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Evaluation of the Feyerherm '81 Spring Wheat Models for Estimating Yields in North Dakota and Minnesota

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ABSTRACT

The Feyerherm '81 spring wheat yield models were evaluated for their ability to estimate yields at the State level in North Dakota and Minnesota. These regression models use a weather index which has been developed using agricultural experiment station data from a wide range of environmental conditions in the U.S.A. Daily weather values are used to simulate stages of plant development and a soil moisture budget. Derived weather and soil moisture variables are then summarized over the stages of development for use in the weather index. The State-level models incorporate the weather index along with trend or technology-related variables. The main recommendation resulting from this evaluation is that further research be done to improve the performance of the weather index.

Key Words: Model evaluation, crop yield modeling, regression models, spring wheat yield models, weather index.

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EVALUATION OF THE FEYERHERM '81 SPRING WHEAT MODELS FOR ESTIMATING YIELDS IN NORTH DAKOTA AND MINNESOTA

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EVALUATION OF THE FEYERHERM '81 SPRING WHEAT MODELS FOR ESTIMATING YIELDS IN NORTH DAKOTA AND MINNESOTA

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INTRODUCTION

The U. S. Department of Agriculture (USDA) is interested in improved procedures for forecasting and estimating average crop yields over large areas (crop reporting districts, states, countries). One approach is to use regression models based on historic values of yield, weather, and various agronomic variables. The Center for Climatic and Environmental Assessment Services (National Oceanic and Atmospheric Administration, U. S. Department of Commerce) has developed and uses these kinds of models for predicting spring wheat yields in several states in the U.S.A. and crop regions in the U.S.S.R. The Statistical Reporting Service (SRS of USDA) uses multiple regression models to develop indicators of durum and other spring wheat yields at the state level during the growing season in the U.S.A.

Presently, the weather variables used in the above models are based on temperature averages and/or precipitation totals over calendar months. Sebaugh (1981a) in an evaluation of the CEAS trend and monthly weather data models points out:

> "Of course, there is little year-to-year agronomic correspondence between the beginning and ending of a calendar month and the beginning and ending of stages of development for a wheat plant (and thus its changing temperature and moisture requirements). Also, wheat plants do not begin developmental stages at the same time each year. Therefore, an inherent difficulty exists in working with monthly weather data."

Dr. Arlin M. Feyerherm in the Department of Statistics at Kansas State University has been developing crop yield regression models which are based on the use of a simulated crop calendar and soil moisture budget. The planting date can be provided or estimated by a "starter" model. Then the stages of crop development, from emergence through ripe, are simulated based on daily weather values. Temperatures are averaged and precipitation is totaled over stages of development, such as heading to milk, rather than over calendar months. This method of defining the weather variables to be used in the regression analysis seems more consistent with available scientific knowledge about plant development.

Another attractive feature of Feyerherm's approach is his attempt to define a "universal" weather index which could be used in modeling spring wheat yields anywhere the crop is grown. The coefficients of individual terms which combine to make up the weather index are estimated based on agricultural experiment station plot data over the entire northern portion of the U.S. Great Plains. These individual term coefficients are then regarded as constant or universal. Only the coefficient of the combined weather index itself (along with any trend or technology terms) is estimated for application over a particular geographic area.

This report contains the first systematic evaluation of Feyerherm's models by the U. S. Department of Agriculture. The purpose is to provide feedback to Dr. Feyerherm and, hopefully, other developers of these kinds of models, about what we regard to be the strengths and weaknesses of his approach. This evaluation was not designed to consider the Feyerherm models for operational use by SRS, but rather to ascertain the potential of the approach for future model development research.

DESCRIPTION OF THE MODELS

The spring wheat yield models provided to USDA under research agreement No. 58-319T-0-0337X by Dr. Arlin M. Feyerherm of Kansas State University in 1981 are based on an approach he has developed over several years (Feyerherm 1977, 1979; Feyerherm and Paulsen 1981a, b). His initial work was funded as part of the LACIE (Large Area Crop Inventory Experiment) project which was designed to test the ability to estimate wheat production through remote sensing and ground-based meteorological observations. Feyerherm (1981a) stated that his "...research was directed toward developing models to predict large-area wheat yields from reported weather and related agronomic data which would be globally applicable except for minor adjustments to correct for local conditions. Such models would need to respond to both abrupt year-to-year yield changes due to environmental effects (weather, diseases, etc.) and long-term shifts due to technological improvements through added nutrients, genetic changes (new cultivars), weed and pest control, irrigation, and other cultural practices."

The models to estimate state level spring wheat yields in North Dakota and Minnesota which Feyerherm has documented under the current research agreement are simplified versions of those described elsewhere (Feyerherm 1977, 1979; Feyerherm and Paulsen 1981a, b). However, the approach remains consistent with his basic philosophy and goals. Actually two models were supplied, the difference being in the method of accounting for long-term shifts in yield due to technological improvements. One model explicitly identifies and includes specific components of technology and will be herein referred to as the "technology" model. The other model accounts for technological change only by the inclusion of trend terms, which are function of the year, and will be referred to as the "trend" model.

Weather Index

Both models include a common "weather index" variable. This variable, AVE_WX, is actually the average of index values derived at weather stations which are within or near the boundary of each state and which have daily values of rainfall and minimum and maximum temperatures available. In order to compute the weather index value for a particular location, the daily weather values for that location must be run through a computer program, WRVPGM'80 (the 1980 version of the Weather-Related Variables Program). This computer program estimates the planting date (if an actual one is not supplied), simulates the stages of development of a spring wheat plant and the contents of a soil moisture budget, and computes values of weather-related variables during each developmental stage. Instructions for using the program are contained in a "Users Manual for Weather Related Variables Program (WRVPGM'80)" which was assembled as a part of this research agreement.

Certain of these weather-related variable values are multiplied by their corresponding coefficients and summed with a constant to obtain the weather index value for each location. The selection of the weather-related variables and the determination of their coefficients and the constant were accomplished by performing regression analysis on an independent set of data.

Use of an independent set of yield/weather data, covering a wide range of environmental conditions, was a key element in the Feyerherm approach to development of a weather index. The data used for spring wheat are described in detail elsewhere (1977, 1981a). Briefly, it consists of 249 location/years over the northern portion of the U.S. Great Plains. The yields are those measured from varietal trials conducted at state agricultural experiment stations and farms over the period 1935 through 1973. Only yields free of episodic events, such as hail and pest damage, were used in the regression. Yields for each variety were adjusted to be comparable to a "standard" variety (Thatcher), using a process which will be described later. The average of the adjusted yields for three varieties was used by Feyerherm to represent a plot yield for a given location/year.

Daily weather records at weather stations near the experimental sites were used to generate values for the weather-related variables (average temperatures, precipitation, evapotranspiration, plant-available water, etc.) for each developmental stage. Stepwise regression procedures were used to determine the subset of variables to be included in the final weather index. Other independent variables are included in this plot-level regression analysis but are not part of the weather index. These include a variable for the amount of nitrogen applied and indicator variables for the locations. These indicator variables account for local differences in soils, fertility, and cropping practices (fallowed or continuous cropping).

The functional form of the weather index thus consists of the intercept (constant) and regression coefficients which are multiplied by their corresponding weather-related variables. These variables were selected using the regression analysis described above. For a detailed description of the weather index, see the Appendix-Weather Index. Feyerherm considers the parameters estimated in this manner "...to be applicable on a global basis." To calculate the value of the weather index for any given location/year the values of the weather-related variables for that location/year are multiplied by their coefficients and summed along with the intercept value. The same coefficients are used for any location or year, i.e., they are "universal."

Trend Model

The trend model for the states of North Dakota and Minnesota is given by:

$$\text{STYLD\_H} = \alpha_o + \alpha_1 * \text{TREND1} + \alpha_2 * \text{TREND2} + \alpha_3 * \text{AVE\_WX} + \text{Error}$$

AVE_WX is an average of the weather index values for the state, and STYLD_H is the state yield per harvested area. TREND1 equals harvest year minus 1955, if harvest year is less than or equal to T_O, and equals T_O minus 1955 otherwise. TREND2 equals harvest year minus T_O, if harvest year is greater than T_O, and equals zero otherwise. T_O is 1963 for North Dakota and 1968 for Minnesota. TREND2 is included only if its coefficient is statistically significant.

Technology Model

The technology model is given by:

$$\text{ASTYLD\_H} = \beta_o + \beta_1 * \text{TREND1} + \beta_2 * \text{TREND2} + \beta_3 * \text{AVE\_WX} + \text{Error}.$$

TREND1, TREND2, and AVE_WX are as previously described. ASTYLD_H is an adjusted state yield per harvested area and is equal to STYLD_H - TECH + EE_HLØSS. EE_HLØSS is the estimated yield loss due to rust and equals STYLD_H * EEF/(100-EEF) where EEF is the percent loss in yield due to rust. TECH is what Feyerherm calls "identified" technology and is the sum of NI, FALINC, and AVDYA which are defined below.

From previous work by Feyerherm and Paulsen (1981a), the AVE_WX coefficient in both models is expected to be "...less than unity, which is as it should be if the model is to reflect the fact that mean yields over a large area are less variable from year to year than are yields over a small area." The coefficients for the terms in TECH are all assumed to be unity so TECH is simply subtracted from the state yield to indicate what the yield would be without the effects of this identified technology. The trend terms are present to account for the effects of unidentified technology.

Nitrogen

NI is the increase in yield due to the application of nitrogen and equals 0.065 * AVNI. AVNI is the average amount of nigrogen in pounds/acre as determined by USDA survey data published in the Fertilizer Outlook and Situation series of reports published by the USDA Economic Research Service. The constant 0.065 was the estimate of the coefficient for the nitrogen variable from the previously described agricultural experiment station plot regression analysis.

Fallow Increment

In Feyerherm's previous work, two sets of weather-related variables could be computed for each weather station, one set using a continuous cropping soil moisture budget and the other using a fallowed budget. The resulting weather index values could then be combined based on the relative area devoted to each cropping practice. Presently, Feyerherm only runs a continuous cropping soil moisture budget and uses the variable FALINC to indicate the increase in yield due to fallowing. FALINC is considered to be zero in Minnesota. Data on fallowing versus continuous cropping is not collected in Minnesota because continuous cropping is the predominant cropping practice.

In North Dakota, FALINC is computed as the sum over the nine crop reporting districts (CRDs) of $INC_i * FL_i * P_i$ divided by 10000, $i = 1, 2, \ldots, 9$. INC_i is the average difference in yields between fallow and continuous cropping, FL_i is the percent of wheat harvested area which was on fallowed ground, and P_i is the percent of state-wide harvested area in CRD i.

Differential Yielding Ability

In the past, Feyerherm used a ratio to compare the yields of wheat varieties to a standard. He now uses a difference and describes the procedure in "Data Base Documentation for Test Data for KSU Spring Wheat Model" which was provided under the research agreement. For a given year and state, AVDYA is computed as $\Sigma q_k DYA_k / \Sigma q_k$ where the summation in each case is over k for N varieties, q_k is the percent of area in a given state planted to variety k in the specified year, and DYA_k is the differential yielding ability for variety k. The procedure used for calculating DYA is the same as the procedure used to adjust the plot yield values used in the regression analysis to obtain the weather index coefficients.

Data Base

Figures 1 and 2 show the historic all spring wheat (durum and other spring wheat) yields (quintals/hectare) for North Dakota and Minnesota as reported by U.S.D.A.'s Statistical Reporting Service. Although values are available back to the thirties, Feyerherm only used data from 1955 for his state level model development. One reason is that daily weather values are not available for many stations prior to 1948, and it is desirable to initialize and then run the soil moisture budget for several years so that inaccuracies resulting from errors in the initial values may be minimized. Another reason is that nitrogen data are not available at the state level prior to 1954, although very little was applied.

Daily weather data were used from six stations in North Dakota, five stations in Minnesota, and two stations in South Dakota.

EVALUATION OF THE MODELS

As a first step in the evaluation of these models, Kestle and Sebaugh (1981) prepared a working paper, "A Review of the Sources, Accuracy and Availability of the Input Data Required to Run Feyerherm's Spring Wheat Model and Preliminary Testing Performed by Feyerherm." This paper laid the groundwork for and suggested areas for further evaluation as presented in "Outline for Further Evaluation of the Feyerherm Spring Wheat Yield Model" (Sebaugh, 1981b).

The remainder of this section consists of subsections which discuss evaluation results for particular types of analysis. Indicators of yield reliability obtained from bootstrap tests over a ten-year period (1970-79) are given for the models as provided by Feyerherm and for each subsequent modification or analysis.

Further information about the indicators of yield reliability and bootstrap testing may be found in Wilson, et al. (1980), Wilson and Sebaugh (1981), and Sebaugh (1981a). The Appendix - Statistical Formulas provides details on many of the indicators of yield reliability.

Figure 1. USDA reported all spring wheat yields for North Dakota 1931-1980 (quintals/hectare)

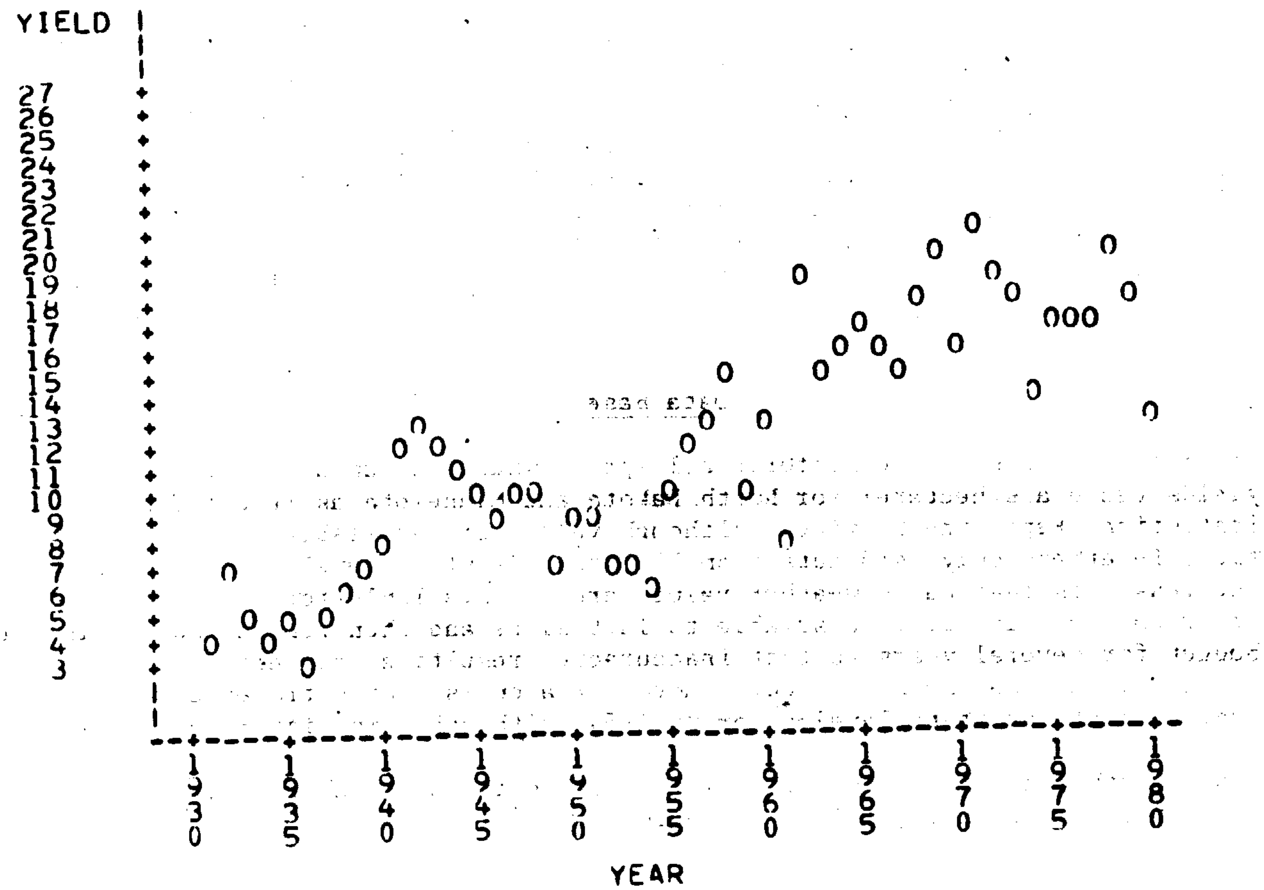
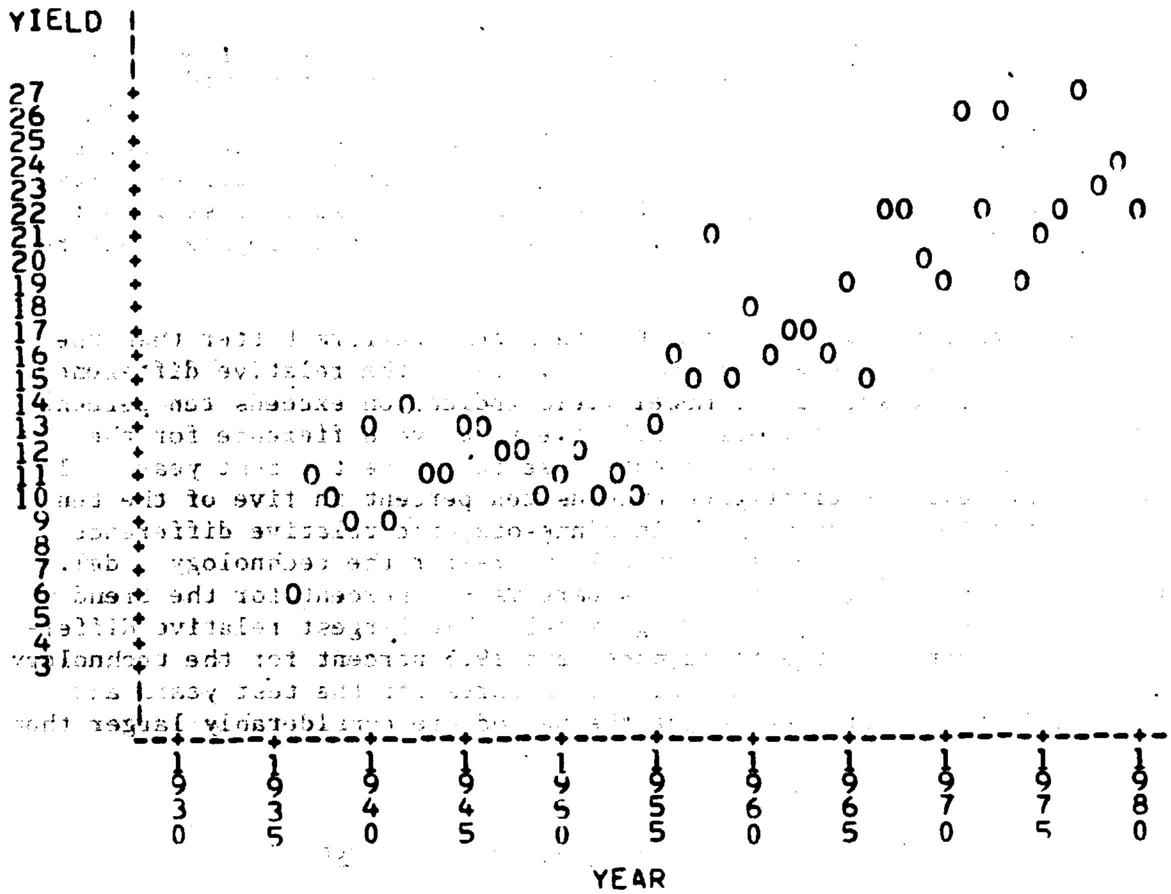


