# PREDICTION OF THE MOISTURE CONTENT OF EASTERN CANADIAN CORN USING MEASUREMENTS OF CAPACITANCE AND TEST WEIGHT[1]

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## ABSTRACT

A statistical regression model for rapid prediction of moisture content based on measurements of dielectric capacitance and test weight was developed for Eastern Canadian corn (*Zea mays* L.). For 336 samples of the 1986 crop, dielectric readings were determined with a Model 919 grain moisture meter, test weight values with an Ohaus half-litre measure and moisture content values by a single-stage air-oven procedure. The regression model, which incorporates linear terms for dielectric reading and test weight plus an interaction term which is a product of the two, is an excellent predictor of corn moisture as indicated by analysis of the residuals and by the high value of the coefficient of determination ($R^2 = 0.95$) and low value of the standard error of estimate (SEE = 0.85). Although the relationship between moisture content and dielectric reading for Ontario samples differed from that for Quebec samples, the proposed regression model helped to compensate for the difference. This model was also effective in predicting moisture content for 365 samples of 1987-crop Eastern Canadian corn. As well, it yielded a better fit to 1986-87 crop data than did the dielectric-based regression model used in CGC Corn Moisture Conversion Table No. 9.

# INTRODUCTION

The moisture content of corn (*Zea mays* L.) has a considerable influence on the quality in terms of storability, processing properties and economic value. Corn must often be dried soon after harvesting to prevent deterioration due to sprouting and to growth and development of microorganisms, insects and mites. Watson (1987) noted that for high moisture content ranging from about 20% to 32%, corn kernels have a soft texture and are easily cut and punctured by harvesting and handling equipment, whereas below 12% moisture content the kernels are very brittle. It is the organic components, not the water, for which corn is valued. Removal of moisture requires energy and increases cost.

In Canada, the Model 919 grain moisture meter (AACC 1983a) - known as the Motomco 919 meter in the United States - is used by the Canadian Grain Commission (CGC) for the rapid determination of moisture content of grain during official grading; it is also widely used by the Canadian grain industry. The Model 919 meter was developed during the late 1940's by the Grain Research Laboratory (GRL) and adopted in 1958 by the CGC (Martens and Hlynka 1963).

The meter does not measure grain moisture content directly; it measures an electrical property of the grain which is a function primarily of the moisture content. The relative dielectric capacitance of the sample is displayed on the meter dial in arbitrary centesimal-scale units. Dielectric readings for samples of a given grain at a fixed temperature are highly correlated with moisture content values as determined by appropriate laboratory reference procedures (Nelson 1984). For each type or class of grain under consideration, statistical regression analysis is used to develop calibration equations for moisture content as a function of dielectric reading.

Several factors in addition to moisture content, temperature and type of grain affect the dielectric reading for a grain sample. These include: test weight; uniformity of distribution of moisture content throughout the individual kernels of the sample; kernel size and shape; soundness of the grain sample; presence of foreign material such as chaff, straw, weed seeds and grains of other classes; cultivar; growing locations; and growing season (Nelson 1987).

Nelson (1981) considered test weight to be an important factor affecting the dielectric properties of a grain sample. Test weight is the weight of grain per unit volume and is thus a measure of bulk density. Hlynka and Bushuk (1959) discussed the factors affecting test weight in some detail. It is influenced by both the density of packing of the grain and the density of the grain. Density of packing is affected by kernel shape, degree of uniformity of kernel size, and size and shape of measurement container. Density of the grain is determined by its biological structure and chemical composition, including moisture content. As water is less dense than dry grain, it follows that grain density and test weight are inversely related to moisture content. Nelson (1981) observed that the range of test weight values encountered increases with higher moisture content.

Nelson (1984) developed two regression models for expressing the dielectric constant of shelled, yellow-dent U.S. corn as a function of frequency, moisture content and bulk density. His models were based upon observed linearity of the square root and cube root of the dielectric constant with bulk density for corn in the moisture range 10 - 33%.

This paper reports the development of a statistical regression model, incorporating measurements of dielectric capacitance and test weight, which appears to offer considerable promise for use in rapid prediction of the moisture content of Eastern Canadian corn. The Model 919 meter was used to measure dielectric capacitance values and the development of the regression model is based upon samples from the 1986 crop of Eastern Canadian corn.

