistical separation with the least significant difference method and a probability level of $\alpha = 0.05$.

Work by Holaday (1964) and Weller (1987) considered only RC data that fell to the left of the baseline reference, since these studies considered the baseline as a set of maximum combined RC properties. In the present study, the distance from the baseline, either to the left or to the right, was hypothesized as a departure from a set of optimum RC properties as defined by the baseline reference.

Wet Milling

Laboratory wet milling was conducted to verify the extent of damage to samples indicated by DV. Due to the large number of treatments tested to determine DV, a smaller group of 24 treatments was selected for laboratory wet milling. The group of treatments exhibited a DV range that in some cases seemed to follow, while in other cases seemed to contradict the theory of increased DV with increased severity of drying conditions (Table I). Laboratory-scale wet milling quantified milling characteristics and determined the accuracy of the DV method. Previous data from

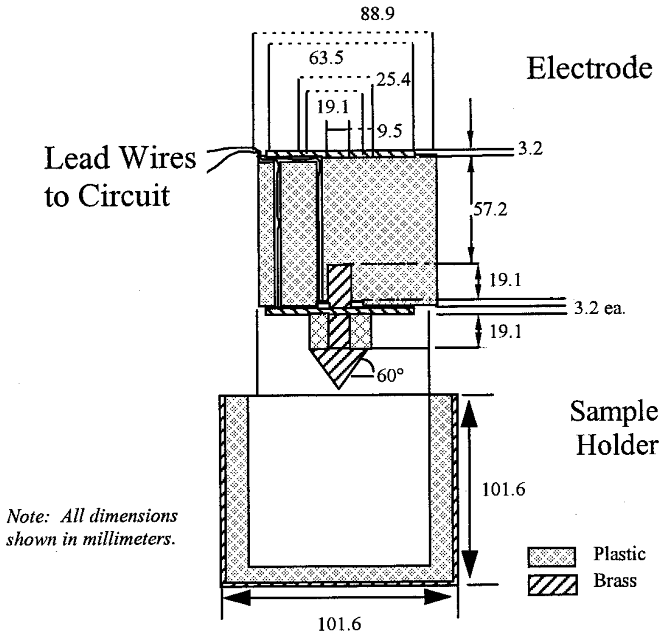

Fig. 2. Probe used to measure resistance.

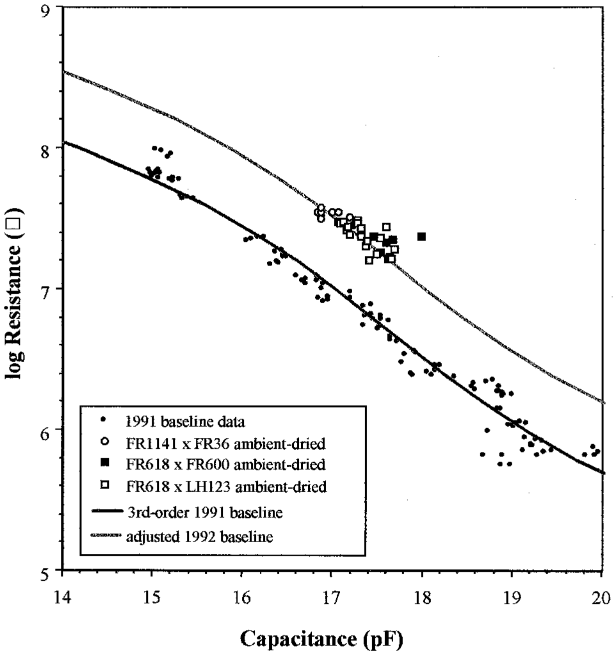

Fig. 3. Change in resistance and capacitance properties of ambient-dried corn from two crop years.

Holaday (1964) suggested that reduced starch yields would correspond to a DV above a threshold value. The laboratory wet milling attempted to demonstrate that starch yields were lower, and general milling ability was reduced when a large DV was measured.