Figure 2. USDA reported all spring wheat yields for Minnesota 1936-1980 (quintals/hectare)



Original Data and Bootstrap Methods

Table 1 shows the indicators of yield reliability using the data and models provided by Feyerherm and follows his methods for bootstrap testing. His yield data are for all wheat, which includes some winter wheat, and there are some minor errors in the data used in the technology models (Kestle and Sebaugh, 1981).

Feyerherm used data from 1955 to 1969 to estimate the trend breakpoint for the technology model and then used the same breakpoint for the trend model. A separate decision was made each test year, for each model, as to the inclusion of TREND2 in the model. Also, Feyerherm assumed that estimates could not be made in the current year for rust loss, nitrogen applications, fallowed area, and varietal improvements. For his bootstrap tests, he assumed rust loss to be zero in the current year and used the values for the technological factors from the previous year.

As can be seen from Table 1, the North Dakota models perform better than the Minnesota models. For example, the absolute value of the relative difference ($|rd|$) for the North Dakota trend model yield indication exceeds ten percent in only three of the ten test years, while the relative difference for the Minnesota trend model exceeds ten percent in seven of the ten test years. In North Dakota, the relative difference exceeds ten percent in five of the ten test years for the technology model. In Minnesota, the relative difference exceeds ten percent in seven of the ten test years for the technology model. In North Dakota, the relative root mean square is 9.1 percent for the trend model and 11.6 percent for the technology model. The largest relative differences are -17.8 percent for the trend model and 19.3 percent for the technology model. In Minnesota, the relative root mean squares for the test years and the largest relative differences during the period are considerably larger than those found for North Dakota.

Corrected Data and Current Technology Values

The errors in the rust loss and the technology variables were corrected and the yields were converted to all spring wheat. Also, the current year's rust loss and technology values were used, including interpolated AVDYA values during the seventies. This was done because it was assumed that values for rust loss and the technology factors could be estimated in the current year, e.g., through the use of the June enumerative and objective yield surveys. No changes were made in the method of estimating the break point in trend or of determining the inclusion of the TREND2 term. An Appendix shows the corrected data values.

Using data from 1955 through 1979, the following models result:

Trend Models

North Dakota:

$$E(STYLD\_H) = -1.10 + 0.82\ TREND1 + 0.69\ AVE\_WX,$$

$$(R^2 = 0.82,\ s = 1.55).$$

Table 1. Indicators of Yield Reliability for the Feyerherm Spring Wheat '81 Models Using the Original Data and Bootstrap Methods

Indicator of Yield Reliability (Unit)*	North Dakota Trend	North Dakota Tech.	Minnesota Trend	Minnesota Tech.
Bias = B(Q/H)	-0.28	0.93	0.37	-0.01
Relative Bias = RB (%)	-1.5	5.2	1.6	0.0
Mean Square Error = MSE $(Q/H)^2$	2.59	4.26	16.09	12.78
Root Mean Square Error = RMSE (Q/H)	1.61	2.06	4.01	3.57
Relative Root Mean Square Error = RRMSE (%)	9.1	11.6	17.6	15.7
Variance = Var $(Q/H)^2$	2.52	3.40	15.96	12.73
Standard Deviation = SD (Q/H)	1.59	1.84	3.99	3.57
Relative Standard Deviation = RSD (%)	9.1	9.9	17.3	15.7
Percent of Years $\|rd\| > 10\%$ (%)	30.	50.	70.	70.
rd of Largest $\|rd\|$ (%)	-17.8	19.3	-27.9	-26.9
rd of Next Largest $\|rd\|$ (%)	-12.1	15.3	22.1	-20.6
rd of Smallest $\|rd\|$ (%)	3.4	2.0	-4.8	4.1
Percent of years direction of change from the previous year in the predicted yields agrees with the observed yields (%)	67.	67.	22.	56.
Percent of years direction of change from the average of the previous three years in the predicted yields agrees with the observed yields (%)	100.	86.	14.	43.
Pearson correlation coefficient between observed and predicted yields	0.73	0.64	0.02	0.44

*See Appendix - Statistical Formulas.

Minnesota:

$$E(STYLD\_H) = 2.79 + 0.40\ TREND1 + 0.39\ TREND2 + 0.61\ AVE\_WX,$$

$$(R^2 = 0.74,\ s = 2.09),$$

Technology Models

North Dakota:

$$E(ASTYLD\_H) = -3.91 + 0.60\ TREND1 - 0.20\ TREND2 + 0.72\ AVE\_WX,$$

$$(R^2 = 0.81,\ s = 1.60),$$

Minnesota:

$$E(ASTYLD\_H) = -1.98 + 0.31\ TREND1 - 0.36\ TREND2 + 0.65\ AVE\_WX,$$

$$(R^2 = 0.74,\ s = 2.08).$$

The values of R^2 and s, the sample standard error of regression, given along with the technology models were calculated using STYLD_H = ASTYLD_H+TECH-EE_HLØSS for each of the twenty-five years in the model development base period and computing residuals from the observed values of STYLD_H. It can be seen that over the model development base period there is little difference in the results obtained within each state depending on the type of model. However, the results in North Dakota are somewhat better than those obtained in Minnesota for both the trend and technology models.

The TREND2 variable in the North Dakota trend model is not statistically significant. The TREND2 variable in the technology model for both states has a negative coefficient. Since the trend terms in the technology models are said to represent unidentified technology, the implication of the negative coefficients is that there has been a negative impact on yields since 1963 in North Dakota and 1968 in Minnesota due to unidentified technology. There is no readily apparent explanation in defense of this finding.

Commonality analysis has been used as an aide in studying the relative influences of several independent variables in a regression equation (Pedhazur, 1982). The total variance of the dependent variable explained by the regression equation is partitioned into contributions which are unique to individual independent variables and those attributable to combinations of independent variables. The unique contribution of an independent variable is defined as the increase in explained variability when the independent variable is added as the last variable in the equation. Commonalities result from correlations between independent variables.

Table 2 shows the results of a commonality analysis performed on the trend models given above. As previously noted, in Minnesota, 74 percent of the total variation in yields from 1955 to 1979 could be explained by the trend model which included two trend terms and the average weather index. Sixty percent of the variability is explained by fitting the trend terms alone and 16 percent of the

Table 2. Commonality Analysis of the Feyerherm Spring Wheat '81 Trend Models Using Corrected Data

Source of variation	Percent of variance in STYLD_H explained by each type of variable	
	Trend(1)	Weather(2)
North Dakota		
Unique to 1, Trend	37	
Unique to 2, Weather		37
Common to 1 and 2	8	8
Total	45	45
Minnesota		
Unique to 1, Trend	58	
Unique to 2, Weather		14
Common to 1 and 2	2	2
Total	60	16

Table 3. Commonality Analysis of the Feyerherm Spring Wheat '81 Technology Models Using Corrected Data and Current Technology

Source of Variation	Percent of variance in STYLD_H Explained by Each Type of Variable		
	Rust Loss and Technology(1)	Trend(2)	Weather(3)
North Dakota			
Unique to 1, rust loss and technology	-1		
Unique to 2, trend		14	
Unique to 3, weather			38
Common to 1 and 2	23	23	
Common to 1 and 3	-5		-5
Common to 2 and 3		-4	-4
Common to 1, 2, and 3	16	16	16
Total	33	49	45
Minnesota			
Unique to 1, rust loss and technology	0		
Unique to 2, trend		10	
Unique to 3, weather			16
Common to 1 and 3	48	48	
Common to 1 and 3	-2		-2
Common to 2 and 3		0	0
Common to 1, 2, and 3	2	2	2
Total	48	60	16

variability is explained by fitting AVE_WX alone. The unique contribution of the weather term is then 74 percent minus 60 percent or 14 percent. The unique contribution of the trend terms is 74 percent minus 16 percent or 58 percent. The percent of variability common to both trend and weather is then calculated as 60 percent plus 16 percent minus 74 percent or 2 percent.

In North Dakota, 82 percent of the total variation in STYLD_H from 1955 to 1979 is explained by the trend model. Of that, 37 percent is a unique contribution of TREND1 and 37 percent is a unique contribution of AVE_WX. There is a small contribution of 8 percent from the commonality between TREND1 and AVE_WX.

The unique contribution of the average weather index is smaller in Minnesota than in North Dakota. Also, the trend model in Minnesota does not provide as good a fit to the observed data (s=2.09 as compared to s=1.55 in North Dakota). The indication of smaller relative importance attributable to the average weather index may be evidence that the poorer performance of the Minnesota model is related to the weather index.

Table 3 shows the results of a commonality analysis performed on the technology models given above. The small negative percent estimates can be regarded as estimates of very small or zero percents. In both states, the unique contribution of the rust loss and technology variables appears to be zero. Most of the variance in STYLD_H explained by these variables is shared in common with the trend variables. As was the case with the trend models, the proportion of variance explained by the weather variable is much less in Minnesota than in North Dakota, and the Minnesota model does not provide as good a fit to the observed data (s=2.08 as compared to s=1.60 in North Dakota).

Whereas the previous analysis was based on the models fit over the entire time period, 1955-1979, Table 4 shows the indicators of yield reliability which result from bootstrap testing over the test years 1970 to 1979. The changes from Table 1 are negligible for the trend models, as only a few yield figures were changed to reflect the definition of yield as all spring wheat (both durum and other spring wheat) rather than all wheat, which includes some winter wheat. The use of the current year's rust loss and technology values produced minor changes in the results for the technology models. The changes were not always improvements, as might have been expected.

Respecification of Trend

As was pointed out in the previous subsection, the negative signs on the TREND2 terms in the technology models cannot be justified by known developments in technology. Since Feyerherm determined the trend breakpoint for both the trend and technology models by what was optimal for the technology models, there may also be a problem with the definition of the trend variables in the trend models. Therefore, an analysis of the specification of the trend terms will be conducted in this subsection.

This analysis will differ from Feyerherm's in several ways. One difference is that a separate analysis will be conducted for each type of model, trend and technology, and the breakpoint will not necessarily be the same for both models in the same state. Secondly, all of the data from 1955 to 1979 will be considered

Table 4. Indicators of Yield Reliability for the Feyerherm Spring Wheat '81 Models Using Corrected Data and Current Technology

Indicator of Yield Reliability (Unit)*	North Dakota Trend	North Dakota Tech.	Minnesota Trend	Minnesota Tech.
Bias = B (Q/H)	-0.26	1.08	0.47	0.87
Relative Bias = RB (%)	-1.5	6.1	2.1	3.8
Mean Square Error = MSE $(Q/H)^2$	2.58	4.33	16.28	13.79
Root Mean Square Error = RMSE (Q/H)	1.61	2.08	4.03	3.71
Relative Root Mean Square Error = RRMSE (%)	9.1	11.7	17.7	16.3
Variance = Var $(Q/H)^2$	2.51	3.17	16.06	13.03
Standard Deviation = SD (Q/H)	1.58	1.78	4.01	3.61
Relative Standard Deviation = RSD (%)	9.1	9.5	17.2	15.3
Percent of Years $\|rd\| > 10\%$ (%)	30.	40.	70.	90.
rd of Largest $\|rd\|$ (%)	-17.8	21.1	-27.9	-26.3
rd of Next Largest $\|rd\|$ (%)	-12.1	19.8	21.5	22.1
rd of Smallest $\|rd\|$ (%)	3.4	3.1	-4.3	-5.6
Percent of years direction of change from the previous year in the predicted yields agrees with the observed yields (%)	67.	67.	22.	44.
Percent of years direction of change from the average of the previous three years in the predicted yields agrees with the observed yields (%)	100.	100.	14.	43.
Pearson correlation coefficient between observed and predicted yields	0.73	0.66	0.03	0.39

* See Appendix - Statistical Formulas.

in the analysis. Feyerherm excluded 1970 to 1979 so that the bootstrap test year results would be entirely independent of the trend specification. Of course, that independence is desirable, but not at the expense of degrading the residuals from trend to be modeled by weather. Using the data from 1970-1979 to specify trend means that the bootstrap test results are somewhat dependent on the trend specification. However, this modification should favor a more complete evaluation of the performance of the weather component of the model. Since the greatest year-to-year changes in yield are usually due to weather, our emphasis is on developing the best possible set of residuals from trend and ascertaining how well the model can explain that variability.

The trend models are analyzed first. Three methods of specifying trend are considered. The first method simply considers a single linear trend term over the entire time period, 1955 to 1979. The second method, similar to Feyerherm's for the technology model, considers two piecewise continuous linear trend terms. The first portion covers the time period from 1955 to a breakpoint and the second portion covers the time period from the breakpoint to 1979. However, a model is eliminated from further consideration if the TREND2 coefficient is negative. The third method considers a single linear trend term from 1955 to a breakpoint with no further increment from the breakpoint to 1979. All possible breakpoints from 1960 to 1975 are considered for the last two methods.

