YRB 78-12

EVALUATION AND SELECTION OF WEATHER VARIABLES FOR NRED YIELD SIMULATION MODEL

Bruce W. Strand[1/]

Renewed interest in the impacts of weather variations on crop yields have resulted in the need to incorporate weather variables in economic models. The proper selection and application of weather variables in the Natural Resources Economics Division (NRED) yield simulation model is the topic of this paper.

For weather variables to be used in a national yield simulation model for NRED, they must be selected from the large number of variables used in various yield models based on criteria established by the aims of NRED yield study group. The criteria for consideration of weather variables are that they must: a) furnish monthly estimates of a weather index. b) be effective in modeling the impacts of weather on crop yields for large regions of the U.S. to avoid massive data problems. c) be simple to compute and use. Using the existing data base, it must be able to be readily computed from existing data without the use of specialized assistance from climatologists or agronomists. Historical and cross-sectional monthly weather data is presently available to NRED. d) be a currently acceptable method of estimating weather impacts on crop yields.

Using the criteria outlined above, the weather indexes considered for this project are: 1) the AE/PE[*] aridity index of Thornthwaite; 2) the AE-PE index as used by several researchers (the absolute moisture deficiency index); 3) the Palmer "X" drought index; 4) the "M" index of Perrin and Heady; 5) estimated soil moisture used as an index, and the "Z" index used by C. Sakamoto. 6) The Blaney-Criddle formula for comsumptive-use is also discussed. There are a great number of existant weather/crop models varying in complexity and scope, but these indexes were recommended because they can be readily computed from the available data set. No attempt has been made here to adequately describe even a small fraction of those models.[**]

I have not considered the direct use of temperature and rainfall data as weather indexes in yield equations. Variables generated from meteorological data have repeatedly been shown to be better estimators of crop yields than the direct use of climatological data such as temperature or precipitation.[2/3]

---

[*] AE is actual water use, PE is potential maximum water use. Both terms will be discussed further.

[**] For a review of crop-yield models, see: Strand, Bruce, (1975) "Weather-crop Models: A review and classification of their methodologies." FDCD working paper in progress, April, 1977.

OBTAIN COPY

Table #1 is a table of these methods along with their generalized formulas and general data requirements.

PLANT-WATER RELATIONSHIPS

The timing and quantity of water available for plant growth and development is the major factor in controlling plant yields for most of the agricultural regions of the U.S. In some of the northern portions of the U.S., solar energy available for plant growth and development as indexed by frost free period or net solar radiation are the limiting constraints on crop yields, but for the U.S. as a whole, the timing and availability of water for plants is the most common constraint to crop yields.

Most commonly used weather indexes seek to model and quantify these plant-water-atmosphere relationships but their basic approaches differ in slight but important ways. The aim of this paper is not to review and explain the basis of plant-water relationship modeling, but rather, to compare a few methods and to characterize each variable. Nevertheless, all the indexes are based on the concepts of the relationships between moisture demands and moisture supplies to the plant, and a familiarity with plant-water relationships would aid in understanding the weather indexes.[5]

The work of C. Warren Thornthwaite on potential evapotranspiration (PE) has underlain most modern attempts of assessing plant-water

TABLE #1

Variable	What it represents	source of data	generalized formuala
soil moisture s	soil moisture regime integrates the effects of rainfall, water in storage, and depletion	soil moisture measurements, more commonly, it is estimated by using a water-balance model.	$Ds= P-AE\pm RO$
AE/PE	relative supply of moisture to moisture demand. A dimensionless parameter. value between 1 and 0.	estimates of AE and PE are from a water-balance model.	AE/PE, where $AE=f(PE)$ and $PE=f(T, site...)$
AE-PE	Absolute deficiency of water use to water demand	Estimates of AE and PE are from a water-balance model.	AE-PE, where $AE=f(PE)$ and $PE=f(T, site...)$
Palmer's Z index	moisture deficiency of water supply, adjusted for long-term trend of moisture supply	Estimates of AE and PE are from water-balance, d and k are from temp. and precip. mean data.	$z=dk$, where $k=(\overline{PE}+\overline{R})/(P+L)$, and $d=p-\overline{p}$
"M"	adjusted AE-PE formula, absolute moisture defic with long term PE mean.	Estimates of AE and PE from water-balance, long-term mean AE/PE also from water-balance	$AE-(\overline{AE}/\overline{PE})PE$ where $AE=f(PE)$, $PE=f(\overline{t},site...)$
Blaney-Criddle	PE adjusted for site and crop.	Temperature and site data. Crop coeffic.,	$PE= Kf$, where K is crop coefficient, $f=f(\overline{t},sunlight)$