The laboratory-scale wet-milling process followed the procedure described by Eckhoff et al (1996) and used a 100-g sample for each milling run. Samples were batch steeped in 500-mL screw-top Erlenmeyer flasks for 36 hr in 180 mL of steeping solution consisting of distilled water, 0.2% sulfur dioxide, and 0.5% lactic acid. Samples to be milled were identified only by code to prevent bias during milling. Replicates were arranged in a randomized complete block design. Treatment means were compared using the least significant difference method and a probability level for statistical significance of $\alpha = 0.05$. A total of 24 treatments was wet-milled using two to four replicates per treatment.

RESULTS AND DISCUSSION

Resistance and Capacitance Properties of Ambient-Dried Corn

A third-order polynomial was fitted to the RC data collected on ambient-dried corn samples. Prior to curve-fitting, the data were examined for differences due to hybrid. Since the differences were small and within the range of variability caused by other sources, the data were pooled to generate the baseline reference equation:

$$C' = 151.4 - 55.98x + 8.063x^2 - 0.4012x^3 \qquad (R^2 = 0.97)$$

where C' is the predicted capacitance, in picofarads (pF), $x = \log_{10}(R_c)$, and R_c is the measured resistance of the corn sample, in ohms. Although the data were highly linear ($r = 0.96$), a cubic relationship gave the best intuitive fit to the data at the extreme portions of the data set (Fig. 3, Table II).

RC data collected on all ambient-dried samples in 1992 were consistently shifted away from the baseline reference created in 1991. This shift in the baseline reference may be a normal year-to-year occurrence or may be an indication of the unusual nature of the 1992 growing season. Potential causes for the shift are changes in corn properties due to growing conditions, differences in air flow rates used to dry ambient samples, and perhaps other unknown factors as well. This indicates that the baseline would have to be calibrated for each crop year and an ambient dryer used, which diminishes the usefulness of the method in a commercial setting. Additional research would be needed to determine cause and effect relationships for the year-to-year shift.

Since the shift was not explained by possible instrument errors, and because it was not possible to collect additional RC data to create an entirely new baseline, a second baseline reference was developed to evaluate samples for dryer damage in 1992. Ambient-dried resistance-capacitance data were not collected over a range of moistures as in 1991. Therefore, an entirely new baseline reference could not be developed. A baseline was developed by shifting the 1991 baseline upward 0.5 units on the log resistance scale, to fit the RC data for ambient-dried corn collected in 1992 (Fig. 3). The equation in its revised form is:

$$C' = 151.4 - 55.98\,(x - 0.5) + 8.063\,(x - 0.5)^2 - 0.4012\,(x - 0.5)^3$$

The correlation of the adjusted baseline to the 1992 ambient-dried corn data was relatively high ($r = 0.80$), but there was some loss in accuracy compared to the 1991 cubic relationship. Since material was not available to collect additional data for a complete baseline, the shift in the baseline was accepted as the best possible solution. Additional data to create an entirely new baseline for 1992 would have been preferable to extrapolating the baseline from 1991. The RC data from ambient-dried corn collected in 1992 does suggest a parallel relationship to the 1991 baseline.

TABLE I
Description of Laboratory Wet-Milled Samples

Sample and Treament No.	Dryer Type[a]	Temperature (°C)	Drying Rate (g)[b]	DV (pF)[c]	Description/Rationale
FR1141 × FR36					
A1	Batch	Ambient	0.01	0.10	High quality, low temperature dried corn.
A2	Batch	50	0.07	0.20	Low temperature dried at low air flow rates.
A3	Tray	50	0.10	1.11	Low temperature dried at high air flow rates. High DV.
A4	Batch	70	0.18	0.59	Low temperature dried at high air flow rates. High DV.
A5	Batch	90	0.32	0.72	Low temperature dried at high air flow rates. High DV.
A6	Tray	90	0.41	2.10	High DV for this temperature.
A7	Batch	115	0.35	0.57	High temperature dried at low air flow rates.
A8	Tray	115	0.77	1.56	High temp., high air flow, three times larger DV than A7.
FR618 x FR600					
B1	Batch	Ambient	0.02	0.29	TFHT[d]
B2	Batch	50	0.05	0.16	TFHT
B3	Batch	70	0.19	1.08	TFHT
B4	Batch	90	0.29	0.94	TFHT
B5	Batch	115	0.39	1.50	TFHT
FR618 x LH123					
C1	Batch	Ambient	0.01	0.11	TFHT
C2	Batch	50	0.06	0.46	TFHT
C3	Batch	90	0.18	2.26	TFHT
C4	Batch	115	0.34	1.17	TFHT
Commercial Source					
EY	CF	55	· · ·	1.14	High quality, high density dent corn.
SV	CON	50–55	· · ·	0.46	Low-temperature commercially dried. Low DV expected.
G	CF	99	· · ·	0.16	High-temperature commercially dried. High DV expected.
H	CCF	99	· · ·	0.26	High temperature commercially dried. High DV expected due to temperature.
P	CF	99	· · ·	0.17	High DV expected.
OFD	· · ·	· · ·	· · ·	2.05	Unusual DV, browned kernels. Drying method not known.
W	CF	136	· · ·	0.26	Higher temperature than other elevators. Low DV. Browned kernels.