Forty-one models were fit with AVE_WX and the trend terms just described. The residuals after fitting AVE_WX alone ($Y-\hat{Y}$) are shown in Figure 3. From the North Dakota figure, it appears that yields increased in the fifties and early sixties but have since become level. Indeed, the models with the smallest mean square errors are ones with a single linear trend from 1955 to 1963, 1964, 1965, 1966, or 1967. The CEAS trend and monthly weather data spring wheat model for the state of North Dakota (LeDuc, 1981) obtained similar results with a single linear trend over 1955 to 1966. The Minnesota yields have continued to increase for a longer period. The smallest mean square errors were obtained from models with a single linear trend from 1955 to 1973, 1974, 1975 or 1979. The CEAS spring wheat model for the state of Minnesota has a single linear trend from 1955 through 1978.

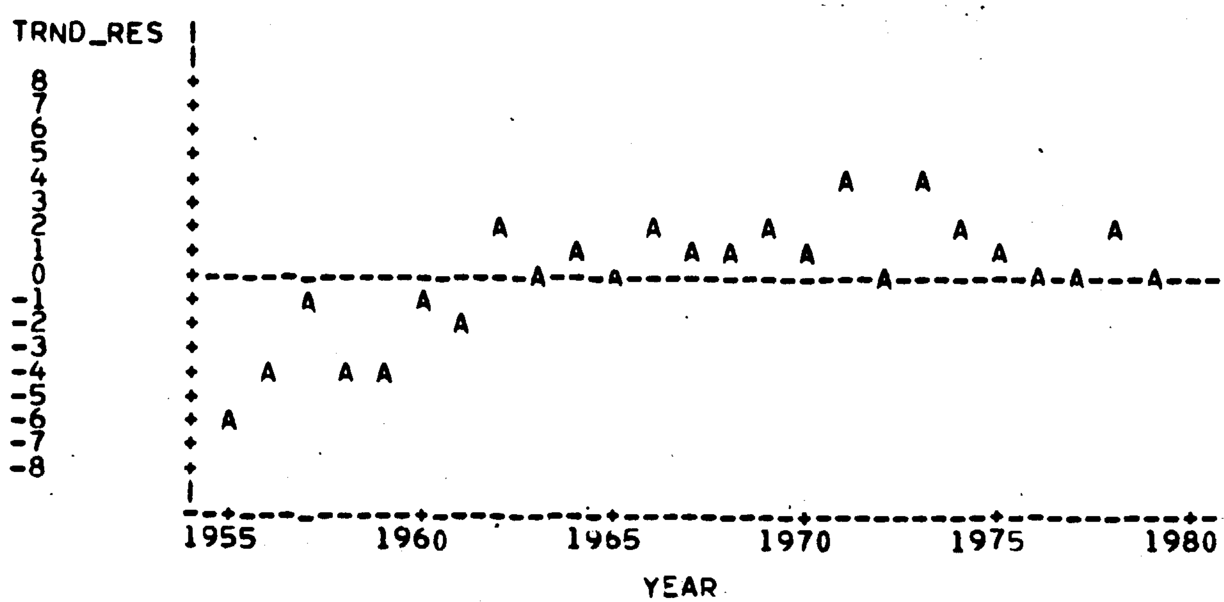
Figure 4 shows the technology model residuals ($Y-\hat{Y}$) which result from predicting the adjusted state yields knowing the value of the weather index. One can see a pattern in both states of negative residuals predominantly occurring in the late fifties and early sixties and again in the middle to late seventies with positive residuals in the middle years. No wonder Feyerherm's TREND2 term occurred with a negative coefficient in the technology models.

This pattern of residuals could result from the influence of some factor on yields other than one already in the model. In other words, the question arises as to whether there might be some factor or factors other than weather, rust loss, or the technology functions of applied nitrogen, fallowing and varietal improvements which could be incorporated in the models and improve yield prediction.

Bond and Umberger's (1979) study of factors affecting wheat yields during the 1949 to 1976 time period mentions two other factors which could be considered. One is an economic factor, U. S. Government farm programs, and the other is a technological factor, use of herbicides.

Figure 3. Feyerherm spring wheat '81 trend model residuals after fitting weather index

A. North Dakota



B. Minnesota

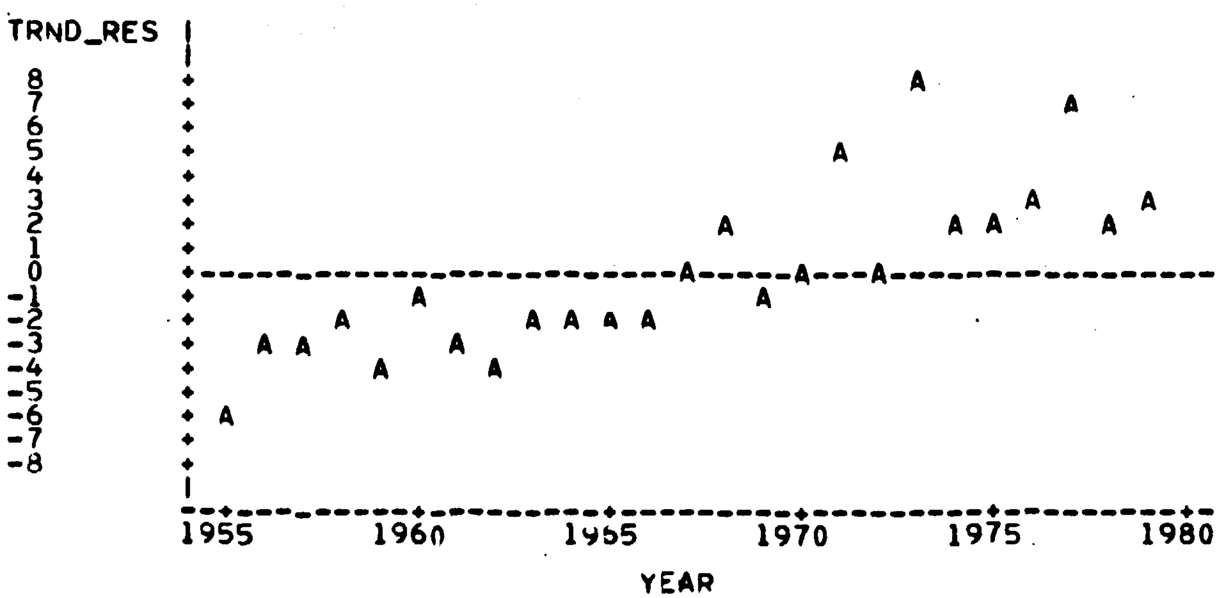
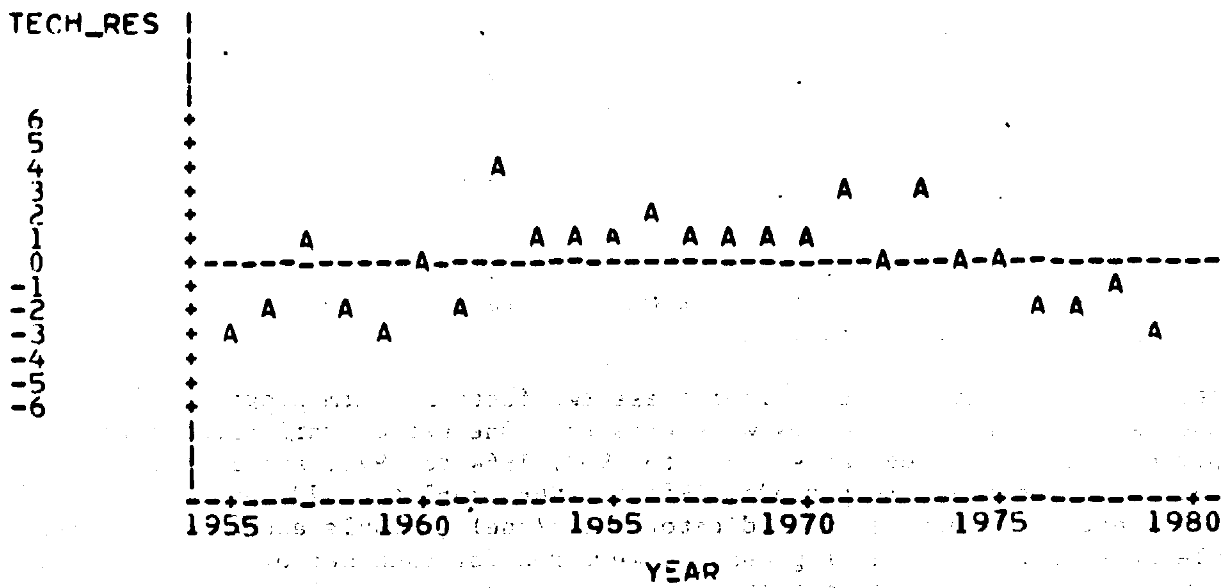


Figure 4. Feyerherm spring wheat '81 technology model residuals after fitting weather index

A. North Dakota



B. Minnesota

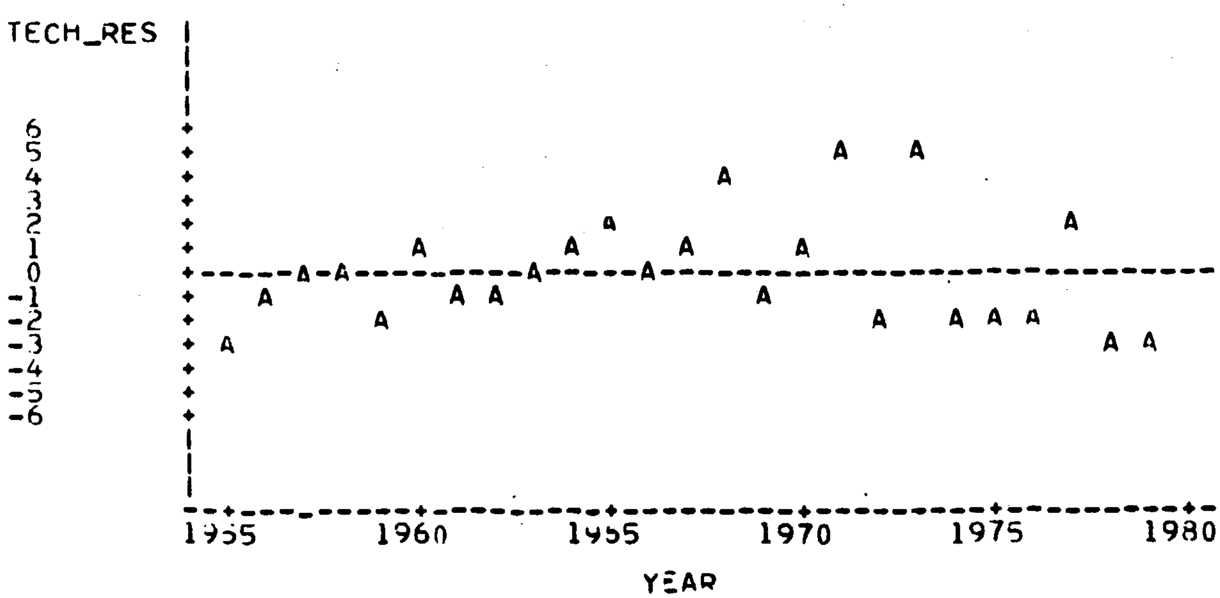


Figure 5 shows area (in hectares) planted to both durum and other spring wheat. In North Dakota, there was a sharp drop in planted area in the early fifties. In the mid to late sixties, the planted area began a sporadic increase which continued until the mid seventies, at which time it became somewhat level. Planted area is not published prior to 1955 in Minnesota. The data for 1956 through 1980 show the same pattern of increase and leveling off as was seen in North Dakota. The changes in planted area correspond to various government diversion programs which have been in effect. Some of these programs would be expected to have a greater impact on soil productivity than others. However, one would certainly expect some decline in average yielding ability due to lower average soil productivity in the early to late seventies. As Bond and Umberger (1979) comment, "...as wheat acreage increases, soils of lower productivity are brought into production."

Herbicide use, in particular 2,4-D, increased rapidly during the fifties and early sixties. Since then, most of the wheat acreages in need of broadleaf weed control have received treatment.

Considering the impact on yields from these two factors, farm programs and herbicide use, several trend variables were created. One set of variables broke the time period into the three parts, 1955 to 1963, 1964 to 1973, and 1974 to 1979. The other set used the time periods, 1955 to 1966, 1967 to 1973, and 1974 to 1979. For each time period, an indicator (zero/one) variable and a linear trend variable were created. Then regressions were run for each set of variables using AVE_WX with (1) each of the indicator and linear trend variables alone, (2) all possible combinations of variables from two different time periods, and (3) all possible combinations of variables from three different time periods.

There was little difference in the results for the two sets of variables (1963 or 1966 as the first breakpoint). Slightly lower mean square errors were found in both states for a model which had a linear trend variable for the 1955 to 1966 time period (positive coefficient) and an indicator variable for the 1974 to 1979 time period (negative coefficient). The linear trend variable may be reflecting the benefit of herbicide use and the indicator variable could be reflecting a reduction in average soil productivity associated with increased acreage.

These results also helped in deciding which breakpoints to use in the trend models. For North Dakota, a single linear trend was used from 1955 to 1966. In Minnesota, a single linear trend was used from 1955 to 1973.

Using data from 1955 through 1979, the following models result:

Trend Models

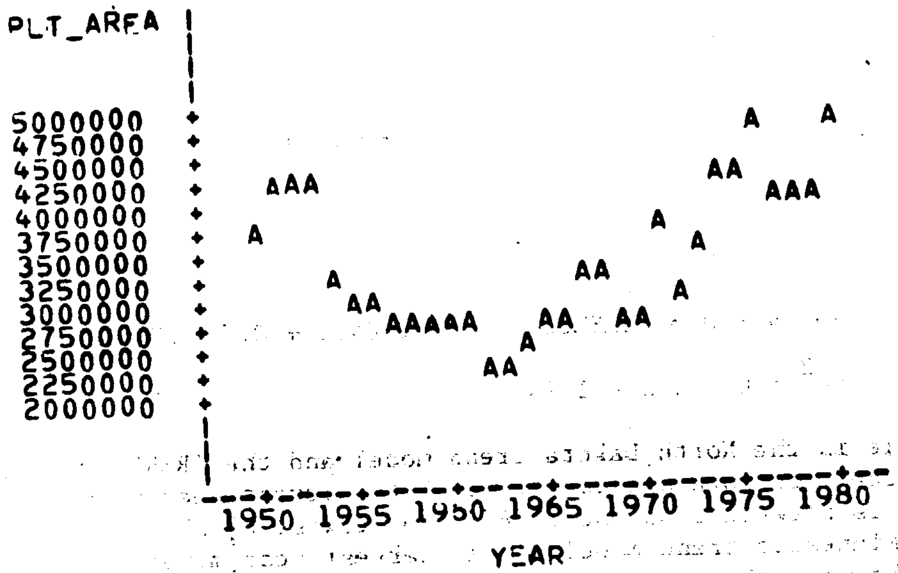
North Dakota:

$$E(STYLD\_H) = 0.36 + 0.56\ TREND + 0.64\ AVE\_WX,$$

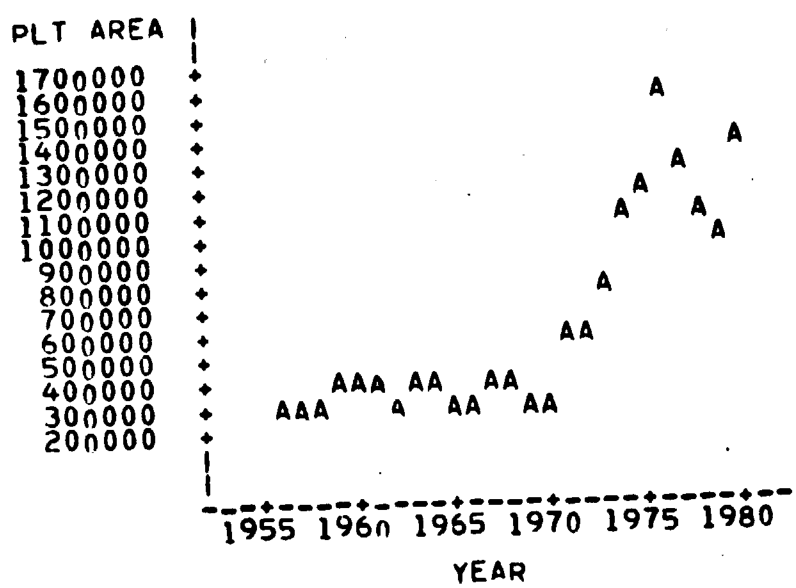
$$(R^2 = 0.82,\ s = 1.51).$$

Figure 5. Planted area (hectares) for all spring wheat

A. North Dakota



B. Minnesota



Minnesota:

$$E(STYLD\_H) = 1.89 + 0.47\ TREND + 0.63\ AVE\_WX,$$

$$(R^2 = 0.75,\ s = 1.99),$$

Technology Models

North Dakota:

$$E(ASTYLD\_H) = -1.95 + 0.35\ TREND1 - 2.95\ TREND2 + 0.64\ AVE\_WX,$$

$$(R^2 = 0.84,\ s = 1.45),$$

Minnesota:

$$E(ASTYLD\_H) = -0.74 + 0.33\ TREND1 - 3.18\ TREND2 + 0.59\ AVE\_WX,$$

$$(R^2 = 0.77,\ s = 1.94).$$

The TREND variable in the North Dakota trend model and the TREND1 variable in the technology model for both states are equal to harvest year minus 1955 if the harvest year is between 1955 and 1966 and otherwise equal to 11. The TREND variable in the Minnesota trend model equals harvest year minus 1955 if the harvest year is between 1955 and 1973 and is otherwise equal to 18. The TREND2 variable in the technology model for both states is equal to zero for 1955 through 1973 and is equal to one for 1974 through 1979.