relationships. His 1955 publication outlines a proceedure for computing PE and from this actual evapotranspiration (AE) using monthly or daily temperature and precipitation data[6/] in a budgetary proceedure of calculating additions and depletions to soil moisture.

AE/PE RATIO

The ratio of AE to PE expresses the ratio of actual water use to potential maximum water use. If water is plentiful, actual water use (AE) will equal the potential water use (PE) and the AE/PE index will equal 1. This represents a condition of no moisture stress. At other times when moisture supply falls short of moisture demand, the indexes will have a value less than 1. It is possible under some situations for AE to be zero when PE is greater than zero. Plant life stops.*

Researchers using monthly and daily estimates of the ratio of AE to PE as well as the difference between AE and PE have had some success in relating this index to final crop yields in regression equations. Yao (1968)[7/] used the AE/PE ratio to assess the climatic limits to growth in China and crop success[8/] in Africa . Fitzpatirck and Nix[9/] have shown AE/PE to be effective in modeling Australian wheat yields. Bridge[10/] used AE/PE to model wheat yields in the northern Great Plains. This researcher has related AE/PE values to corn yields in France, Mexico and Argentina.

---

* This excludes the special case of plants which store water in their tissues for later use, such as some desert plants.

AE-PE

An alternative formulation of a moisture stress index is AE-PE. The index AE-PE expresses the absolute shortfall of moisture supply to moisture demand. Thus if water is plentiful, AE will equal PE and the term will equal zero. With decreasing moisture supply, the term becomes negative. This index has the advantage of being bounded on one side only and of having a counterpart in the physics of plants. In contrast, the AE/PE ratio can only range from an undefined (AE=0,PE/0) or zero, to 1. (AE=PE). In regression analysis, AE-PE is to be perfered to AE/PE because of the problem of scale. Variables with a range of values close to the scale of values of the dependent variable (i.e.,yields) are better in regression equations. Yields as the most common dependent variable used in weather-crop equations and they will have values far larger that the AE/PE ratio which leads to large coefficients in the regression equations. Albrecht,[11/] in a study of Missouri valley crop production found the variables AE/PE and AE-PE to be equally effective in "explaining" variations in crop yields.

Two other weather indexes that are closely related to the indexes AE/PE and AE-PE are Palmers' drought index and Perrins and Heady's "M" index. Palmers' drought index,"X" uses the Thornthwaite water balance procedure to estimate weather variables and to create long-term mean values for this weather variable. Through a series of manipulations involving long-term mean values for potential evapotranspiration (PE) and rainfall (P) Palmer generated monthly departures of rainfall and temperature from the "climatically appropriate" values. His drought index considers drought duration, and weights the different monthly contributions to drought.

Perrin and Heady (1975) in a modeling of U.S. Wheat yields use an index they call "M" which they derived from Palmers' work. Their "M" index is: $M = AE - (LtAE/LtPE) * PE$, where LtAE and LtPE are the long-term averages for AE and PE. They found this index to be superior to AE-PE , AE/PE or Soil Moisture estimates when used in a regression equation to predict wheat yields.

SOIL MOISTURE

The use of estimated soil moisture as a variable in weather-crop yield regressions has been shown useful in a number of studies.[12,13] In locations where stored soil moisture plays a dominant role in crop yields, this variable is especially useful in yield equations. Russian spring wheat yields have been clsoely assocatied with moisture stored in the soil at the beginning of the growing season.[14]

BLANEY-CRIDDLE

Blaney and Criddle (1950) developed a method for estimating consumptive-use (PE) by various crops for the western U.S.[15] Their estimates require temperature and daytime hours data as well as an emperical PE coefficient that depends on the type and location of the crop. USDA/SRS Technical Release No.21 contains most of the basic elements necessary to estimate comsumptive use.[16] While this method is primarily designed to aid irrigation planners, adaption of its use for a weather index should be possible. An obvious shortcomming is that the model is both site and crop specific. Extending site estimates of PE for large areas presents problems.