## MATERIALS AND METHODS

### Samples

This study is based on 336 samples of the 1986 crop of Eastern (the term "Eastern" denotes the corn-growing areas of Ontario and Quebec) yellow-dent corn. These samples were all mechanically shelled, had moisture content values of 20 - 38% and were classed as "cool and sweet" by grain inspectors of the CGC Grain Inspection Division immediately prior to dielectric measurement and moisture testing. All samples were freshly harvested when collected, and tested that day or shipped via air express to Winnipeg and tested the following day. There were 249 samples from 19 counties of Ontario and 87 samples from 10 counties of Quebec.

Table 1 gives the mean, standard deviation, minimum and maximum values for moisture content and test weight by region. The Ontario corn samples tended to be lower in moisture content and higher in test weight than the Quebec samples.

## Procedures

Prior to testing, corn samples were cleaned using a No. 12 Round Hole sieve with 4.76 mm openings (CGC 1987a) and by hand-picking impurities such as pieces of cob and large fragments of kernels.

Dielectric readings were determined for corn samples using a Model 919 grain moisture meter with a 3.5-inch diameter test cell (sample size: 175 g) (AACC 1983a). Each dielectric value is the average of at least three meter readings. For corn samples at temperatures other than 22°C, dielectric values were adjusted to a 22°C base using the temperature conversion equation for CGC Corn Moisture Conversion Table No. 8.

Moisture content values were determined in duplicate on samples of whole seed by a single-stage, 72-hour, 103°C air-oven reference procedure (sample size: 50 g) (AACC 1983b).

Test weight values, in units of g $(0.5\ L)^{-}$ , are the average of duplicate determinations with an Ohaus half-litre measure (CGC 1987b).

## RESULTS AND DISCUSSION

Dielectric reading was highly positively correlated ($r = 0.94$) with moisture content, while test weight was negatively correlated with both moisture content ($r = -0.66$) and dielectric reading ($r = -0.80$). These correlations are statistically highly significant (p-value less than 0.001) as each is computed for 336 observations.

## Candidate Regression Models

Three candidate regression models for predicting corn moisture were considered and evaluated:

Model A: (Linear in dielectric reading)

$$MC_i = B_0 + B_1DR_i + E_i$$

Model B: (Linear in dielectric reading and test weight)

$$MC_i = B_0 + B_1DRi + B_2TW_i + E_i$$

Model C: (Linear in dielectric reading and test weight, but with an interaction term)

$$MC_i = B_0 + B_1DR_i + B_2TW_i + B_3DR_iTW_i + E_i$$

For the above models $B_0$, $B_1$, $B_2$ and $B_3$ are regression parameters and:

$n$ = number of corn samples

$MC_i$ = moisture content value for the ith sample

$DR_i$ = dielectric value for the ith sample

$TW_i$ = test weight value for the ith sample

In each case, $i = 1, 2, \ldots\ldots, n$ and the error terms $E_i$ are assumed to be independent normally distributed random variables each with mean zero and common variance.

Models involving quadratic terms were also considered, but these were less satisfactory and are not discussed.

## Model Fitting

Least squares regression procedures were used to fit each of the three candidate regression models to the data sets for the Eastern region, Ontario and Quebec. Regression summaries of quality of fit for each model, by region, are given in Table 2. In comparing quality of fit between regression models, high values of the coefficient of determination ($R^2$) and low values of the standard error of estimate (SEE) are preferred.

For each region, the models B and C incorporating test weight information produced better fits, as measured by these criteria, than did Model A which is based solely on dielectric reading.

The fit of Model A to the data for all of the Eastern corn samples yielded values of $R^2 = 0.89$ and SEE = 1.30. The residuals from this fit are plotted against test weight in Figure 1. In general, if a particular regression model fits the data well, then the residuals, when plotted against one of the regressor variables in the model, should appear randomly scattered in a narrow band centered about a horizontal line through zero. Also, when plotted against a variable not in the model, the residuals should exhibit no trend other than random scatter with respect to that variable. The apparent quadratic trend of the residuals with respect to test weight suggests that test weight is an important explanatory variable which should be added to the model.