The improvement in R^2 and s by respecifying trend is not very great. The results for the technology models improved more than for the trend models.

Bootstrap testing of the technology model was complicated by the indicator variable which is zero for 1955-1973 and one for 1974-1979. That variable cannot be used for bootstrap test years 1970-1974. Therefore, bootstrap testing of the technology model was conducted with TREND1 only for test years 1970 through 1974. TREND2 was included for test years 1975 through 1979.

Table 5 gives the indicators of yield reliability from the bootstrap tests. Respecifying trend resulted in a smaller root mean square error for all four models. There are fewer relative differences greater than ten percent and the size of the largest relative difference is decreased in all cases. The improvements were greatest in the Minnesota models (where there was more room for improvement).

Figures 6 and 7 show the USDA reported yield (observed) and predicted yield from the trend model for each bootstrap test year. In North Dakota, there were three years when the relative differences were greater than ten percent. In two of the years, 1971 and 1973, the predictions were too low. In 1976, the prediction was too high. The model, however, did a good job of predicting the low yield in 1974. The predicted yield was too high in both 1972 and 1977. The reported yields dropped from 1971 to 1972, but the predicted yield increased. In Minnesota, there were three test years with relative differences greater

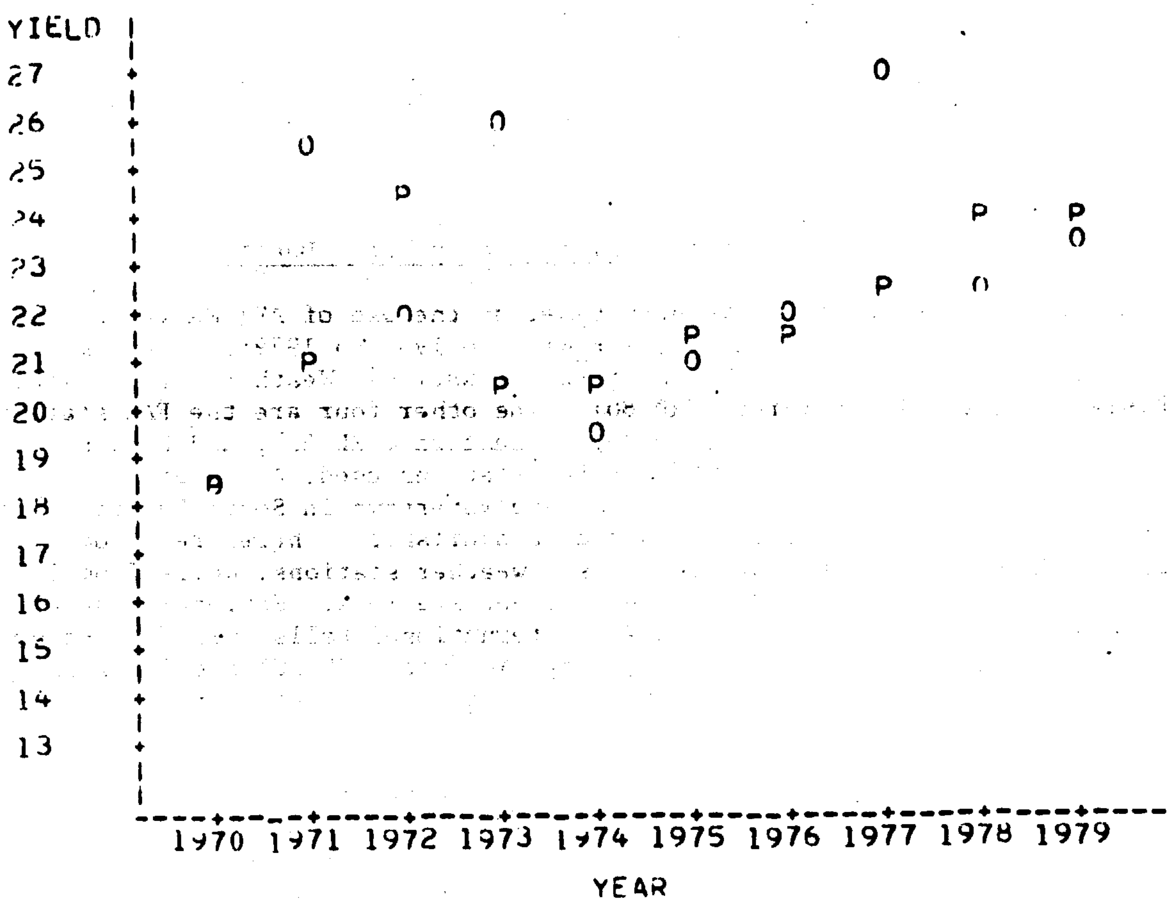
Table 5. Indicators of Yield Reliability for the Feyerherm Spring Wheat '81 Models with Trend Respecified

Indicator of Yield Reliability (Unit)*	North Dakota Trend	North Dakota Tech.	Minnesota Trend	Minnesota Tech.
Bias = B (Q/H)	0.16	0.59	-0.95	-0.09
Relative Bias = RB (%)	0.9	3.3	-4.2	-0.4
Mean Square Error = MSE $(Q/H)^2$	2.28	2.12	8.00	8.88
Root Mean Square Error = RMSE (Q/H)	1.51	1.46	2.83	2.98
Relative Root Mean Square Error = RRMSE (%)	8.5	8.2	12.4	13.1
Variance = Var $(Q/H)^2$	2.26	1.77	7.09	8.87
Standard Deviation = SD (Q/H)	1.50	1.33	2.66	2.98
Relative Standard Deviation = RSD (%)	8.4	7.3	12.2	13.1
Percent of Years $\|rd\|$ > 10% (%)	30.	10.	30.	60.
rd of Largest $\|rd\|$ (%)	-14.6	13.3	-22.1	20.0
rd of Next Largest $\|rd\|$	12.0	9.0	-17.2	18.5
rd of Smallest $\|rd\|$ (%)	0.6	-2.5	-1.6	-1.0
Percent of years direction of change from the previous year in the predicted yields agrees with the observed yields (%)	67.	67.	33.	33.
Percent of years direction of change from the average of the previous three years in the predicted yields agrees with the observed yields (%)	100.	86.	43.	71.
Pearson correlation coefficient between observed and predicted yields	0.73	0.78	0.33	0.23

*See Appendix - Statistical Formulas.

Figure 6. USDA North Dakota reported yields (O) and trend model predicted yields (P) for the bootstrap test years (quintals/hectare) with the trend terms respecified

Figure 7. USDA Minnesota reported yields (O) and trend model predicted yields (P) for the bootstrap test years (quintals/hectare) with the trend terms respecified



than ten percent, all occurring because the prediction was too low, 1971, 1973, and 1977. In 1972 and 1978 the predictions were too high. The 1971 to 1973 pattern in reported yields is down in 1972 and up in 1973. However, the pattern of predicted yields is just backwards, up in 1972 and down in 1973.

In summary, even though trend respecification improved the performance of all models, there are still serious limitations in the ability to accurately predict yields, particularly in Minnesota. The problem would appear to be with the weather index value since it has the greatest potential for year-to-year fluctuation.

Since the performance of all the models did improve with the trend respecified, the definitions of the trend terms developed in this subsection will be used in the analyses performed in following subsections as well.

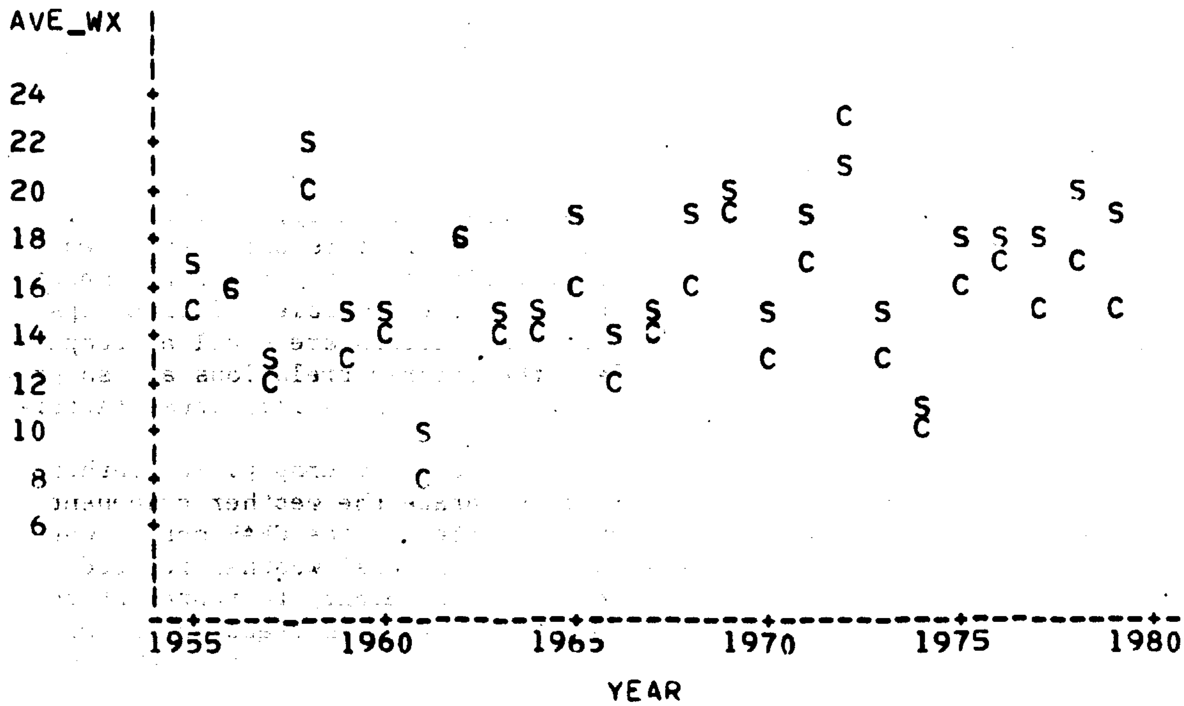
Use of Denser Weather Station Data in North Dakota

The results obtained so far have been based on the use of AVE_WX values supplied by Dr. Feyerherm. In North Dakota, AVE_WX from 1955 to 1979 is the simple average of six weather stations. Two of them are National Weather Service stations at Bismarck (CRD 60) and Fargo (CRD 80). The other four are the FAA stations at Minot (CRD 10), Grand Forks (CRD 30), Jamestown (CRD 50), and Dickinson (CRD 70). For Minnesota, three of the FAA stations used, Alexandria (CRD 40) and Redwood Falls (CRD 70) in Minnesota, and Watertown in South Dakota (near CRD 40), did not have complete weather data available. Therefore, from 1955 to 1964, AVE_WX is a simple average of six weather stations, while from 1965 to 1979 it is a simple average of nine weather stations. National Weather Service Stations used for Minnesota are International Falls (CRD 20), Rochester (CRD 90), and St. Cloud (CRD 50), MN, Fargo ND (near CRD 10) and Sioux Falls, SD (near CRD 70). The sixth complete station is the FAA station at Grand Forks, ND (near CRD 10).

The Atmospheric Science Department at the University of Missouri-Columbia, under an agreement with NOAA, has prepared county level daily weather values from 1948 to 1980 for North Dakota. About a hundred stations over the state were used, there being more complete data in recent years. These are the same stations used to compute the monthly climatic division weather values published by the National Climatic Center. In a manner similar to that used to compute the monthly values, daily climatic division values were formed by taking a simple average of the county values within each climatic division in North Dakota.

Climatic divisions and crop reporting districts (CRDs) are the same in North Dakota, i.e., they follow the same county boundaries. The daily weather values were processed through Feyerherm's WRVPGM'80 to calculate WX values for each CRD. Then, AVE_WX for each year from 1955 to 1979 was calculated as the weighted average of the WX values using the harvested all spring wheat area of each CRD as the weight. Figure 8 is a plot of the two sets of AVE_WX values over the 1955-1979 time period. In 23 of the 25 years the value computed as the simple average of station data (S) is higher than the value computed as the weighted average of CRD values (C). In fact, a paired sample t-test rejects the hypothesis that the difference between the values is zero ($P<0.0001$). The average difference is 1.66 quintals/hectare. Since values for the component parts of WX for all six North Dakota stations were not available, no attempt will be made to explain the difference.

Figure 8. North Dakota AVE_WX values in quintals/hectare, S represents station data and C represents CRD data



The results of the bootstrap test are shown in Table 6. The indicators of yield reliability reveal a somewhat degraded performance for both the trend and the technology models (as compared to Table 5). One might expect the use of AVE_WX values based on a larger, more representative set of weather stations to produce results which are at least as good as those obtained using only six stations. The absence of any improvement in model performance when more representative weather values are used in the WX equation causes doubt to be raised about the adequacy of the WX equation itself.

Technology Models

There are many components of yield which one would like to take into account when developing a crop yield model, e.g., the response of the plant to weather conditions, the effect of so-called episodal events, like hail, pest, or disease damage, the effect of economic factors, such as government programs or the prices of fertilizer or wheat, the effect of changes in farm management techniques or new varieties, and local factors, such as soil types or fertility. However, it is difficult to quantify many of these factors and then, even if one were able to do so, it would be extremely difficult to obtain a complete data set which would allow investigation of all the possible relationships and interactions. The effects of some of these factors are small as compared to the effects of other factors and, also, the inter-correlations are so great that it is difficult to quantify the contribution of some individual factors.

Because of these problems, many researchers who develop crop yield/weather models based on historic data simply try to separate the weather component from all others. For example, the independent variables in the CEAS spring wheat models for North Dakota and Minnesota consist of several weather related variables and a trend variable (a function of the year number) to represent the effect of non-weather factors (LeDuc, 1981). Feyerherm's trend models are similar in concept but have one important difference. The coefficients of the individual weather-related variables are estimated from an independent plot-level data set, whereas the individual coefficients for the CEAS model are estimated using the state level yield/weather data. Feyerherm's use of the independent data set should, theoretically at least, make it easier to separate the effects of weather from the other factors.

Feyerherm's technology models attempt to directly incorporate the factors of rust loss, nitrogen application, varietal improvement, and fallowing. A value for each of these factors is independently derived or estimated each year. This approach seems desirable since one has the feeling of being able to better understand the dynamics of changes in yield level by separating out the various components. When projecting to the following year, one may not feel as confident about projecting the value of a trend term as one would about estimating the values for rust loss or the various technological factors. So even if the performance of the technology models is no better than the performance of the trend models (see Table 5), one may feel more confident in using the technology models.

Table 6. Indicators of Yield Reliability for the Feyerherm Spring Wheat '81 Models Using a Denser Weather Station Network

Indicator of Yield Reliability (Unit)*	North Dakota Trend	Tech.
Bias = B (Q/H)	0.17	0.55
Relative Bias = RB (%)	1.0	3.1
Mean Square Error = MSE $(Q/H)^2$	3.84	3.75
Root Mean Square Error = RMSE (Q/H)	1.96	1.94
Relative Root Mean Square Error = RRMSE (%)	11.0	10.9
Variance = Var $(Q/H)^2$	3.81	3.45
Standard Deviation = SD (Q/H)	1.95	1.86
Relative Standard Deviation = RSD (%)	10.9	10.2
Percent of Years $\|rd\| > 10\%$ (%)	40.	30.
rd of Largest $\|rd\|$ (%)	21.1	22.7
rd of Next Largest $\|rd\|$ (%)	-14.1	14.5
rd of Smallest $\|rd\|$ (%)	1.3	1.7
Percent of years direction of change from the previous year in the predicted yields agrees with the observed yields (%)	67.	67.
Percent of years direction of change from the average of the previous three years in the predicted yields agrees with the observed yields (%)	86.	86.
Pearson correlation coefficient between observed and predicted yields	0.62	0.62

*See Appendix - Statistical Formulas.