SPATIAL VARIATIONS

Any attempt to select a single best weather index applicable for the entire US. will probably fail. Crop/weather relationships are not consistant through out the entire U.S. The humid East is agriculturally different from the arid west. The South grows crops which vary considerably from those in the northern states., With these regional crop differences and weather differences go different crop-yield/ weather relationships, and the same weather variable may not be suited to model all these different situations. Williams[17/] in a study of variations in weather-crop relationships in Canada found that in the drier regions of Canada, only one weather variable was necessary to account for 40% of yield variance. In the more humid regions, at least three weather variables were necessary to predict variations in yields. His results would argue for different weather crop models in various regions across the country.

An important distinction must be made in modeling western irrigated agriculture from rainfed agriculture in the humid east. Irrigation removes most of the effect of severe moisture stress in reducing crop yields. For this reason, weather indexes which incorporate moisture stress in modeling are of little use in the irrigated areas of the west. In addition, irrigated fields are often subjected to abnormal energy exchanges due to their wettness. Most irrigation is practiced in arid or semi-arid regions where a large fraction of the sunlight that reaches the ground are used to heat the air. This hot air, when passing over an irrigated field, tends to evaporate water at a rate higher than would normally be expected from estimates derived from temperature and sunlight data. For this reason, special formulas have been created to account for the excessive heat loads and abnormally high rates of AE in irrigation plots.

Weather variables based on the water balance formula are not well suited for modeling crop yields in irrigated areas. Thornthwaite derived his formulas for PE from watershed data and did not provide for the higher rates of heat transfer found in irrigated areas.

The reverse is not true. Comparisons of the various methods of estimating PE show that Blaney-Criddle method estimates which are designed for use in irrigated regions fit the climate in the humid East very well.[18/]

COMPARISON OF METHODS

There have been several comparison of weather-crop indexes for specialized areas in the world, but no direct comparisons for all the models. A logical first step in comparing the weather variables indexes is to review comparisons of the components of those variables.

McGuiness and Bordne (1973) in a comparison of various estimates of PE which is used in all weather indexes against a "standard" lysimeter measurement of PE in North central Ohio discovered that of the methods using only temperature as an imput in their estimates of PE, the Blaney-Criddles method gave the closest fit to the "standard" curve as compared with Thornthwaite and Harmon and Papadakis methods.[19/]

Inspection of the results of McGuinness and Bordne showed that the Blaney-Criddle, Jensen-Haise, Christensen, Penman, van Bavel and Pan evaporation methods all gave estimates within 10% of the "standard" curve. (p.18). Thus any of these formulations of PE used in a weather index would be equally effective in the humid East.

A different situation occurs in the irrigated lands of the western U.S. In a comparison of various comsumptive-use formulas for western irrigation regions, Cruff and Thompson[20/] concluded that for arid regions, the Blaney-Criddle method was the most practical of the six methods for estimating PE. It should be noted that they used adjusted pan evaporation as their "standard", one which McGuinness & Bordne found did not work well in the East. In addition, because of the specialized crop coefficients used by the Blaney-Criddle formula, this method should give better results. If the other methods used are adjusted for crop specific conditions, they should also give comparable results, although this test has not been done.

"M" vs. "Z" INDEX

A comparison of the basic weather indexes based on relative ratings by agromonists and climatologists produce differing rankings in the effectiveness of weather indexes in predicting crop yields. Droest and Shaw concluded that Palmers' index was not as useful as the direct use of AE and PE estimates from the Palmer procedure in modeling U.S. corn yields.[21/] Sakamoto[22/] in modeling Australian and Argentine wheat yields concluded that Palmers' index, together with temperatuare departures explained more of the yield variations than using either AE/PE or soil moisture in estimating wheat yields. Perrin and Heady[23/] in a review of U.S. corn yields concluded that their "M" index was also better than either AE-PE or Soil Moisture in estimating corn yields.