The fit of Model B to the Eastern data gave values of $R^2 = 0.91$ and SEE = 1.18. Figure 2 shows the residuals from the fit of Model B plotted against test weight and dielectric reading. The residuals exhibit marked quadratic trends in relation to test weight and dielectric reading, which indicates that quadratic terms involving test weight and dielectric reading should be considered for addition to the model.

However, the correlation ($r = -0.80$ for the Eastern data) of test weight with dielectric reading suggests that the use of an interaction term, involving a product of dielectric reading and test weight, may eliminate the need for quadratic terms for those two variables. The need for an interaction term is strongly indicated in Figure 3 by the apparent linear relation between moisture content and the product of dielectric reading and test weight.

Model C has a linear term in dielectric reading, a linear term in test weight and an interaction term which is a product of dielectric reading and test weight. To avoid problems of multicollinearity, the dielectric reading and test weight variables were centered by subtracting their respective observed means. A least squares fit of a non-centered version of Model C to the Eastern data, yielded a condition number of $K = 1062$, indicating severe multicollinearity between regressor variables. (The condition number (K) is the ratio of the largest eigenvalue to the smallest eigenvalue of the correlation matrix of the regressor variables. Montgomery and Peck (1982) suggested that generally if K is greater than 1000, then severe multicollinearity is indicated, while if K is less than 100, there is no serious multicollinearity problem.) In contrast, the least squares fit of the centered version of Model C to the Eastern data produced a value of $K = 10$, showing that multicollinearity problems had been eliminated.

For the fit of Model C to the Eastern data, $R^2 = 0.95$ and SEE = 0.85, which represent a marked improvement over the values for Models

B and A. Residuals are plotted against test weight and dielectric reading in Figure 4. In comparison to the corresponding residual plots for Model B, the overall scatter in residuals has been reduced and the quadratic trends in the residuals have been removed.

The variability of the residuals tends to increase with increasing dielectric reading and to decrease with increasing test weight, suggesting that the error variances for Model C may be heteroscedastic (non-constant). Thus, in order to develop prediction intervals based on the fit of Model C, weighted least squares procedures could be used.

Both residual analysis and comparison of $R^2$ and SEE values indicate that of the three candidate regression models, Model C provided the best fit.

## Split-Sample Analysis

To gain insight into the sensitivity of the conclusions reached in the model-fitting stage, a procedure which Green (1978) referred to as split-sample analysis was applied to the data. Each of the Eastern, Ontario and Quebec data sets were split into two data sets and the regression models A, B and C were fitted to each of the partial data sets. This paper discusses the split-sample analysis for just the Eastern corn data, but similar findings were obtained for both the Ontario and Quebec data sets.

The Eastern corn data set was split into two halves by sorting the data records into ascending order by test weight within moisture level and then assigning the odd-numbered records to one data set, SS-1, and the even-numbered records to a second data set, SS-2. The original data set was divided in this systematic manner, rather than randomly, so as to ensure that the two resulting partial data sets would have approximately the same marginal distributions of moisture content and test weight values.

Regression summaries of quality of fit for each candidate regression model for the two split-sample Eastern corn data sets, SS-1 and SS-2, are presented in Table 3. As measured by $R^2$ and SEE values, Models B and C yielded better fits to the data sets than did Model A, which does not use test weight information. Model C performed best overall in terms of quality of fit.

These results of the split-sample analysis help to substantiate the conclusions reached in the model-fitting stage.

## Cross Validation

The prediction performance of the three candidate regression models were examined using a procedure known as double cross validation (Green 1978). The regression equations obtained by fitting Models A, B and C to the first split-sample Eastern data set, SS-1, were used to predict moisture content values for the second split-sample data set, SS-2. These predicted moisture content values were then compared to the observed values of moisture content for SS-2 by fitting a simple linear regression model with predicted moisture content as the dependent variable and observed moisture content as the regressor variable. Similarly the regression equations determined by fitting Models A, B and C to SS-2 were used to predict moisture content values for SS-1, which were then contrasted with the observed moisture content values for that data set.