However, as mentioned earlier, estimating the contribution to yield by these various non-weather factors is a true challenge. Figure 9 shows the values of Feyerherm's TECH(T) term and its components, NI(N), FALINC(F), and AVDYA(D). Table 7 gives the Pearson correlation coefficients of these variables with yield per harvested area, the various respecified trend terms, and each other.

NI.

As described previously, NI = 0.065 * AVNI where AVNI is the average amount of nitrogen applied (lbs/acre). AVNI is actually the product of two values published at the state level, an estimate of the percentage of acres in the state receiving nitrogen and the estimated average application rate per acre receiving nitrogen. The 0.065 coefficient is an estimate of average yield response to nitrogen application from the plot-level regression analysis.

It is not clear that a coefficient estimated at the plot level can be used with state-level fertilizer data. Bond and Umberger (1979) believe that since the response to fertilizer application varies widely with climate, soils, and cropping practice (continuous/fallow), data by subregions would be much more useful. Unfortunately, the only data known to be available at a sub-state level is fertilizer sales, for all purposes. However, it is possible this information could be used to generate weights for the CRDs. Bond and Umberger (1979) present evidence for North Dakota of different yield levels on fertilized wheat depending on geographic area and cropping practice.

FALINC.

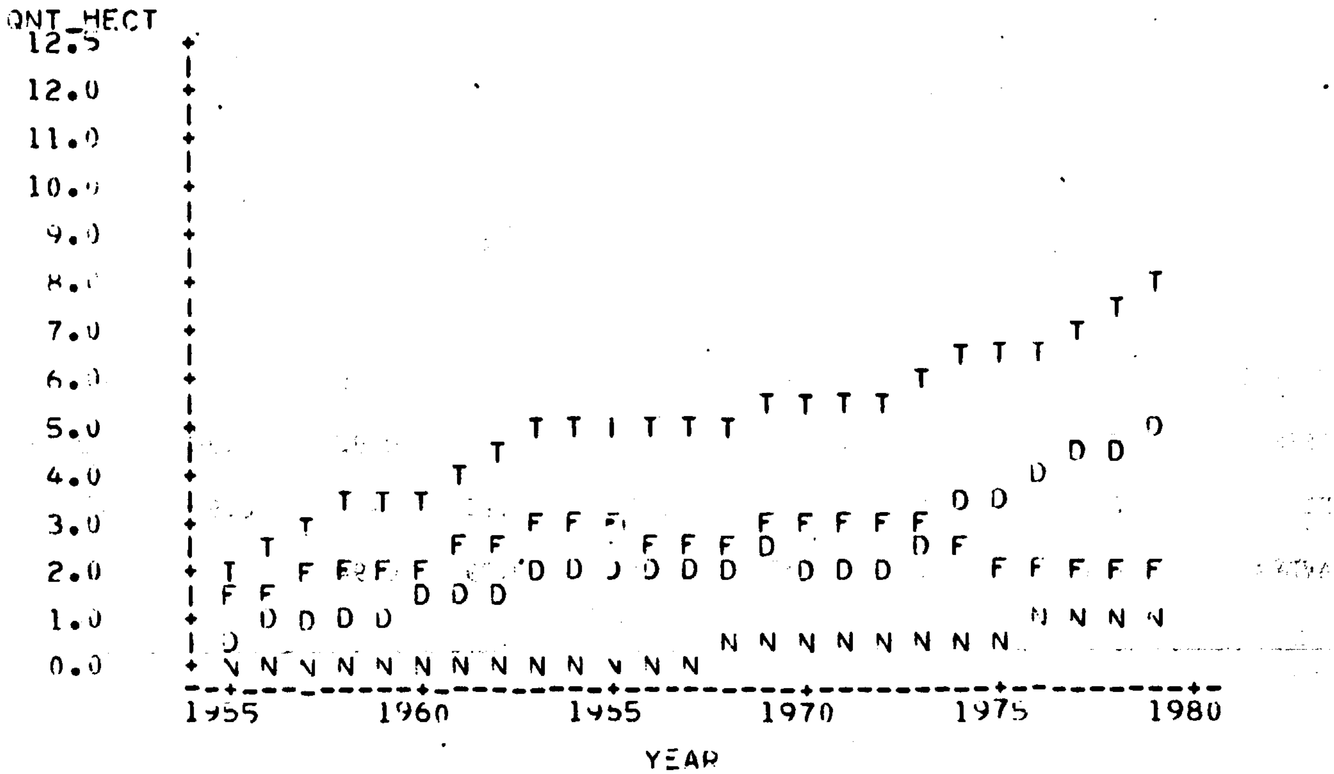
This variable is intended to represent the increment in yield each year due to fallowing. FALINC is computed as the sum over the CRDs of INC_i * FL_i * P_i divided by 10000, i = 1,...,9. The arithmetic mean, minimum, and maximum values of these variables is given for each North Dakota CRD in Table 8. Minnesota does not publish wheat data by cropping practice. The predominant cropping practice is continuous cropping. Therefore, Feyerherm used zero values for FALINC in Minnesota.

INC_i is the difference in reported yields between wheat harvested on land which was not cropped the previous year and wheat harvested on land which was cropped the previous year. Feyerherm uses a long-term average of INC_i for each CRD. P_i is the percent of state-wide harvested area in CRD i. Feyerherm uses the yearly value of P_i, but, as can be seen in Table 8, it has been a nearly stable quantity over time. FL_i is the percent of wheat harvested area in each CRD which was on fallowed ground. Feyerherm uses the yearly value of FL_i which has been quite variable over the 1955 to 1979 time period and is, therefore, primarily responsible for the fluctuation in FALINC values.

Figure 10 shows the spring wheat planted area in North Dakota for all cropping practices and for fallowed land. As was seen before in Figure 4, the total planted area decreased in the early fifties to a fairly stable level through the early sixties, and then began to increase, doubling by 1980. The amount of fallowed land increased some with the initial increase in total planted area in the sixties but leveled off through the seventies. Indeed, Figure 11 shows an increase in the portion of total planted area on fallowed land from around fifty percent in the mid-fifties to around eighty percent in the early seventies.

Figure 9. Values of TECH(T) and its components: NI(N), FALINC(F) and AVDYA(D) - units are quintals/hectare

A. North Dakota



B. Minnesota

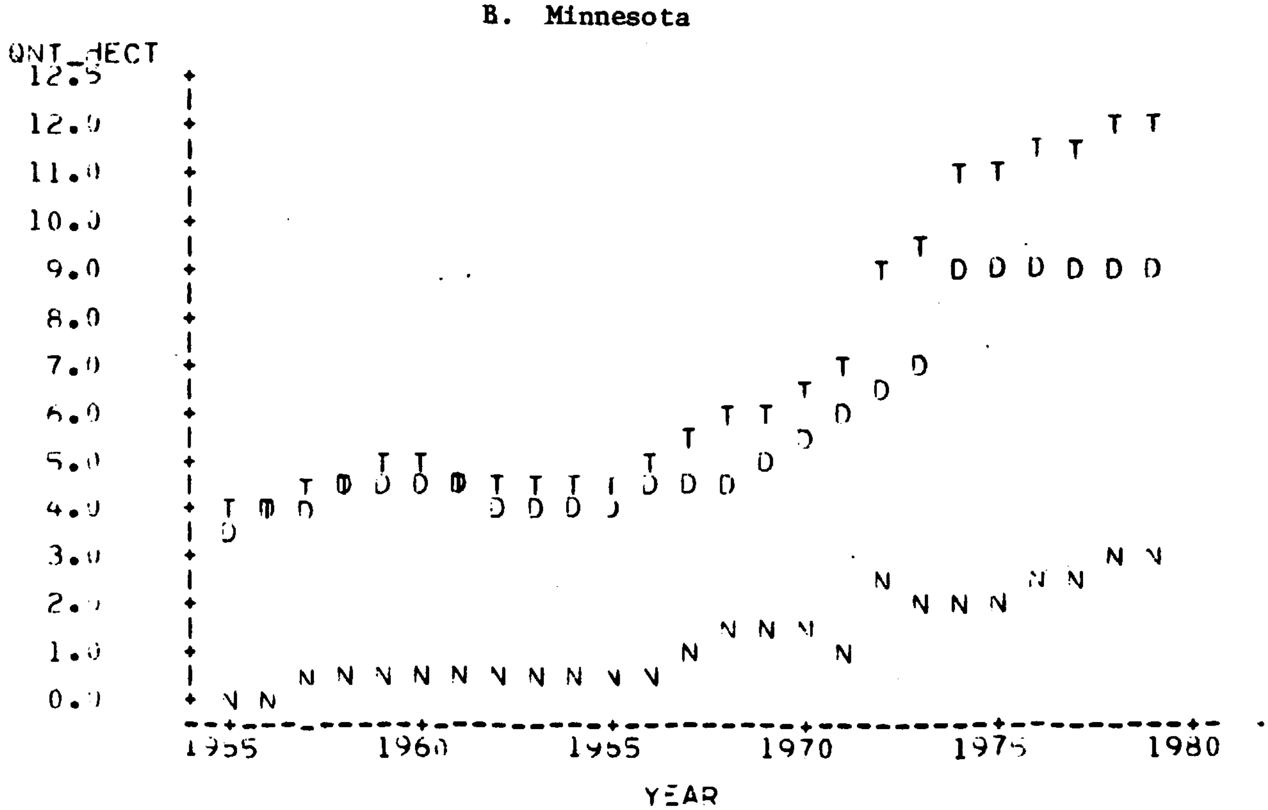


Table 7. Pearson Correlation Coefficients Between Selected Variables in the Feyerherm '81 Spring Wheat Models. Upper Triangle Contains Values for North Dakota and Lower Triangle Contains Values for Minnesota.

MN/ND	STYLD_H	TREND	TREND1	TREND2	TECH	NI	AVDYA	FALINC
STYLD_H	-	0.71	0.71	0.20	0.64	0.53	0.50	0.45
TREND	0.77	-	1.0	0.41	0.86	0.68	0.72	0.55
TREND1	0.65	0.93	-	0.41	0.86	0.68	0.72	0.55
TREND2	0.44	0.63	0.41	-	0.74	0.79	0.89	-0.47
TECH	0.70	0.86	0.62	0.89	-	0.92	0.96	0.17
NI	0.73	0.89	0.69	0.79	0.97	-	0.93	-0.08
AVDYA	0.68	0.82	0.58	0.92	0.99	0.94	-	-0.11

Table 8. Arithmetic Mean (Minimum-Maximum) of the Component Variables and FALINC for Each CRD in North Dakota Over the Period 1955 to 1979 (n=25)

CRD	INC(q/ha)	FL(%)	P(%)	FALINC(q/ha)
10	5.1 (1.3-9.7)	91 (78-97)	16 (15-18)	0.5 (0.1-1.1)
20	6.7 (3.1-10.0)	76 (43-93)	12 (10-13)	0.4 (0.1-0.7)
30	2.9 (-0.3-6.8)	67 (34-90)	19 (17-20)	0.3 (0.0-0.7)
40	5.6 (1.9-9.9)	75 (54-91)	9 (7-10)	0.3 (0.1-0.5)
50	6.5 (2.8-10.5)	63 (34-86)	10 (9-12)	0.3 (0.1-0.5)
60	3.2 (-0.4-6.7)	55 (34-79)	10 (8-12)	0.1 (0.0-0.2)
70	5.9 (1.5-9.2)	80 (57-96)	9 (7-12)	0.3 (0.0-0.5)
80	5.6 (2.2-10.0)	48 (22-77)	7 (5-8)	0.1 (0.0-0.3)
90	4.5 (0.3-7.9)	34 (13-63)	9 (7-11)	0.1 (0.0-0.2)
State		63 (47-86)		2.3 (1.0-4.1)

Figure 10. North Dakota all spring wheat planted area (hectares) for all cropping practices (A) and fallowed land (F)

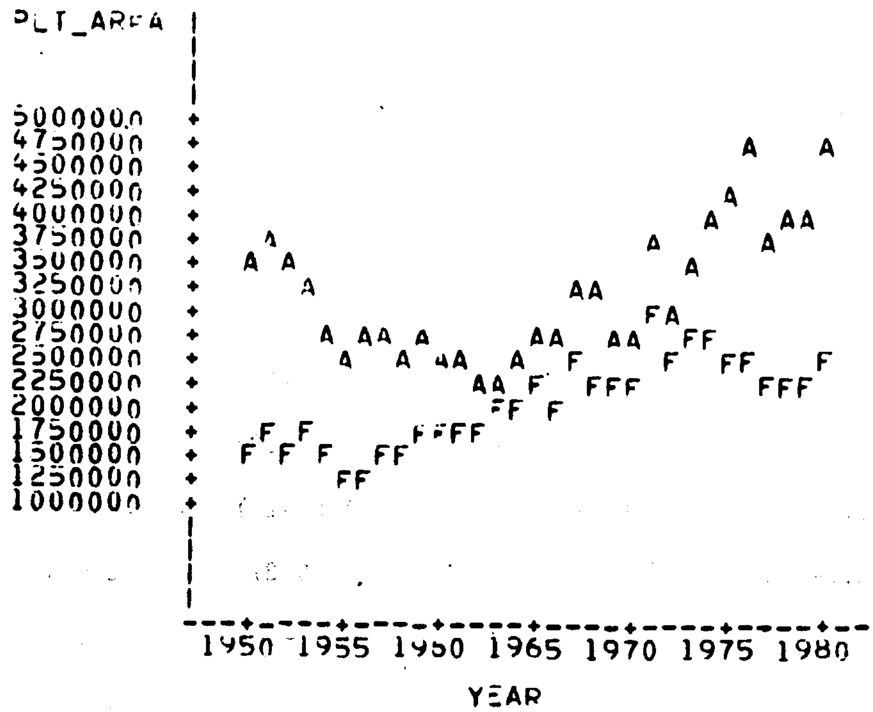
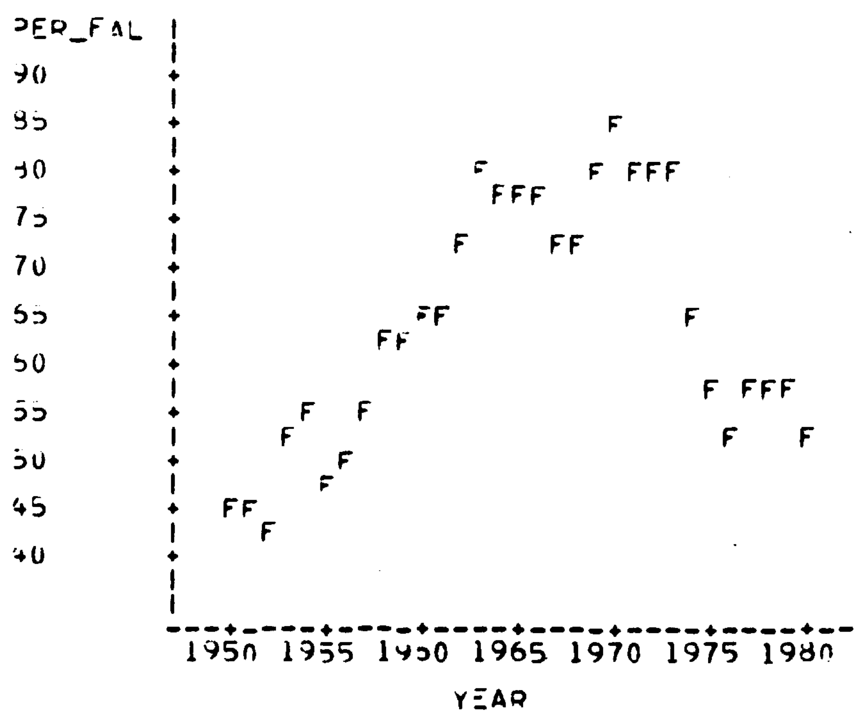


Figure 11. Percent of all spring wheat planted area on fallowed land in North Dakota



However, the percent of fallowing fell to almost fifty percent by 1980 as the amount of total planted area increased but the amount on fallowed land did not. This increase in total planted area can, therefore, be seen to reduce yields both because of lower average soil productivity, as mentioned previously, and because of a reduction in the percent of fallowed land (Bond and Umberger, 1979).