As mentioned before, the "M" index is really the AE-PE index which is then adjusted to account for "average" moisture stress in a given period. Sakamoto, utilizing Palmers' "Z" index together with the temperature anomaly is accounting for "average" temperature. His model of Argentine wheat yields utilizes dummy variables to account for sudden events such as climatic, political, or economic events that affect crop-yields as well as temperature departure and temperature departure squared and precipitation departure all in this multiple linear regression equation of wheat yields. Sakamoto's report also uses dummy variables to represent occassional or rare events, and the selection or modeling of a crop-weather relationship based on the specific crop conditions of an area.

SUGGESTED METHODOLOGY FOR CREATING WEATHER-CROP/YIELD EQUATIONS

The methods mentioned here have a common logical basis in the formulation of the weather crop-yield models. Because weather impacts on crop yields in different ways, crop yield equations must if possible be adapted to suit the crop. For example, corn yields are most sensitive to moisture stress during the grain filling period. In contrast, winter wheat yields in dry climates such as steppe regions, are closely related to the amount of soil moisture in the spring available for plant growth.

In general, a weather/crop yield model that models the climatic and technological factors effecting it will be successful. Sufficient research by agronomists on the environmental constraints of plant growth have been done to offer suggested models of crop growth and yields for most crops. A modeling process that selects those climatic and technological variables based in part on agronomic research and in part on technical/economic /political considerations is probably the best method available.

With these points in mind, two examples are given of the proceedure used by the author to create weather-crop/yield equations. In the first example, national Argentine wheat yields are predicted using climatic variables generated by the Thornthwaite water-balance porceedure for the Rosario, Argentina area. Table#2 is a listing of the weather variables initially found to correlate well with wheat yields. A listing and explaination of those variables can be found in the Appendix. These are not all the variables that correlated well with yields, but rather a selection of those variables that seemed logically correct for the crop and site studied.

With each subsequent equation, the climate variables with the lowest "t" statistic was removed and the equation rerun with the remaining variables. This selection procedure was continued untill all the remaining variables in the yield equation were significant at the 90% confidence level. Equation #8 is an example of this. In cases where two variables had "t" statistics which were very close or where highly correlated with each other, a correlation matrix was generated with the remaining variables compared with the variable with the highest "t" statistic in the equation. The two variables were then compared agianst the most significant variable in the equation. That varible with the lowest correlation was retained with the assumption that the intercorrelation would be less. In the example of ARgentine wheat presented here, the two variables, R5 and S5 being highly intercorrelated, were selected based on thier correlation with ACTET5, the highest "t" variable in the equation.

ARGENTINE WEATHER-WHEAT YIELD EQUATIONS (COEFFICIENTS)

VARIABLE	#1	#2	#3	#4	#5	#6	#7	#8*	#9	#10
#C	5957	6231	7021	7582	8115	8453	7346	8741	984	853
ACTET5	11.3	11.7	12.6	12.4	12.8	12.4	12.2	15.9	10.3	12.1
PPE3	2.07	2.11	2.17	2.25	2.32	2.54	2.61	2.75	2.88	2.91
SM2	-7.04	-7.25	-7.26	-6.45	-6.64	-6.84	-6.46	-4.66	-6.08	-6.12
SM7	-5.39	-5.36	-5.23	-5.30	-6.12	-5.46	-3.11	-3.27	-3.92	-4.22
S5	99.1	102.3	113.3	118.8	125.5	120.9	102.2	116.4	6.26	----
R5	-6420	-6669	-7467	-7833	-8359	-8094	-6952	-8235	----	----
SAE5	2.42	2.44	2.59	2.41	2.24	2.23	2.01	----	----	----
SM8	4.11	4.12	4.48	3.67	3.61	2.58	----	----	----	----
TREND	15.1	14.3	13.6	10.5	9.31	----	----	----	----	----
R7	-517.9	-503.9	-513.9	-117.4	----	----	----	----	----	----
ACTET7	4.08	3.84	3.57	----	----	----	----	----	----	----
SM10	0.865	0.709	----	----	----	----	----	----	----	----
SM1	-0.347	----	----	----	----	----	----	----	----	----
R^2	0.83	0.83	0.83	0.82	0.82	0.81	0.80	0.76	0.69	0.67
S.E.E.	136	126	118	114	109	107	105	111	121	121