Table 4 summarizes the prediction performances for each candidate regression model on the two split-sample data sets. For each model, a regression summary is given for the least squares fit of predicted moisture content as a linear function of the observed moisture content. Were a regression model to predict perfectly, then points corresponding to observed and predicted moisture content values would all lie exactly along an equal-value line. Thus in comparing quality of prediction between regression models, high values of R , low values of SEE, slope values near 1.0 and intercept values near 0.0 are preferred. In terms of these criteria for prediction, Models B and C are superior to Model A, while Model C clearly performed best overall. Note that it is important to consider slope and intercept values when assessing prediction performance, so as to safeguard against situations in which predicted and observed values are linearly related but are not closely scattered about the equal-value line.

Cross validation procedures were also applied to the split-sample data sets for Ontario and for Quebec. Results supporting Model C were obtained, but these are not discussed.

Split-sample analysis and double cross validation thus support the findings from the model-fitting stage that for the purpose of predicting the moisture content of Eastern Canadian corn: (i) Model C is the best of the three candidate regression models; and (ii) in addition to dielectric reading, test weight is also an important regressor variable.

## Prediction Performance on 1987-Crop Eastern Corn

Hurburgh et al (1987) documented year-to-year variability in the relation of dielectric properties to moisture content for combine-shelled U.S. corn in the moisture range 10 - 32%. To address the issue of possible year-to-year variation in the relationships between moisture content, dielectric reading and test weight for Eastern Canadian corn, the prediction performances of regression Models A, B and C were evaluated for the 1987 crop.

Measurements were taken on 365 samples of "cool and sweet" 1987-crop Eastern corn, of which 205 samples were from Ontario and 160 from Quebec. Table 5 lists the mean, standard deviation, minimum and maximum values of moisture content and test weight by region for these samples. In comparison to the 1986 samples, the 1987 samples were generally lower in moisture content and higher in test weight. These differences limit the extent to which the 1987-crop data can be used to validate models fit to the 1986-crop data.

The regression equations obtained by fitting Models A, B and C to the 1986-crop Eastern corn data set were used to predict moisture content values for the 1987-crop Eastern corn data set. These predicted values were then compared to the observed moisture content values for the 1987 crop by fitting predicted moisture content as a linear function of observed moisture content and then examining the R , SEE, slope and intercept values for the resulting line. As shown in Figure 5 and Table 6, Model C was an effective predictor of moisture content for 1987-crop Eastern corn and gave the best prediction performance as, despite a slightly higher SEE value, it was the only one of the models to yield slope and intercept near 1.0 and 0.0 respectively.

### Ontario and Quebec Corn

During the course of data analysis, it became apparent that the relationship between moisture content and dielectric reading for Ontario corn differed from that for Quebec corn, with Quebec corn tending to yield higher dielectric values for given moisture content. For example, the least squares fit of moisture content as a linear function of dielectric reading gave a slope of 0.26 for 1986-crop Quebec corn, as compared to 0.39 for 1986-crop Ontario corn.

The reason for the apparent difference in dielectric response for Ontario and Quebec corn was not resolved by this study, although the extent of difference was compared for each of the three candidate regression models. The regression equations generated by fitting Models A, B and C to the 1986-crop Ontario data set were used to predict moisture content values for the 1986-crop Quebec data set, and vice-versa. Predicted and observed moisture content values were then compared by fitting predicted moisture content as a linear function of observed moisture content. Table 7 summarizes the prediction performance for each model on the two data sets by listing the $R^2$, SEE, slope and intercept values for the linear fit of predicted moisture content on observed moisture content. For these prediction criteria Model C performed by far the best.

Thus, Model C helped to adjust for the difference in dielectric response between the Ontario and Quebec data sets, whereas Models A and B were less effective in this respect.

## Comparison with CGC Corn Moisture Conversion Table No. 9

The performance of regression Model C, in terms of data-fitting quality and prediction capability, suggested that the grain trade may benefit considerably by adopting such a model for rapid determination of corn moisture content. To investigate the potential benefit, Model C was compared to the "Table 9 Model", the dielectric-based regression model used in CGC Corn Moisture Conversion Table No. 9 which was introduced August 1, 1987.