[a] Batch = laboratory batch dryer; tray = steam-heated tray dryer; CF = cross flow; CON = concurrent flow; CCF = countercurrent flow.

[b] Reported as g of $H_2O/(g \cdot hr)$.

[c] DV = displacement value in picofarads. Least significant difference = 0.38 pF ($\alpha = 0.05$).

[d] THFT = Treatments that tended to follow the hypothesized trend.

The change in dryers used to dry ambient corn samples my have caused the upward shift in the baseline. While this is a possibility, it raises a serious concern as to the effectiveness of the method. Although ambient air flow may alter RC properties, and thus DV, it has been shown that ambient air at a wide range of flowrates does not affect wet-milling quality (Watson and Hirata 1962).

DV and Drying Temperature

For batch-dried corn, DV correlated to a limited extent ($r = 0.66$) with drying temperatures for both crop years (Tables III and IV). The DV means ranged from 0.23 to 1.04 and from 0.10 to 2.26 pF over the range of the drying temperatures for 1991 and 1992 data, respectively. Least significant difference analysis ($\alpha = 0.05$) of means from each drying temperature show significant increases in DV as drying temperature increased above 70°C. However, there were also significant differences in DV when drying at the same temperature using different batch dryers (Table IV). The drying rates were higher in the tray dryer and these treatments had typically higher DV.

Wet-Milling Results

The laboratory-scale milling yields followed expected trends associated with the severity of drying conditions, including reduced solids in the steepwater, starch yield and starch recovery, and increased fiber and gluten yields with increased severity of drying conditions. (All yields are reported as a percentage of total dry corn solids.) These trends have been documented in previous research (Watson and Hirata 1962, Vojnovich et al 1975, Weller 1987). When considering characteristics of corn with a wide or unknown range of variability caused by hybrid, growing conditions, drying methods, or other unknown factors, starch recovery is a useful descriptor of wet-milling quality. This is because recovery measures yield against the theoretical maximum for a particular sample. Starch recoveries in the present study showed no significant changes between ambient and 50°C for the batch-dried treatments (Table V), which is similar to the result reported by Weller (1987) and Watson and Hirata (1962). The protein contents of the starch fractions, a measure of the quality of the recovered starch fraction, were consistently <0.35%, even for the most severely dried treatments.

The treatments dried at severe conditions (115 or 136°C) had significantly lower starch yields and recoveries, while starch yields were significantly higher in treatments dried at 30–55°C (Table V). Starch yield and recovery decreased significantly at ≥70°C for batch-dried treatments and correlated to drying temperature ($r = -0.81$ and -0.78, respectively). This result is supported by previous studies with batch-dried corn (MacMasters et al 1959, Watson and Hirata 1962, Weller 1987).

Starch recovery for the 55°C concurrent flow commercial dryer (SV) was significantly higher than the 50°C batch treatments (A3, A2, B2, C2), as well as the commercially dried sample dried at 52°C (EY), probably because of differences in hybrid characteristics. Even though 99°C is considered a moderately high drying temperature, moistures at harvest of the H and P treatments were rather low (~19-22%), which apparently resulted in less damage than if the samples had been dried at 99°C from higher moistures. The EY treatment had good milling characteristics even though the sample had a significantly higher kernel density (1.31 g/cm^3) compared to lower densities of dent corn with good milling characteristics (1.25–1.29 g/cm^3). A high-density kernel is usually more difficult to steep adequately, resulting in lower starch recovery. An example of poor-milling, high-density corn was FR618 × LH123 (1.30 g/cm^3), which had significantly higher density and lower starch recovery (87.7%) than its batch-dried counterparts, even though it had been dried at 30°C.