The same procedure was followed in creating Argentine weather corn yield equations. Table #3 is a listing of the weather equations and the weather variables and coefficients that were initially found to correlate well with corn yields. Here again, seven weather variables were removed from the initial equation in the same step-wise manner as in the wheat yield equations. Significantly higher r^2's were obtained because of the effect of good correlation of a trend variable with the corn yields.

CONCLUSIONS

This review of large scale weather-crop yield equations applicable to NRED use suggests that: A) there is a common hydrological basis for all these weather-crop yield models and that these basic methods have been compared in literature. In addition, B) Procedures used to incorporate these basic hydrological varaibles tend to follow logical sequences which can be projected to almost any area which NRED seeks yield estimates.

In regards to the Palmer index methods of Perrin and of Sakamoto, a comparison of these two methods has not been done but questions arrise as to both their utilities. Because of the availability of the Palmer drought index data on magnetic tape for computer use for this project, a methodology based on either of these two indexes or a proceedure suggested by these proceedures should be employed.

ARGENTINE WEATHER-CORN YIELD EQUATIONS (COEFFICIENTS)

Variables	#1	#2	#3	#4	#5	#6	#7*	#8	#9	#10
#c	84.63	83.56	80.82	82.15	73.05	66.49	67.85	8.504	5.527	7.864
ACTET6	.1969	.1975	.1991	.1958	.2000	.2052	.1916	.1904	.1918	.1712
FERT	.0996	.0983	.0961	.0961	.0902	.0910	.0943	.0989	.1010	.0842
ACTET10	-.0727	-.0737	-.0741	-.0779	-.0771	-.0746	-.0682	-.0648	-.0672	-.0756
PPE3	-.0282	-.0279	-.0275	-.0271	-.0247	-.0242	-.0252	-.0239	-.0233	-----
R5	-79.28	-77.76	-75.10	-76.06	-66.89	-60.40	-62.11	-3.056	-----	-----
S5	1.118	1.093	1.046	1.058	.9158	.8205	.8302	-----	-----	-----
SM1	-.0463	-.0473	-.0473	-.0493	-.0206	-.0228	-----	-----	-----	-----
SM7	.0089	.0106	.0181	.0182	.0126	-----	-----	-----	-----	-----
SM2	.0333	.0352	.0350	.0371	-----	-----	-----	-----	-----	-----
PPE9	-.0014	-.0011	-.0012	-----	-----	-----	-----	-----	-----	-----
SM8	.0103	.0081	-----	-----	-----	-----	-----	-----	-----	-----
SAE5	.0021	-----	-----	-----	-----	-----	-----	-----	-----	-----
R^2	.955	.954	.954	.953	.948	.944	.939	.918	.914	.822
S.E.E.	1.169	1.095	1.036	.993	1.001	.992	.993	1.112	1.099	1.531

* All variables singificant at 95% confidence level.

In conclusion, Lowrey[24/] in a review of crop-yield/weather models suggested that no really universal model is possible because of the great diversity of crops and cultural practices in the world as well as the diversity of crop-climate interactions. With this in mind, the use of dummy variables to represent "steps" in the time-series yield equations, and the selection of appropriate coefficients based on probable physiological responses to local climates appears to be a logical choice in weather-crop modeling methodology.

FOOTNOTES

[1] Prepared by Mr. Bruce Strand for USDA/ERS,NRED under contract #12-17-06-5-1901.

[2] Baier,W. and G.W. Robertson (1968) "The preformance of soil moisture estimates as compared with the direct use of climatological data for estimating crop yields", Agricultural Meteorology, 5(1968):17-31.

[3] Fitzpatrick,E.A. and H.A. Nix,(1969) "A model for simulating soil water regime in alternating fallow-crop systems", Agricultural Meteorology 6(1969):303-319.

[4] Monthly estimates of weather indexes were considered the most useful time scale because of data constraints.