Table 9 is based on data for the 1982 through 1986 crops of Ontario corn. It uses a prediction equation in which moisture content is expressed as a linear function of dielectric reading for corn samples in the 20 - 30% moisture range, but as an inverse quadratic function of dielectric reading for samples above 30% moisture.

To provide a common basis for comparison, regression Model C and the Table 9 Model were each fitted to data for 956 corn samples from the 1986 and 1987 Ontario and Quebec corn crops. In Figures 6A and 6B, observed moisture content values for these samples are plotted against moisture values estimated using the fit of Model C and that of the Table 9 Model, respectively. The quality of fit achieved with model C was superior, as it yielded points that tend to lie much closer to the equal-value line, particularly in the higher moisture range.

## CONCLUSIONS

The moisture content of Eastern Canadian corn was highly positively correlated with dielectric reading, while both moisture content and dielectric reading were negatively correlated with test weight. For 336 samples of 1986-crop Eastern Canadian corn, the correlation between moisture content and dielectric reading was r = 0.94, while test weight was negatively correlated with both moisture content and dielectric reading.

In addition to dielectric reading, test weight is an important explanatory variable to consider when attempting to predict the moisture content of Eastern Canadian corn. For prediction of corn moisture content from dielectric reading and test weight information, a statistical regression model, with linear dielectric reading and test weight components and with an interaction component which is a product of dielectric reading and test weight, is effective as indicated by residual analysis and by the relatively high R (0.95) and low SEE (0.85) values for the model. During the development of a prediction equation, the variables dielectric reading and test weight should be centered by subtracting their respective means, so as to avoid problems of multicollinearity.

Split-sample analysis and double cross validation procedures were applied to the 1986-crop data to confirm the effectiveness of the recommended regression model. As well, this regression model was a good predictor of moisture content for 365 samples of 1987-crop Eastern Canadian corn. It also provided a better fit to 1986-87 crop data than did the dielectric-based regression model used in CGC Corn Moisture Conversion Table No. 9.

The relationship between moisture content and dielectric reading for Ontario corn differed from that for Quebec corn, with Quebec corn tending to yield higher dielectric values for given moisture content. The reason for this was not resolved by this study, although the use of the above-mentioned regression model, with linear terms in dielectric reading and test weight plus an interaction term, did help to adjust for the differences.

On the basis of the data for the 1986 and 1987 crops of Eastern Canadian corn, this regression model for predicting moisture content from dielectric reading and test weight values appears very promising. The grain trade may benefit considerably by application of such a model to the problem of rapid determination of moisture content in Eastern Canadian corn.

## ACKNOWLEDGEMENTS

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Table 1: Descriptive statistics by variable by region, 1986 crop

| Region | Mean | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|
| Moisture content, % | | | | |
| Eastern | 27.0 | 3.9 | 19.8 | 38.1 |
| Ontario | 25.8 | 3.4 | 19.8 | 36.9 |
| Quebec | 30.4 | 3.2 | 22.1 | 38.1 |
| Test weight, g $(0.5 L)^{-1}$ | | | | |
| Eastern | 328 | 17.6 | 276 | 377 |
| Ontario | 335 | 14.7 | 290 | 377 |
| Quebec | 311 | 12.5 | 276 | 345 |

Table 2: Summary of quality of fit for each of the candidate regression models, 1986 crop

| Region | Regression model | Coefficient of determination $R^2$ | Standard error of estimate SEE |
|---|---|---|---|
| Eastern | A | 0.89 | 1.30 |
| | B | 0.91 | 1.18 |
| | C | 0.95 | 0.85 |
| Ontario | A | 0.92 | 0.95 |
| | B | 0.94 | 0.81 |
| | C | 0.95 | 0.72 |
| Quebec | A | 0.79 | 1.49 |
| | B | 0.85 | 1.24 |
| | C | 0.88 | 1.12 |

Table 3: Summary of quality of fit for each of the candidate regression models as applied to the two split-sample eastern corn data sets, 1986 crop

| Data set | Regression model | Coefficient of determination $R^2$ | Standard error of estimate SEE |
|---|---|---|---|
| SS-1 | A | 0.90 | 1.23 |
| | B | 0.92 | 1.11 |
| | C | 0.96 | 0.82 |
| SS-2 | A | 0.88 | 1.38 |
| | B | 0.90 | 1.24 |
| | C | 0.95 | 0.88 |