Starch Yield and Recovery as a Function of Displacement Value

Using DV to detect corn wet-milling quality was relatively unreliable. While DV correlated somewhat with drying air temperature for batch dryers ($r = 0.66$), there was only moderate correlation

TABLE II
Baseline Reference Equation Coefficients[a]

	1st Order (linear)	2nd Order	3rd Order
A	33.96	31.14	151.4
B	–2.444	–1.601	–55.98
C	· · ·	–0.06200	8.063
D	· · ·	· · ·	–0.4012
R^2 value	0.96	0.96	0.97

[a] Polynomials have the general form: $C' = A + Bx + Cx^2 + Dx^3$ where C' is the predicted corn sample capacitance, in picofarads, x is $\log_{10}(R_c)$, R_c is the measured corn sample resistance (ohms), A, B, C, D, ... are coefficients for the polynomials.

TABLE III
Displacement Values (DV) for Each Hybrid and Drying Temperature Treatment[a]

Temperature (°C)	Tray Dryer DV (pF)
FR27 × FRMo17	
Ambient	0.23e[b]
50	0.31de
70	0.42c–e
90	0.69b
115	1.04a
FR618 × FR600	
Ambient	0.27e
50	0.28e
70	0.41de
90	1.02a
115	0.35de
FR1087 × LH123	
Ambient	0.27e
50	0.33de
70	0.62bc
90	0.96a
115	0.48cd
LSD	0.20

[a] From 1991 crop year.

[b] Values followed by a common letter in the same column are not significantly different using the least significant difference (LSD) method and a probability level of $\alpha = 0.05$.

TABLE IV
Statistical Comparison of Displacement Values (DV)[a] from Tray- and Batch-Dried Samples[b]

Temperature (°C)	Batch Dryer DV (pF)	Tray Dryer DV (pF)
FR1141 × FR36		
30	0.10wx[c]	· · ·
50	0.20t–x	1.11hi
70	0.59m–s	1.20f–h
90	0.72j–q	2.10c
115	0.71j–q	1.56ef
FR618 × FR600		
30	0.29s–x	· · ·
50	0.16v–x	1.22f–h
70	1.08h–k	0.35q–x
90	0.94h–n	0.77i–p
115	1.50e–g	0.69k–r
FR618 × LH123		
30	0.11wx	· · ·
50	0.46p–w	0.96h–m
90	2.26bc	2.16bc
115	1.17gh	2.51b
LSD	0.38	

[a] DV were analyzed together with commercially-dried samples. Therefore, the letter "a" does not appear in the table.

[b] From 1992 crop year.

[c] Values followed by a common letter are not significantly different using the least significant difference (LSD) method and a probability level of $\alpha = 0.05$.

with starch yield and recovery (*r* = –0.41 for both). However, the method clearly was not a reliable indication of starch yield and recovery for commercial samples (*r* = –0.03 and –0.10, respectively). This large decrease in correlation indicates that the DV method may work to some degree when measuring properties of samples that are similar to samples used to create the baseline, but it does not perform when measuring properties of samples of unknown hybrid and growing condition.

Examining data from known hybrid and drying conditions, there is a large amount of variation in ability to detect poor milling quality. Furthermore, when samples obtained from commercial sources are considered, this variability becomes larger. DVs of 1.0 to 1.2 pF were measured for samples with a wide range of starch yields (47–67%) and starch recoveries (66–91%) (Table V). Recoveries ranging from 66 to 91% indicate a range of poor to excellent milling characteristics, while the corresponding range of DV from 1.0 to 1.2 pF was nonsignificant. Treatments of FR1141 × FR36 dried with the tray dryer at 50, 90, and 115°C had significantly higher DVs than those dried with the laboratory batch dryer. However, they also had significantly higher starch yields.