In previous work, Feyerherm ran two soil moisture budgets, one for continuous cropping and one for fallowing. Two values of the weather index were then computed for each location which could be combined using the relative area devoted to each cropping practice. This procedure allowed for some interaction between weather and the contribution to yield due to fallowing. For example, in a year with good rainfall the contents of the simulated soil moisture budget at planting and the simulated evapotranspiration from jointing-to-dough may be quite similar for both budgets. Whereas in a year with poor moisture, use of a fallowed budget would result in a higher contribution to yield due to a greater amount of moisture in the soil moisture budget at planting.

The use of one, continuous cropping budget and long-term average for INC1-INC9 prohibits almost all interaction between weather and the contribution to yield due to fallowing. The only way weather could influence the value of FALINC is through FL1-FL9. For example, if the weather is very poor and land is abandoned to fallowing in the current year, next year's FL values may be higher, resulting in a higher FALINC value.

The use of individual yearly values of INC1-INC9, rather than long term averages, would, theoretically at least, allow for some interaction between weather and contribution to yield due to fallowing. Since yearly INC values are the differences between estimated CRD fallow yields and continuous cropping yields in the same year, differential effects of weather on the yield for each cropping practice should be reflected.

In order to investigate the possible relationship between INC values and weather, the WX values calculated at the CRD level for the study of denser weather data were used. Table 9 shows the correlation coefficients for each CRD between INC and WX in the same year and WX in the previous year, LAG_WX. None of the correlation coefficients are statistically significant at the 0.05 level. It is surprising that in eight of the nine CRDs the correlation coefficient between INC and WX is positive. A positive coefficient indicates a tendency for larger differences between fallowed and continuous cropped yields to occur in years with better weather, i.e., larger values of the weather index.

Figure 12 shows the values of INC plotted over time for the two highest producing CRDs in North Dakota over the past ten years. In CRD 10, the average of INC over 1955-79 is 5.1 quintals/hectare with a range from 1.3 to 9.7. In CRD 30, the average of INC over 1955-79 is 2.9 quintals/hectare with a range from -0.3 to 6.8. The negative value reflects a year in which the average yields from continuous cropped land were reported to be higher than the average yield from fallowed land.

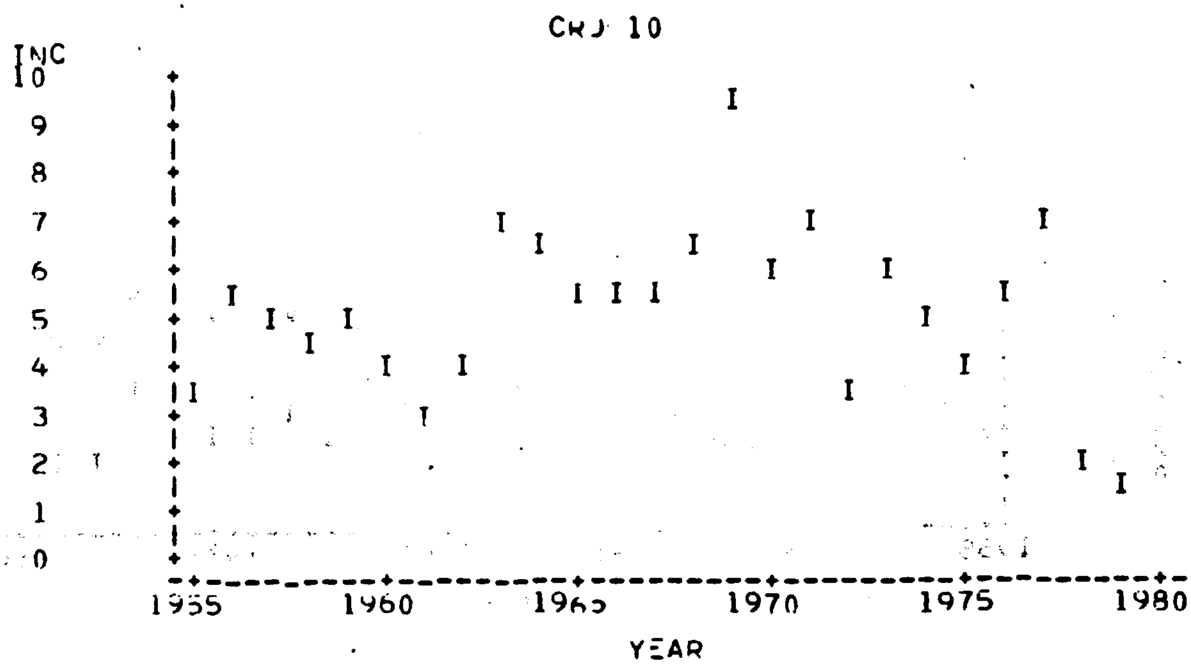
Figure 13 shows the values of both INC and WX plotted over time for CRDs 10 and 30. In CRD 10, there is no overlap between the five years with the lowest WX values (1957, 1961, 1966, 1967, and 1974) and the five years with the highest INC values (1963, 1964, 1969, 1971, and 1977). In CRD 30, 1961 has both the

Table 9. Pearson Correlation Coefficients by CRD Between INC= (Fallow Yield-Continuous Yield) in North Dakota and Feyerherm's Weather Index in the Same Year (WX) and the Previous Year (LAG_WX)

CRD	WX(n=25)	LAG WX(n=24)
10	0.12	0.08
20	0.17	0.32
30	-0.03	-0.25
40	0.39	0.32
50	0.26	0.37
60	0.12	-0.11
70	0.18	-0.14
80	0.24	0.33
90	0.33	0.10

Figure 12. Yearly values of INC = (Fallow Yield minus Continuous cropping yield) in North Dakota - units are quintals/hectare

A. CRD 10 (Northwest)



B. CRD 30 (Northeast)

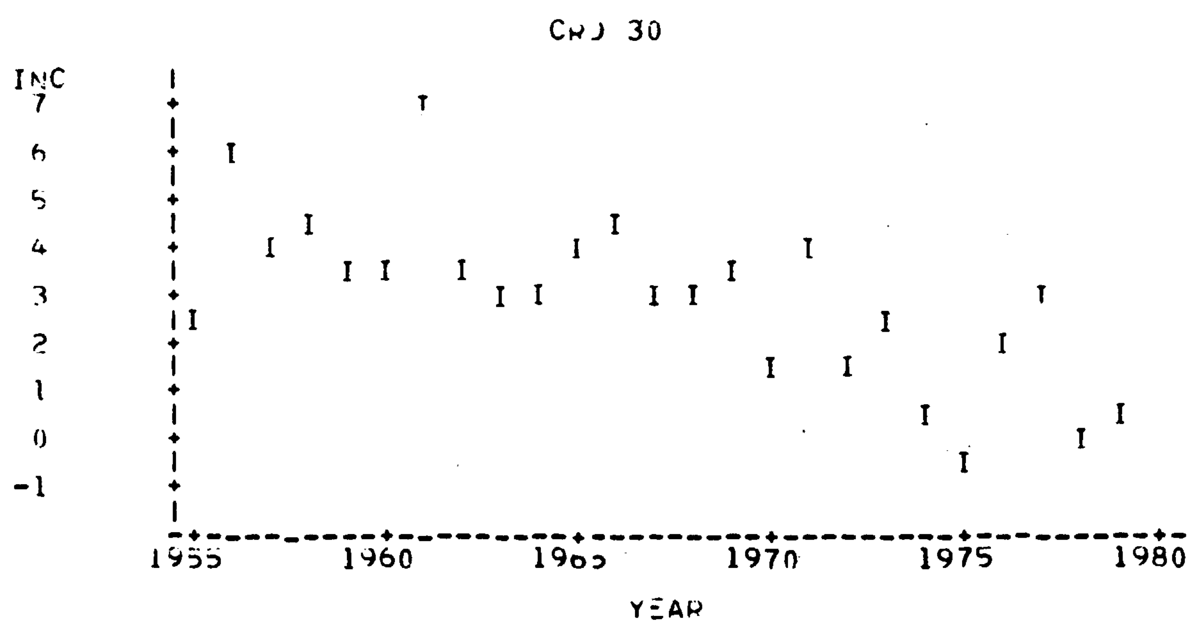
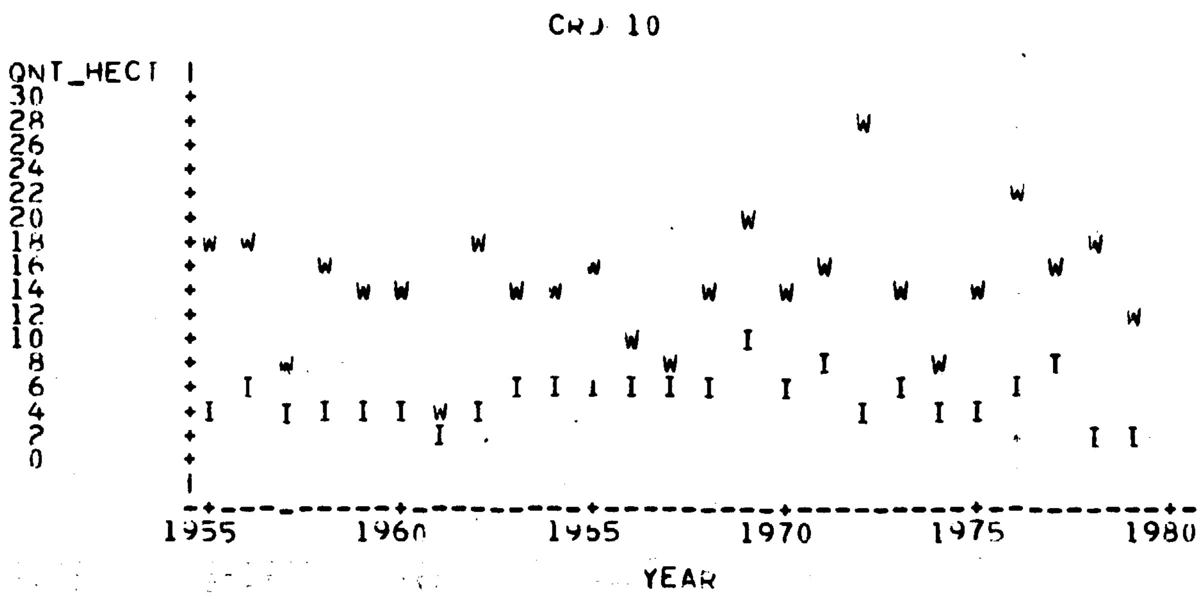
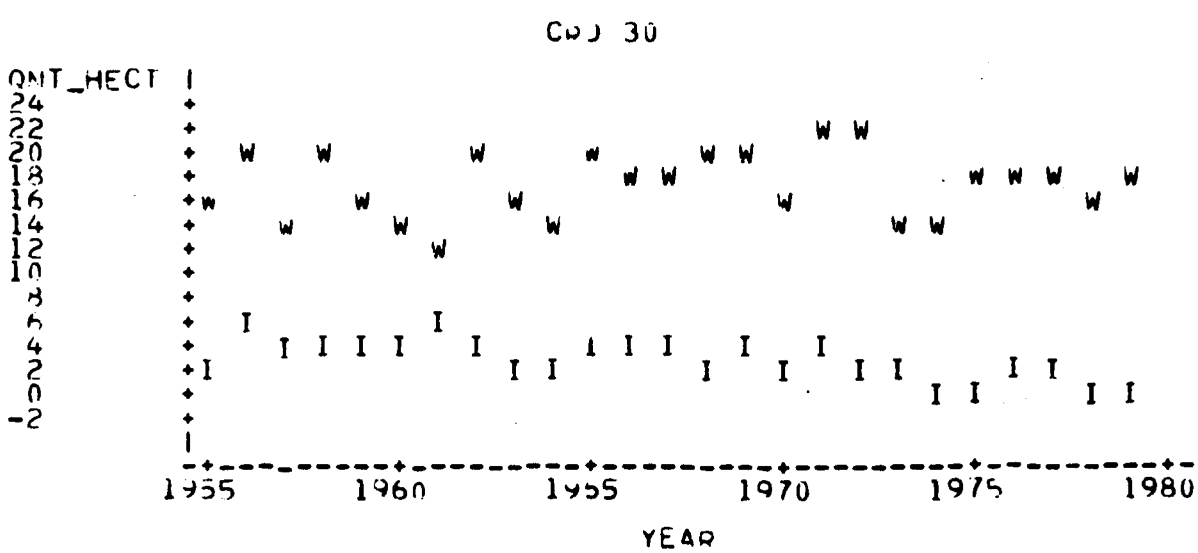


Figure 13. Yearly values of Feyerherm's weather index (W) and INC (I) in North Dakota - units are quintals/hectare

A. CRD 10 (Northwest)



B. CRD 30 (Northeast)



lowest WX value and the highest INC value. However, the remaining four of the five years with the lowest WX values (1957, 1960, 1964, and 1973) do not overlap the remaining four years with the highest INC values (1956, 1958, 1965, and 1966).

The failure here to uncover an explanation for the variability over time of INC values within a CRD could be the result of a number of factors. Either the WX values or the INC values may be inaccurate. The WX values may not be properly reflecting the stress on wheat. The reporting of yields by the two cropping practices, particularly at the CRD level, may not be accurate. INC values are computed as the difference between yields on land which was cropped the previous year and yields on land which was not cropped the previous year. Since these two types of land may not be comparable, INC values include differences in land quality as well as differences in stored soil moisture. Also, there may be some other factors involved which were not considered here. At any rate, the average CRD values of INC which Feyerherm uses seem reasonable in that the three smallest values are for the CRDs adjacent to the Red River Valley which incur the least moisture stress. Average values for INC derived from Bond and Umberger (1979) are 3.5 quintals/hectare for the western CRDs (10, 40, 70), 4.5 quintals per hectare for the central CRDs (20, 50, 80), and 3.2 quintals/hectare for the eastern CRDs (30, 60, 90). These values are lower than Feyerherm's, particularly for the western and central CRDs.

When yearly INC values for each CRD are used in the technology model for North Dakota instead of CRD longterm averages, the performance over the model development base period (1955-79) is degraded somewhat. The R-squared value drops from 0.84 to 0.80 and the standard error of regression increases from 1.45 to 1.61. A bootstrap test was not performed.

AVDYA.

The difference in yield levels over time due to the introduction of new varieties is estimated by AVDYA. For a given year and state, AVDYA is computed as $\Sigma q_k DYA_k / \Sigma q_k$ where the summation in each case is over k for N varieties, q_k is the percent of area in a given state planted to variety k in the specified year, and DYA_k is the differential yielding ability for variety k. In effect, AVDYA is then a weighted average of DYA values with the percentages, or q values, serving as the weights. A variety is included in a specified year if the percentage of durum plus other spring wheat acreage planted to that variety is one percent or more in North Dakota or three percent or more in Minnesota and if sufficient varietal trial data are available. The q values are not available from standard sources for every year between 1955 and 1979, so linear interpolation of AVDYA values is performed between years with known q values. Much more interpolation must be done in Minnesota than in North Dakota.

Differences in yields between new varieties and a "standard" variety (yield of new variety minus yield of standard variety) at the same location in the same year are used to calculate DYA. Feyerherm uses varietal trial data from agricultural experiment stations and cooperating farmers. The data are described in greater detail in the "Users Manual for Differential Yielding Ability Program (DYAPGM'80)." Thatcher is used as the standard variety (DYA= 0.00). Differences with Thatcher are computed directly for new varieties in the fifties and sixties and DYA is calculated as the mean difference. However, Thatcher was dropped from varietal trials in the early seventies, so various "intermediate" varieties are used for some varieties introduced in the sixties and seventies. Differences in yields between these new varieties and an intermediate variety (yield of new variety minus yield of intermediate variety) are calculated for the locations and years the two varieties are both planted and the mean difference is computed. In a similar fashion, the mean difference between the intermediate and Thatcher is derived. The DYA value for the new variety is then the sum of these mean differences, or DYA = mean (yield of new variety minus yield of intermediate) plus mean (yield of intermediate minus yield of Thatcher). Therefore, it can be seen that the intermediate needs to have some common location/years with both the new variety and the standard. In some cases, more than one intermediate is used with an expanded "chain rule."