Table 4: Summary of predictive performance for each of the candidate regression models for the eastern region, 1986 crop

(A): Prediction on split-sample SS-2 using fit to SS-1

| Regression model used for prediction | Regression summary for the least squares linear fit of predicted moisture content on observed moisture content | | | |
|---|---|---|---|---|
| | Coefficient of determination $R^2$ | Standard error of estimate SEE | Slope | Intercept |
| A | 0.88 | 1.31 | 0.89 | 2.79 |
| B | 0.90 | 1.18 | 0.90 | 2.53 |
| C | 0.95 | 0.85 | 0.94 | 1.59 |

(B): Prediction on split-sample SS-1 using fit to SS-2

| Regression model used for prediction | Regression summary for the least squares linear fit of predicted moisture content on observed moisture content | | | |
|---|---|---|---|---|
| | Coefficient of determination $R^2$ | Standard error of estimate SEE | Slope | Intercept |
| A | 0.90 | 1.14 | 0.88 | 3.22 |
| B | 0.91 | 1.07 | 0.92 | 2.32 |
| C | 0.96 | 0.81 | 0.97 | 0.87 |

Table 5: Descriptive statistics by variable by region, 1987 crop

| Region | Mean | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|
| Moisture content, % | | | | |
| Eastern | 24.3 | 2.4 | 20.0 | 31.7 |
| Ontario | 23.6 | 2.1 | 20.0 | 30.0 |
| Quebec | 25.1 | 2.4 | 20.4 | 31.7 |
| Test weight, g $(0.5\ L)^{-1}$ | | | | |
| Eastern | 343 | 11.8 | 313 | 376 |
| Ontario | 347 | 11.2 | 320 | 276 |
| Quebec | 339 | 11.0 | 313 | 364 |

Table 6: Summary of predictive performance for each of the candidate regression models on 1987-crop data set using fit to 1986-crop data set

| Regression model used for prediction | Regression summary for the least squares linear fit of predicted moisture content on observed moisture content | | | |
|---|---|---|---|---|
| | Coefficient of determination $R^2$ | Standard error of estimate SEE | Slope | Intercept |
| A | 0.94 | 0.43 | 0.74 | 6.26 |
| B | 0.91 | 0.52 | 0.70 | 7.60 |
| C | 0.94 | 0.57 | 0.94 | 1.49 |

Table 7: Summary of predictive performance for each of the candidate regression models, 1986 crop

(A): Prediction on Quebec data set using fit to Ontario data set

| Regression model used for prediction | Regression summary for the least squares linear fit of predicted moisture content on observed moisture content | | | |
|---|---|---|---|---|
| | Coefficient of determination $R^2$ | Standard error of estimate SEE | Slope | Intercept |
| A | 0.79 | 1.96 | 1.17 | -3.14 |
| B | 0.82 | 1.87 | 1.25 | -5.78 |
| C | 0.88 | 1.21 | 1.00 | 0.74 |

(B): Prediction on Ontario data set using fit to Quebec data set

| Regression model used for prediction | Regression summary for the least squares linear fit of predicted moisture content on observed moisture content | | | |
|---|---|---|---|---|
| | Coefficient of determination $R^2$ | Standard error of estimate SEE | Slope | Intercept |
| A | 0.92 | 0.62 | 0.62 | 10.00 |
| B | 0.83 | 0.89 | 0.59 | 11.76 |
| C | 0.95 | 0.69 | 0.93 | 1.78 |

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B - residual versus dielectric reading

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Figure 6. Comparison of fitted and observed moisture content for 1986- and 1987-crop Eastern Canadian corn for the least squares regression fit of:

A - Model C

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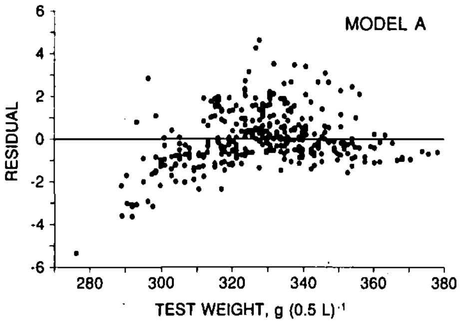
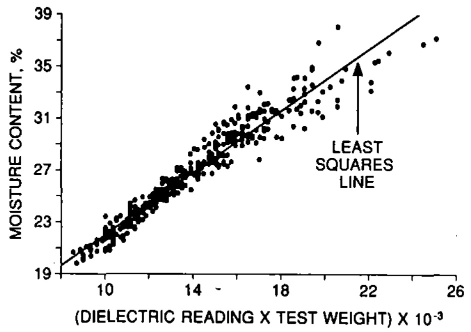


Figure 1



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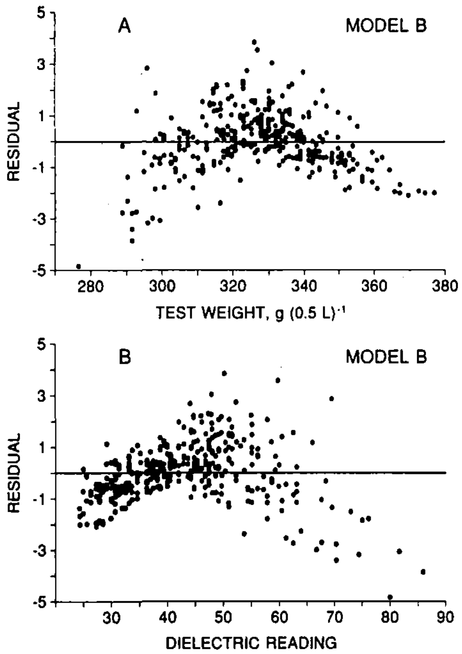

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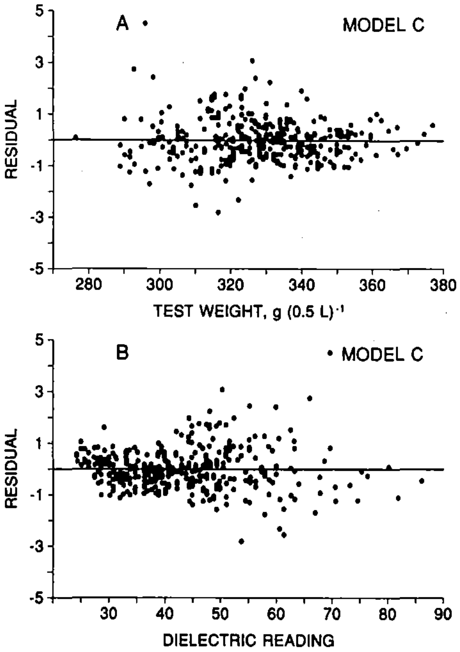

Figure 4

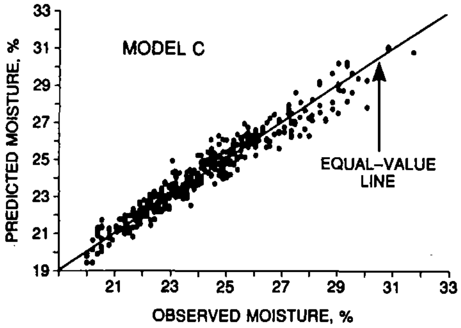

Figure 5

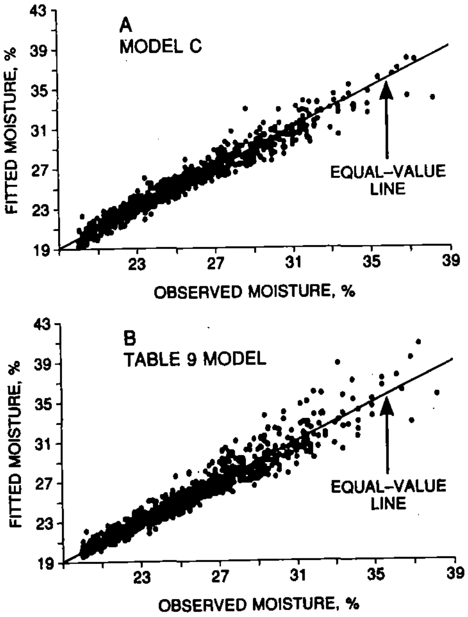

Figure 6