The relatively good correlation of DV to drying air temperature in both crop years (*r* = 0.66) is attributed to the relatively small amount of hybrids and growing conditions used in the preliminary stages of this study. While some of the performance could be attributed to the method used to create the 1992 baseline, other factors such as growing conditions and location may have also played a role. Correlation of physical properties (test weight, kernel density, kernel volume, and 100 kernel weight) with DV was small (Rausch 1993), and thus are not reported here.

TABLE V
Comparison of Displacement Values (DV) with Starch Yield and Recovery

Treatment	Dryer Type[a]	(°C)	DV (pF)[b]	Starch Yield[c]	Starch Recovery
FR1141 × FR36					
A1	Batch	30	0.10wx[d]	65.9c–e	92.2bc
A2	Batch	50	0.20t–x	65.8c–f	91.8bc
A3	Tray	50	1.11hi	67.6ab	92.6bc
A4	Batch	70	0.60m–s	61.4i	85.2hi
A5	Batch	90	0.72j–q	61.4i	84.5ij
A6	Tray	90	2.10c	64.8d–g	89.0d–f
A7	Batch	115	0.57n–t	54.8i	77.2m
A8	Tray	115	1.56ef	57.2jk	81.4kl
FR618 × FR600					
B1	Batch	30	0.29s–x	64.7e–g	90.3c–e
B2	Batch	50	0.16v–x	66.4b–d	91.8bc
B3	Batch	70	1.08h–k	62.1hi	87.0f–h
B4	Batch	90	0.94h–n	61.9i	86.3g–i
B5	Batch	115	1.50e–g	56.1kl	77.9m
FR618 × LH123					
C1	Batch	30	0.11wx	64.2fg	87.7fg
C2	Batch	50	0.46p–w	64.4e–g	87.9fg
C3	Batch	90	2.26bc	57.1jk	79.3lm
C4	Batch	115	1.17gh	47.3m	64.5n
Commercial Source					
EY	CF	52	1.14g–i	66.8a–c	91.2b–d
SV	CON	55	0.46p–w	68.2a	95.8a
G	CF	99	0.16v–x	64.9d–g	91.1b–d
H	CCF	99	0.26s–x	64.7e–g	90.8b–e
P	CF	99	0.17u–x	67.1a–c	92.9b
OFD	· · ·	· · ·	2.05cd	63.7gh	88.6e–g
W	CF	136	0.26s–x	57.9j	82.6jk
		LSD	0.38	1.7	2.3
Correlations (*r* values)					
Batch-dried with DV		0.66	· · ·	–0.42	–0.42
Batch-dried with °C		· · ·	0.66	–0.81	–0.78
Commercial with DV		–0.71	· · ·	0.03	–0.10
Commercial with °C		· · ·	–0.71	–0.84	–0.78

[a] Batch = laboratory batch dryer; tray = steam-heated tray dryer; CF = cross flow; CON = concurrent flow; CCF = countercurrent flow.

[b] Letter "a" not shown because some treatments analyzed for DV were not wet-milled.

[c] Yields reported as percentage of total dry corn solids.

[d] Values followed by a common letter in the same column are not significantly different using the least significant difference (LSD) method and a probability level of $\alpha = 0.05$.

SUMMARY AND CONCLUSIONS

The baseline relationship between log-resistance and capacitance was affected by a set of undetermined parameters, such as yearly growing conditions and ambient air flowrate used to dry samples for the baseline. As a result, DV appears to be a poor indicator of starch yield and recovery. To some degree, DV correlates with starch yield and recovery (*r* = –0.42) for batch-dried samples, but with insignificant correlation with commercially obtained samples ($r \leq -0.10$).

In verifying the quality of selected samples of corn, starch yield and recovery were significantly lower in batch and commercially dried treatments when dried at temperatures >70 and 100°C, respectively. Yield and recovery were significantly higher in treatments with drying temperatures of 30–55°C. Starch recovery for a sample commercially dried at 55°C was significantly higher than for other commercial samples dried at temperatures ranging from 99 to 136°C.

Because the method performed differently with batch-dried samples grown in the same fields than with commercial samples, it is possible that differences in growing environment affect DV. For the method to be useful in a commercial setting, an understanding of the factors affecting the baseline reference relationship, as well as the effects of geography, hybrid, growing conditions, and other factors needs to be developed.

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