Since more data are available in North Dakota, an investigation was conducted there on two factors which have an impact on the DYA calculations. One factor is the choice of method to use when estimating mean differences in yields and the other factor is the choice of varieties to use as intermediates. Each of these factors will now be discussed.

Feyerherm estimated the mean differences in yields by the arithmetic average over all location/years for which data are available. There would be no problem with this method if values for a given yield difference were available at all locations for each year having an observation at any location. However, there is quite a bit of imbalance in the North Dakota data. Also, there are statistically significant differences in the yield differences among years and/or locations for many varieties. Therefore, a simple average could be biased, depending on the missing location/year observations.

Therefore, another method of estimating the mean differences was considered. Each mean difference in yields was estimated by the intercept of a linear regression model with the observed yield differences as the dependent variable and indicator variables for location and year main effects. Since the intercept is computed as part of a least squares regression, it is called the least squares mean. For a given variety, years and locations were excluded if only one yield difference were available in that year or location. Estimates were not made for varieties with fewer than five total observations. DYA values based on these least squares mean yield differences were computed using data from 1945 to 1979. The DYA values for the direct comparison to Thatcher as well as for several choices of intermediates are given in Table 10 for the hard red spring wheat varieties and in Table 11 for the durum varieties. The error degrees of freedom are from the least squares regression model which provided the mean difference between the variety and Thatcher, for the direct comparison, or between the variety and the first (or only) intermediate variety indicated.

In Tables 10 and 11 it can be seen that the choice of intermediate or intermediate combination can make as much as a six bushel/acre difference in the DYA values for a variety (see Leeds in Table 11). Table 12 summarizes several pieces of information about each variety which can be useful in determining varieties to use as intermediates. The years between 1955 and 1979 during which the variety was seeded on one percent or more of the total planted area

Table 10. Differential yielding ability values for the hard red spring wheat varieties in North Dakota adjusted for location and year, computed directly and using several intermediate varieties. Units are bushels/acre.

Variety	Direct Thatcher (T)	Intermediates Justin	Chris	Waldron and Justin	Waldron and Chris	Olaf and Chris
Rival	1.63(21)[†]					
Mida	2.08(47)					
Cadet	2.00(14)					
Rescue	-2.02(25)					
Redman	-0.13(6)					
Rushmore	0.25(16)					
Lee	1.03(36)					
Selkirk	1.83(51)					
Conley	-1.65(24)					
Chinook	-1.58(12)					
Pembina	-0.03(18)					
Canthatch	0.91(12)					
Crim	1.83(6)					
Justin(J)	1.04(28)		0.32(30)			
Manitou	3.34(19)	3.86(27)	3.15(28)			
Chris(C)	2.35(20)	3.08(30)				
Fortuna	1.20(8)	1.86(11)	2.76(14)			
Polk	0.23(9)	1.98(15)	1.44(15)			
Waldron(W)	1.66(7)	3.49(15)	4.26(31)			6.34(81)
Bonanza		5.64(3)	3.17(4)			
WS 1809		5.89(3)	2.91(4)			
Bounty 208	6.17(5)	8.87(13)	7.86(21)			
Lark			7.53(3)			
Era		17.02(8)	13.81(24)	11.70(49)	12.47(49)	13.55(46)
Olaf(O)			9.10(16)	6.26(82)	7.04(82)	
Ellar			2.43(13)	1.61(43)	2.39(43)	4.71(46)
Wared			11.72(14)	9.82(76)	10.59(76)	12.30(80)
Prodax			12.86(15)	8.33(63)	9.10(63)	12.30(65)
Kitt			11.92(12)	7.29(45)	8.06(45)	9.22(47)
Butte				7.69(36)	8.46(36)	9.53(38)
Solar				11.82(15)	12.59(15)	13.98(16)

[†]Value in parentheses is the error degrees of freedom from the least squares regression equation used to estimate the mean yield difference with the variety.

Table 11. Differential yielding ability values for the durum varieties in North Dakota adjusted for location and year computed directly with Thatcher and using Mindum and Wells as intermediates.
Units are bushels/acre.

Variety	Direct	Intermediates		
	Thatcher	Mindum	Wells	Wells and Mindum
Mindum (M)	1.21(58)[†]		-2.79(27)	
Stewart	5.36(7)	2.88(7)		
Ramsey	2.00(22)	2.81(22)	0.58(11)	4.58(11)
Langdon	2.75(22)	3.56(22)	1.71(11)	5.70(11)
Lakota	4.63(17)	6.69(17)	3.94(17)	7.94(17)
Wells (We)	4.23(29)	8.23(27)		
Leeds	-0.44(10)	4.79(10)	1.52(20)	5.51(20)
Rolette	2.83(5)	6.19(4)	2.21(44)	6.21(44)
Ward			5.92(36)	9.92(36)
Rugby		8.50(2)	5.77(31)	9.76(31)
Crosby		9.03(2)	4.75(30)	8.75(30)
Cando			6.78(17)	10.78(17)
Botno		6.43(2)	3.29(30)	7.29(30)

[†]Value in parenthesis is the error degrees of freedom from the least squares regression equation used to estimate the mean yield difference with the variety.

Table 12. North Dakota hard red and durum spring wheat varieties planted to 1% or more of the wheat area in one of the years 1955, 1957, 1959, 1964, 1969, 1970-75, 1978-79

Variety	Years		Highest percent planted	Comparisons to Variety and Thatcher		Differential yielding ability (bu/ac)		
	1% or more planted	Data for 2 or more locations		One	One or More	One comparison: Average	One comparison: Least squares means	More comparisons: Least squares means
Hard Red Spring								
Thatcher(T)	55-59	45-73	3			0.00	0.00	0.00
Rival	55-57	45-53	1	T	T	1.76	1.63	1.63
Mida	55-59	45-61	4	T	T	1.27	2.08	2.08
Cadet	55	45-54	2	T	T	1.46	2.00	2.00
Rescue	55-57	46-66	2	T	T	-2.11	-2.02	-2.02
Redman	55	47-51	1	T	T	0.52	-0.13	-0.13
Rushmore	55-59	50-63	12	T	T	0.01	0.25	0.25
Lee	55-64	50-65	56	T	T	0.78	1.03	1.03
Selkirk	55-69	54-73	58	T	T	1.69	1.83	1.83
Conley	57-59	56-63	6	T	T	-1.05	-1.65	-1.65
Chinook	59-64	53-64	1	T	T	-1.49	-1.58	-1.58
Pembina	64	60-67	9	T	T	0.40	-0.03	-0.03
Canthatch	64-69	60-68	2	T	T	0.87	0.91	0.91
Crim	69-70	63-69	2	T	T	1.70	1.83	1.83
Justin(J)	69-75	62-76	29	T	T,C	0.87	1.04	0.67
Manitou	69-75	65-76	17	T	T,J,C	3.03	3.34	3.46
Chris(C)	69-78	65-78	18	T	T,J	2.12	2.35	2.79
Fortuna	69-75	66-76	11	T	T,J,C	0.68	1.20	2.08
Polk	69-75	68-73	3	T	T,J,C	0.49	0.23	1.37
Waldron(W)	69-79	68-79	45	C	T,J,C	3.77	4.26	5.30
Bonanza	71-75	70-74	2	C	J,C	3.22	3.17	4.23
WS 1809	71-75	70-77	8	C	J,C	1.97	2.91	4.19
Bounty 208	72-75	71-76	4	C	T,J,C	5.71	7.86	7.98
Lark	72-75	72-75	6	C	J,C	4.31	7.53	7.53
Era	73-79	70-79	5	C	J,C,W&J,W&C,O&C	12.79	13.81	12.93
Olaf(O)	74-79	73-79	23	C	J,C,W&J,W&C	8.09	9.10	6.87
Ellar	75-79	74-79	5	C	J,C,W&J,W&C,O&C	3.22	2.43	2.90
Wared	78-79	74-79	2	C	J,C,W&J,W&C,O&C	10.86	11.72	10.97
Prodax	78-79	74-79	3	C	J,C,W&J,W&C,O&C	11.41	12.86	10.15
Kitt	78-79	75-79	3	W&C	J,C,W&J,W&C,O&C	8.30	8.06	8.50
Butte	78-79	77-79	15	W&C	J,W&J,W&C,O&C	8.18	8.46	8.58
Solar	79	78-79	1	W&C	J,W&J,W&C,O&C	11.70	12.59	12.82

Table 12 (Contd). North Dakota hard red and durum spring wheat varieties planted to 1% to more of the wheat area in one of the years 1955, 1957, 1959, 1964, 1969, 1970-75, 1978-79

Variety	Years		Highest percent planted	Comparisons to Variety and Thatcher		Differential yielding ability (bu/ac)		
						One comparison		More comparisons
	1% or more planted	Data for 2 or more locations		One	One or more	Average	Least squares means	Least squares means
Durum								
Mindum(M)	55-57	45-79	14	T	T	0.94	1.21	1.21
Stewart	55-57	46-53	3	M	T	3.20	2.88	5.36
Ramsey	57-59	56-64	4	M	T	2.46	2.81	2.00
Langdon	57-64	56-64	14	M	T	3.24	3.56	2.75
Lakota	64	60-67	6	M	T	6.66	6.69	4.63
Wells(We)	64-79	60-79	25	M	T	6.27	8.23	4.23
Leeds	69-79	66-75	25	We&M	T,We	2.89	5.51	0.87
Rolette	73-79	72-79	13	We&M	We	4.59	6.21	2.21
Ward	74-79	73-79	18	We&M	We	7.52	9.92	5.92
Rugby	78-79	73-79	6	We&M	We	7.32	9.76	5.77
Crosby	78-79	73-79	3	We&M	We	7.35	8.75	4.75
Cando	78-79	76-79	4	We&M	We	8.97	10.78	6.78
Botno	78-79	73-79	2	We&M	We	4.90	7.29	3.29
Calvin	79	78-79	1	We&M	We	5.25		

are given. This is somewhat approximate since percentage planted data were not available every year. The span of years between 1945 and 1979 for which agricultural experiment station data were available at two or more locations is given. The highest percent planted in one of the years for which that data are reported is also given.

Since data are available at two or more locations for Thatcher only through 1973, intermediates need to be considered for varieties with one percent or more planted after 1973. When the use of an intermediate is required, Feyerherm chooses a single variety for the comparison to the new variety. If the use of the intermediate chain rule is required, Feyerherm again chooses a single combination of intermediates to use for each new variety. In Table 12 Feyerherm's choices of intermediates and intermediate combinations are shown under the column indicated by one comparison to variety and Thatcher. T indicates a mean difference resulting from a direct comparison to Thatcher while C or M indicates that the mean difference in yields between that variety and Chris or Mindum is added to the mean difference between Chris or Mindum and Thatcher. The use of a chain rule is indicated by the symbol "&." W&C means that the mean difference between the new variety and Waldron was added to the mean difference between Waldron and Chris which was added to the mean difference between Chris and Thatcher. We&M is computed in a similar fashion using the chain rules with Wells and Mindum as the intermediates.

Varieties with one percent or more planted after 1973, such as Justin, Manitou, or Chris, have somewhat more direct comparisons with varieties other than Thatcher (see error degrees of freedom in Table 10). Therefore, as part of the investigation concerning the choice of intermediates, these comparisons were used as well as the direct comparison to Thatcher. The use of multiple intermediates and/or intermediate combinations is indicated under the column for one or more comparisons to variety and Thatcher in Table 12 with letters separated by commas. For varieties popular after 1973, Justin, as well as Chris, was used as an intermediate since Justin was adopted in about the same time period and to a greater extent. Olaf was also considered (along with Waldron) as an intermediate with varieties planted in the later years since it was more widely planted in the last few years. For many of the durum varieties a big difference in the DYA values was noticed (in Table 11) depending on whether Mindum was used as an intermediate, either alone or in conjunction with Wells. Therefore, direct comparisons to Thatcher and the use of Wells as a single intermediate were investigated.

The last three columns in Table 12 show three sets of differential yielding ability values. The first two sets are computed using the intermediates recommended by Feyerherm. One of these sets is computed using the arithmetic average method of estimating the mean yield differences and the other using the least squares estimation method. The last column in Table 12 contains a third set of DYA values. They are calculated using the comparisons to the variety and Thatcher indicated under the one or more column and the least squares method of estimating mean yield differences. The DYA is computed as a weighted average of the multiple DYA values indicated by letters or letter combinations separated by commas in Table 12, using the error degrees of freedom shown in Tables 10 and 11 as the weight.

The average DYA values for the state of North Dakota using each of the three methods to compute varietal DYA values are shown in Table 13. Each column of values was smoothed over time and plotted in Figure 14. It can be seen that the use of Feyerherm's intermediates, but using least squares means rather than long-term averages, results in higher state-wide average DYA values. The results using both one or more comparisons and the least squares means are more like the average DYA values using Feyerherm intermediates and long-term averages. Bootstrap test results using the average smoothed DYA values from all three methods are quite similar.

It is difficult to say which set of results is "best" or "correct." There is some suspicion that the average DYA values in recent years have been somewhat overstated. Yield levels have not been rising in North Dakota, as might be expected from the increase in average DYA values. Either the estimates of average DYA values are incorrect, or there is some other factor countering that contribution to increased yields, such as lower average soil productivity and/or a smaller fallowing percentage. At any rate, the average DYA values using the new comparisons and least squares estimates are the lowest in the most recent years.

Obviously, more work needs to be done in this area, particularly when one considers that the methods used here are also used to compute the adjusted yields for use in the plot-level regression analysis which leads to the definition of the weather index, WX.

Other Criteria for Model Evaluation

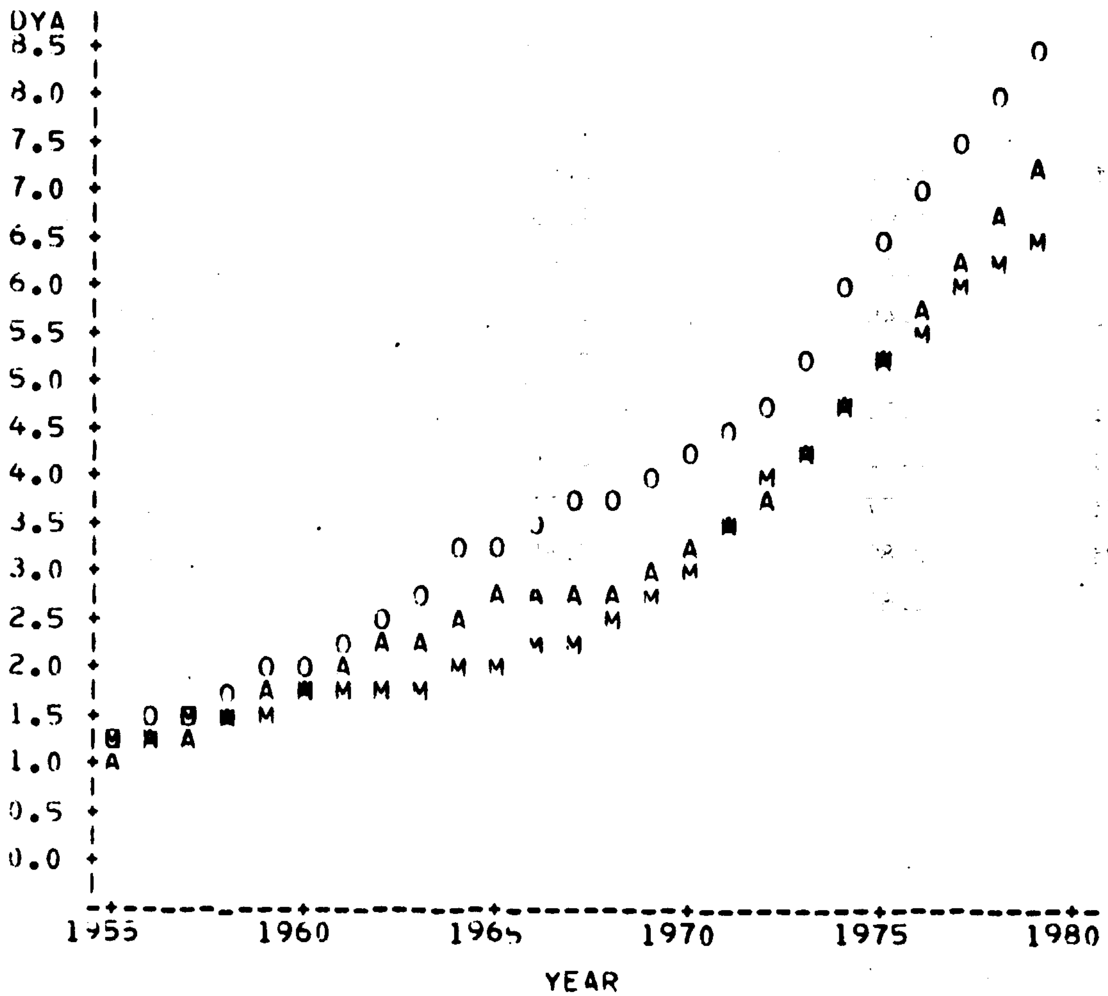
Eight model characteristics to be emphasized in model evaluation are discussed in Wilson, et al. (1980) and Wilson and Sebaugh (1981). They are yield indication reliability, objectivity, consistency with scientific knowledge, adequacy, timeliness, minimum costs, simplicity, and accurate current measure of modeled yield reliability. Our evaluation so far has mainly been concerned with the first of these, yield indication reliability. As we have pointed out, improvements are needed in the performance of the models. In making these improvements, some current features of the models may be changed, which would change an evaluation of the other seven characteristics. Therefore, only brief comments on these other topics will be made in this paper.