[5] For a more complete review of the use of the water balance proceedure in crop yield modeling, see; Strand, Bruce,(1977) "Weather-crop modeling: The application of the Thornthwaite water balance model in crop yield equations", USDA/ERS, FDCD working paper in progress.

[6] Thornthwaite,C.W. and J.R. Mather, (1955) "The Water Balance", Centerton, N.J.: Laboratory of Climatology Publication 3(1):1-86.

[7] Yao, A.Y.M. (1968) "Climatic Hazards to the agricultural potential in the North China Plain", Agricultural Meteorology 6(1969):33-48.

[8] ----------- (1973) "Evaluating Climatic limitations for a specific agricultural enterprise." Agricultural Meteorology, 12(1973):65-73.

[9] Nix,H.A. and E.A. Fitzpatirck,(1968) "An index of crop water stress related to wheat and grain sorghum yields", Agricultural Meteorology 6(1969):321-337.

10/
Bridge, D. (1975) "A simulation model relating effective climate to spring and winter wheat yields on the Northern Great Plains," (Unpublished PhD Dissertation, Department of Geography, Southern Illinois University), August,1975.

11/
Albrecht,J.C. (1971) "A climatic model of agricultural Productivity in the Missouri River Basin." *Publications in Climatology*, Laboratory of Climatology, 24(2):1-107.

11/
Perrin, Richard K. and Earl O. Heady (1975) *Relative Contributions of Major Technological Factors and Moisture Stress to Increased Grain Yields in the Midwest,1930-1971* . CARD,#55, Iowa State U. p.8.

12/
Baier,w. and Geo. W. Robertson,(1967),"Estimating Yield Components of Wheat from Calculated Soil Moisture", *Can. J. Plant Sci.* vol.47:617-629.

13/
Baier,W. and Geo. W. Robertson (1968).op. Cite.

14/
Ulanova, Ye. S. (1975) "Agrometeorological conditions and winter wheat yields", U.S. Joint Publications Research Service, 18 December,1975. JPRS #66418.

15/
Blaney, H.F. and Criddle, W.S. (1950) "Determining water requirements in irrigated areas fropm climatological and irrigation data" U.S. Dept. of Agriculture, Soil Conserv. Service, Technical paper #96.

16/
"Irrigation Water Requirements", U.S. Department of Agriculture, Soil Conservation Service Technical Release #21 april,1967.

17/
Williams, G.V.D. (1972). "Geographical variations in yield-weather relationships over a large wheat growing region." *Agricultural Meteorology*, 9:265-283.

18/
McGuinness,J.L. and Erich F. Bordne, (1972),"A Comparison of lysimeter-derived potential evapotranspiration with computed values", U.S. Department of AGriculture, A.R.S. Technical Bulletin # 1452. p.18.

19/
McGuinness,(1972).p.18.

20/
Cruff, R.W. and T.H. Thompson (1967) "A comparison of methods of estimating potential evapotranspiration from climatological data in arid and subhumid environments" Geological Survey Water-supply paper 1839-M. U.S. Department of Interior. p.1.

21/
Droest, D., personnel communication , April,1977.

22/
Sakamoto, C. (1976) "An index for estimating wheat yields in Australia" CCEA Technical note 76-3, Columbia, Missoiri.

23/
Perrin, p.8.

24/
Lowrey, W.P. (1959) "The falling rate phase of evaporative soil moisture loss- a critical evaluation," Bulletin, American Meteorological Society 40:605-608.

APPENDIX

VARIABLE NAMES AND DEFINITIONS

#C	Regression constant furnished by the computer program
ACTET5, 6,10	Actual evapotranspiration in the 5th,6th, and 10th month. (November, December and April)
PPE3,9	Difference between rainfall (P) and PE in the 3rd and 9th month. (September, March)
R5	AE/PE for November
S5	AE-PE for November
SM1,2..	Soil moisture for July, August,...
SAE5	Summed AE for months 1-5, July through November
FERT	National fertilizer consumption (Nitrogeneous) for Agrentina
TREND	Time variable, 1955=55,1956=56....1961=61,1962=61...1970=61, 1971=62,...