Model inputs are objective and the use of a daily soil moisture budget and crop calendar certainly is more scientific than the use of soil moisture budgets and weather variables based on data for calendar months. The attempted incorporation of important technology variables lends even more credibility to the process although there is still some question as to the optimum way to include this information. Other than rust loss, data concerning episodal events is not included in these models. Also, information concerning economic factors was not included, except as it may influence the amount of nitrogen applied and the amount of fallowing practiced. There is some trade-off in including some of these factors, which may be local in nature, and maintaining the general nature of the basic model which allows it to be easily adapted to particular locations, such as North Dakota, Minnesota, or Russia.

Table 13. Average differential yielding abilities for the state of North Dakota from 1955 to 1979 using three methods of calculating differential yielding ability for each variety; i signifies a year whose value is interpolated

Year	Average Differential Yielding Ability (bu./ac.)		
	One Comparison		More Comparisons
	Averages	Least Squares Means	Least Squares Means
1955	0.72	0.97	0.99
1956i	1.20	1.41	1.36
1957	1.67	1.84	1.72
1958i	1.58	1.73	1.61
1959	1.48	1.62	1.50
1960i	1.72	1.95	1.60
1961i	1.97	2.28	1.69
1962i	2.21	2.61	1.79
1963i	2.46	2.94	1.88
1964	2.70	3.27	1.98
1965i	2.72	3.42	2.05
1966i	2.75	3.56	2.11
1967i	2.77	3.71	2.18
1968i	2.80	3.85	2.24
1969	2.82	4.00	2.31
1970	2.92	3.89	2.89
1971	3.36	4.33	3.72
1972	3.33	4.47	3.69
1973	3.85	5.09	4.64
1974	4.59	5.90	4.76
1975	5.48	6.74	5.23
1976i	5.93	7.16	5.55
1977i	6.38	7.57	5.87
1978	6.83	7.99	6.19
1979	7.19	8.38	6.62

Figure 14. Average differential yielding abilities for the state of North Dakota after smoothing.
Letter represents method for calculating DYA for each variety:
A = averages and one comparison
O = least squares means and one comparison
M = least squares means and one or more comparisons



The use of daily weather data in and of itself makes the operational use of the model somewhat more costly and complicated. Models which use monthly weather values require the averaging or totaling of daily weather values, but only the monthly values need be entered into the computer for use with the model. With Feyerherm's model, the daily values themselves need to be entered into the WRV computer program in order to calculate the values of terms in the weather index equation.

No attempt was made in this report to evaluate the forecasting ability of the Feyerherm models. However, acquisition of daily weather data on a daily or weekly basis would allow timely forecasts using the Feyerherm model. We examined the crop calendar dates for 1970 through 1979 provided by the WRVPGM'80 computer program using our North Dakota CRD daily weather data. The latest heading day for any CRD was July 14, the latest milk stage day was July 24, and the latest dough stage day was August 5. This would indicate that by the middle of July, a forecast could be made using daily weather data for the current year through heading. Feyerherm suggests using long-term averages for the weather terms related to later stages of development (see Appendix-Weather Index). Another forecast using daily weather data for the current year through the milk stage could be made at least by the end of July. The final estimate could be made using all current year weather data by the first part of August.

CONCLUSION

To justify the increased complexity of these models as compared to monthly weather data models, one needs to be able to demonstrate benefits in one or more of the other model characteristics, such as accuracy of yield predictions, timeliness of forecasts, or adaptability to other geographic areas. On the one hand, the requirement of supplying daily weather values for each station to the WRVPGM'80 computer program in order to obtain the values needed to calculate the weather index for each station is greater than the effort required to calculate the terms for a state level monthly weather model. On the other hand, it is precisely the use of an independently derived weather index which should make the Feyerherm model more adaptable to other geographic areas. A shorter time series of yield and weather data should be required to adapt the Feyerherm model to an area than would be required to fit the coefficients for a trend and monthly weather data model whose weather term coefficients are not independently estimated.

However, one has to demonstrate the accuracy of the weather index. Unfortunately, in the present case the Feyerherm '81 spring wheat models for North Dakota perform no better than the CEAS trend and monthly weather data model, and the Feyerherm '81 spring wheat models for Minnesota do not perform as well as the CEAS model (Sebaugh, 1981a). Improved performance needs to be demonstrated to justify the argument of adaptability to other areas, otherwise the whole concept of a "universal" model or "universal" weather index is open to question.

There are two general areas in which recommendations will be given for enchancing the capabilities and overcoming the limitations of the models evaluated. First, top priority should be given to improving the weather index using the plot-level agricultural experiment station yield and associated weather data. Second, the usefulness of the weather index should then be demonstrated by adapting it for use in North Dakota and Minnesota using USDA yield data.

The following specific recommendations are made regarding work on the weather index:

- o Expand the plot-level data base by including years past 1973 for which yield and weather data are available,
- o Consider improved methods for adjusting plot yields to a standard,
- o If available, use observed planting days at the agricultural experiment stations when running WRVPGM'80,
- o Consider the inclusion of a term or terms in the weather index to reflect late planting, since it is often associated with lower yields,
- o Investigate the use of a trend term in order to reflect improved technology, other than varietal improvements and nitrogen application,
- o Investigate the use of additional regression diagnostic and variable selection techniques to improve the prediction ability of the equation.

The following recommendations are made for adapting the new weather index to North Dakota and Minnesota:

- o Correct data values as described in the Working Paper (Kestle and Sebaugh, 1981),
- o Include Williston as a North Dakota weather station,
- o Consider the use of observed planting dates when running WRVPGM'80, for example, the 50 percent planting day for the CRD in which the station is located,
- o Compute the varietal adjustment factor in a manner compatible with that used to adjust the plot-level yields,
- o Investigate how changes in total planted area in both states may be related to changes in yield level, and
- o Reevaluate the method of accounting for changes in the level or percent of fallowing in North Dakota.

Beyond these specific suggestions and recommendations, an attempt to partition current and historic yields into components for weather, technology, disease and insects, and other factors is encouraged. If accurate partitioning can be accomplished, then each component could be independently estimated for a future year. One measure of the accuracy of the historic partitioning would be the accuracy of yield prediction based on the partitioning as measured by the currently used bootstrap testing. It would be desirable for the prediction of each component to be accomplished using a well-defined, objective method, although it would not be necessary for all components to be estimated using the same methodology, such as multiple regression.

The use of an independent, plot-level data base for the development of a weather index is an important step in the ability to partition yield components in the manner suggested. Also, the work already done by Feyerherm in investigating varietal improvements, use of nitrogen, and cropping practices as part of his technology models provides a basis for estimating the technology component. Episodal events affecting wheat yields in North Dakota and Minnesota have already been investigated by Feyerherm (1982). Therefore, the use of knowledge about these various yield components in a systematic attempt to improve the ability to predict yields in a future year is encouraged. It would be desirable for these attempts to be approached assuming two different levels of data input for the future year. For adaption and/or testing in this country, one would assume that certain factors could be estimated with some accuracy during the current growing season, such as amount of planting on fallowed land, percent planted by variety, amount of nitrogen applied, or even amount of abandonment. For adoption in foreign areas, one should make fewer assumptions about the availability of such estimates.

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APPENDIX - WEATHER INDEX

The spring wheat weather index (WX) computed for each year for each weather location is the following function of weather-related variables (WRVs):

1. WX = 389.43 + MOIST + TEMPRE, where

2. MOIST = Measure of effects of moisture deficits,

$$= 1.049 * CN(P) + 3.783 * ET(JD) - 0.232 * ET^2(JD), \text{ and}$$

3. TEMPRE = Measure of effects of excessively high temperature and/or excessive precipitation,

$$= -0.0788 * PR^2(PJ) - 0.2526 * TX(JF)$$
$$-0.3583 * TX(FH) - 0.01454 * TX(HM) * PR(HM)$$
$$-0.00279 * TX^2(HM) - 6.9739 * TX(MD)$$
$$+ 0.03823 * TX^2(MD).$$

4. The predictor variables are computed using daily values of precipitation and minimum and maximum temperatures as input to the computer program WRVPGM'80. They are defined as follows:

CN(P) = Total simulated plant-available water (i.e., the contents) in the six zones of the versatile soil moisture budget at planting,

ET(JD) = Accumulated simulated evapotranspiration from jointing-to-dough stages,

PR(PJ) = Accumulated precipitation from planting-to-jointing,

TX(ab) = Average of daily maximum temperatures from stage a to stage b where ab is, in turn:

JF (jointing-to-flag leaf),

FH (flag leaf-to-heading)

HM (heading-to-milk), and

MD (milk-to-dough).

PR(HM) = Accumulated precipitation from heading-to-milk stages.

5. The coefficients were determined from regression analysis on varietal trial plot data and data from nearby weather stations (n=249 location/years). The dependent variable for each location/year was the average of the adjusted yields for three varieties where each adjusted yield is equal to the differential yielding ability for that variety subtracted from the unadjusted yield. The independent variables included those shown above plus a term for applied nitrogen and a set of indicator variables for the geographic locations of the varietal trials.

APPENDIX - STATISTICAL FORMULAS

Selected Measures of Model Performance

Definition of Terms:

Y_i = Yield as reported by U.S.D.A. for year i ("true," "actual" or "observed" yield).

$\hat{Y}_i$ = Yield as predicted by a model for year i.

$d_i = \hat{Y}_i - Y_i$ = difference between predicted and actual yield for year i.

$rd_i = 100\ d_i/Y_i$ = relative difference for year i.

$i = 1,\ldots,n$ = number of test years and $\Sigma = \sum_{i=1}^{n}$ = summation over the test years.

$\overline{Y} = 1/n\ \Sigma\ Y_i$ = average actual yield.

Measures:

Bias = B = $1/n\ \Sigma\ d_i = \overline{d}$.

Relative Bias = RB = $100\ B/\overline{Y}$.

Mean Square Error = MSE = $1/n\ \Sigma\ d_i^{\ 2}$.

Root Mean Square Error = RMSE = $(MSE)^{1/2}$

Relative Root Mean Square Error = RRMSE = $100\ RMSE/\overline{Y}$.

Variance = Var = $1/n\ \Sigma\ (d_i - \overline{d})^2$.

Standard Deviation = SD = $(Var)^{1/2}$.

Relative Standard Deviation = RSD = $100\ SD/(\overline{Y} + \overline{d})$.

Mean Square Error = Variance + $(Bias)^2$,

or

Accuracy = Precision + $(Bias)^2$.

APPENDIX
Data Values Supplied by Feyerherm with Corrections
Unit of Measure Is Quintals per Hectare

Year	STYLD_H	AVE_WX	NI	FALINC	AVDYA	TECH	EE_HLOSS	ASTYLD_H
				NORTH DAKOTA				
1955	10.2	17.5	0.0	1.6	0.5	2.2	0.9	8.9
1956	11.6	16.4	0.0	1.7	0.9	2.6	0.0	9.0
1957	12.6	13.4	0.0	2.0	1.2	3.2	0.0	9.4
1958	15.5	21.7	0.1	2.2	1.1	3.4	0.0	12.1
1959	10.1	14.9	0.1	2.2	1.1	3.4	0.0	6.7
1960	13.3	15.0	0.1	2.2	1.3	3.6	0.0	9.7
1961	8.1	9.9	0.1	2.4	1.4	4.0	0.0	4.2
1962	19.3	18.4	0.1	2.6	1.6	4.3	0.8	15.8
1963	15.0	15.3	0.2	2.9	1.7	4.8	1.0	11.1
1964	16.0	15.3	0.2	2.8	2.0	4.9	0.3	11.4
1965	17.5	19.4	0.2	2.8	2.0	5.0	1.3	13.8
1966	15.7	14.4	0.2	2.7	2.1	5.0	0.5	11.2
1967	15.2	14.7	0.2	2.6	2.2	5.0	0.2	10.4
1968	18.0	18.9	0.3	2.6	2.2	5.0	0.4	13.3
1969	20.1	20.2	0.4	2.9	2.3	5.6	0.0	14.5
1970	15.9	14.9	0.4	3.0	2.2	5.7	0.2	10.3
1971	21.4	19.5	0.5	2.9	2.0	5.4	0.2	16.3
1972	19.4	21.1	0.5	2.8	2.0	5.3	0.2	14.3
1973	18.5	14.6	0.7	2.8	2.6	6.2	0.0	12.3
1974	13.7	10.9	0.6	2.3	3.5	6.3	0.1	7.4
1975	17.4	17.9	0.6	2.1	3.6	6.3	0.2	11.3
1976	16.6	18.4	0.9	1.9	4.0	6.7	0.0	9.9
1977	16.7	18.1	0.7	2.0	4.3	7.1	0.0	9.7
1978	20.1	20.2	0.8	2.1	4.6	7.6	0.0	12.5
1979	17.7	18.7	1.2	2.0	4.8	8.0	0.0	9.6

APPENDIX: Continued
Data Values Supplied by Feyerherm with Corrections
Unit of Measure Is Quintals per Hectare

Year	STYLD_H	AVE_WX	NI	FALINC	AVDYA	TECH	EE_HLOSS	ASTYLD_H
				MINNESOTA				
1955	12.6	18.5	0.1	0.0	3.7	3.8	0.3	9.1
1956	15.9	19.5	0.2	0.0	3.9	4.1	0.0	11.9
1957	15.2	17.7	0.3	0.0	4.1	4.4	0.2	11.0
1958	21.2	25.0	0.3	0.0	4.3	4.6	0.0	16.6
1959	15.5	19.1	0.3	0.0	4.5	4.9	0.2	10.8
1960	18.5	20.0	0.4	0.0	4.4	4.8	0.0	13.7
1961	16.1	18.8	0.4	0.0	4.3	4.7	0.0	11.3
1962	16.7	22.3	0.4	0.0	4.2	4.7	1.3	13.3
1963	16.7	18.3	0.5	0.0	4.1	4.6	0.0	12.1
1964	15.6	16.0	0.5	0.0	4.0	4.6	0.3	11.4
1965	18.8	20.9	0.5	0.0	4.2	4.7	1.9	15.9
1966	15.3	16.5	0.3	0.0	4.3	4.8	0.3	10.9
1967	21.7	22.9	0.9	0.0	4.5	5.4	0.0	16.3
1968	22.3	20.6	1.3	0.0	4.6	6.0	0.7	17.0
1969	20.2	22.7	1.3	0.0	4.8	6.0	0.0	14.2
1970	18.6	17.7	1.4	0.0	5.4	6.7	0.4	12.2
1971	25.6	21.1	0.9	0.0	6.0	6.9	0.3	19.0
1972	22.2	23.3	2.4	0.0	6.6	9.0	0.0	13.2
1973	26.2	18.2	2.1	0.0	7.2	9.3	0.0	16.8
1974	19.5	16.3	2.1	0.0	8.9	11.0	0.0	8.5
1975	20.8	18.1	2.1	0.0	8.9	11.1	0.0	9.8
1976	21.8	18.1	2.6	0.0	8.9	11.5	0.0	10.3
1977	26.8	19.8	2.5	0.0	9.0	11.5	0.0	15.3
1978	22.7	21.5	2.9	0.0	9.0	11.9	0.0	10.8
1979	23.6	21.6	3.0	0.0	9.1	12.1	0.0	11.5