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RESPONSE OF WINTER AND SPRING WHEAT GRAIN YIELDS TO METEOROLOGICAL VARIATION

FINAL REPORT: CONTRACT NAS9-14282

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ABSTRACT

This report contains mathematical models which quantify the relation of wheat yield to selected weather-related variables. Other sources of variation (amount of applied nitrogen, improved varieties, cultural practices) have been incorporated in the models to explain yield variation both singly and in combination with weather-related variables. Separate models were developed for fall-planted (winter) and spring-planted (spring) wheats. Meteorological variation is observed, basically, by daily measurements of minimum and maximum temperatures, precipitation, and tabled values of solar radiation at the edge of the atmosphere and daylength. Two different soil moisture budgets are suggested to compute simulated values of evapotranspiration; one uses the above-mentioned inputs, the other uses the measured temperatures and precipitation but replaces the tabled values (solar radiation and daylength) by measured solar radiation and satellite-derived multispectral scanner data to estimate leaf area index. Weather-related variables are defined by phenological stages, rather than calendar periods, to make the models more universally applicable. The yield models were developed from experimental plot yields and weather data from nearby recording stations. Application of the models on a regional basis is discussed.

ACKNOWLEDGMENTS

Many have contributed to the yield modeling effort discussed in this report. Support and planning by LACIE management and RT&E personnel combined to give this project a single-minded purposeful direction. Knowledgeable scrutiny of progress reports by the technical monitor, Tom Barnett, was greatly appreciated as were critiques by the Yield Advisory Group of LACIE.

Wolfgang Baier and co-workers in the Agrometeorology section of Agriculture, Canada, provided computer programs of their versatile soil moisture budget which gave us a quick start into modeling. Our yield models rely heavily on the pioneering work of George Robertson, particularly his biometeorological time scale and soil moisture budgets, developed from experimental studies in the fifties and sixties. Baier's spring wheat yield model was the first to relate grain yields to weather-related variables defined by phenological stages using data from a large geographic area, and we have followed through on that concept.

The data bank of daily weather observations, plot and regional yields, and other agronomic measurements were painstakingly collected by hundreds of cooperative weather observers, state experiment station personnel, and USDA-SRS employees. Without their initial contribution in the chain of data collection, storage, retrieval, and analysis events; modeling efforts of this magnitude, using data generated over the past half century, could not be undertaken. Though unnamed, we are extremely grateful for their contribution.

The excellent weather data library at Kansas State University, built up under the direction of L. Dean Bark, provided high quality historical meteorological data for initial investigations of the relation of weather to winter

wheat yields in Kansas over a 60-year period. J. M. Ramirez of North Dakota State University provided phenological and plot yield data that allowed us to test some available yield models early in the project. James McQuigg and co-workers at CCEA-NOAA provided regional climatic and yield data which they had compiled. The National Weather Center at Asheville, North Carolina was able to fill our order for historic daily weather close to branch experiment stations in the U. S. Great Plains.

Aid in providing experiment station yield and phenology data, from varietal trials, was given by Kurt Feltner and F. H. McNeal, Montana; J. R. Welsh, Colorado; Richard Frohberg and Ronald Lund, North Dakota; D. G. Wells, South Dakota; August Dreier, Nebraska; Ed Smith, Oklahoma; Earl Gilmore, Texas; Robert Heiner, Minnesota; Dale Sechler, Missouri; G. M. Brown, Illinois; Fred Patterson, Indiana; and Howard Lafever, Ohio.

Ability and skill in computer programming determines the pace at which projects of this nature advance. Students at Kansas State were more than equal to the task. Don Wagner, Steve McFarland, Kenneth Laws, Bob Owens, and James Bagley launched the project in its first year with follow-on programming by Mike Franzblau, Mike Frerichs, and John Olsowski. Jeanne Sebaugh supervised programming activities and gave shape and substance to the complex network of subroutines which produce yield estimates. Individually and collectively, the contributions of these individuals has been tremendous.

Paulette Johnson carried through a comprehensive study of weather and planting rates of winter wheat. She was assisted by Ann Gironella. S. K. Perng contributed theoretical background for the same problem.

Dale Fjell performed a variety of tasks, and kept the project moving forward. He was assisted in information retrieval and data processing tasks by Steve Houser, Sharon Houser, Jean Beaty, Letty Hammerle, Jeanne Baxter, and

Gary Dickson. Betty Skidmore, Pam Barnes, and Kathy Elliott provided excellent clerical and typing services.

Consultations with agronomic specialists were extremely helpful. Agronomists, Elmer Heyne, Ted Walters, Orville Bidwell, and Larry Murphy at Kansas State University provided valuable information on genetics, varieties, crop calendars, soils, and fertilizers. Floyd Smith and Frank Bieberly gave us estimates of nitrogen use on wheat in Kansas. Merle Eversmeyer provided insights on weather and plant diseases. Conversations with Gerald Barger and Richard Stuff of Lockheed Electronics Corporation provided both agronomic and meteorological input. Jack Bond and Duane Umberger, USDA, called our attention to important information related to factors which comprise so-called technology improvements in yield and shared their findings with us. The combined information from these consultations gave us a balanced view of the relative importance of various agronomic and meteorological factors which affect grain yields.

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1.0 INTRODUCTION AND SUMMARY

This document is the final report for Contract NAS9-14282. In the interest of continuity and completeness we have incorporated results obtained under Contract NAS9-14533. All tasks under both contratts have been aimed at producing crop calendars and yield models which could be driven by readily available meteorological and satellite-derived observations, augmented by known climatological and agronomic characteristics of wheat-producing regions.

Our models were developed from historical experimental plot yield data with meteorological measurements taken at nearby weather stations (see Section 2.0). Regional yields, as estimated by the USDA-SRS, were used to determine a mean level adjustment to apply the plot-based models on a regional basis.

To develop a model using weather data from differing climates, and yield data for different varieties of wheat, it was essential to standardize in some sense:

(a) rate of development over particular periods of the calendar,

(b) precipitation effects,

(c) a variety's yielding ability.

For (a), we needed a model to follow plant development (a crop calendar) and to express rates of development in meteorological units rather than calendar days. For (b), we needed a soil-moisture budget to more properly express the differential effect of one inch of precipitation under different climates and at different times. For (c), we needed to express yielding ability in terms of a standard (check) variety to remove yielding ability as a source of variation in model development and then to replace it as a contributing factor to yield determination.

The "standardization" process for (a) was accomplished with Robertson's biometeorological time scale (BMTS)(10). Scalar multipliers were developed to apply the BMTS, originally developed for Marquis spring wheat, to winter wheat climates and varieties (see Section 3.0). No adjustments were made for spring wheat.

For (b), Baier and Robertson's versatile soil moisture budget (VSMB)(3), though developed for spring wheat under Canadian climates, was found to give satisfactory results in the middle of the U. S. Great Plains winter wheat region and was assumed sufficiently accurate for universal application. A description of the VSMB and a budget which uses satellite-derived multispectral scanner data appears in Section 4.0.

For (c), it was necessary to develop varietal yielding ability (VYA) factors for commonly planted winter and spring wheat varieties. Procedures for development and values obtained for VYA's are given in Section 5.0.

Symbols, mathematical forms, and threshold values for the variables which appear in our winter and spring wheat models are shown in Section 6.0. The form and substance of the yield models is given in Section 7.0 together with a discussion on application on a regional basis.

Finally, Section 8.0 shows results of applying the models on a Crop Reporting District (CRD) basis and then aggregating to a state level over a ten-year period in the states of Kansas and North Dakota.

2.0 DATA SET FOR MODEL DEVELOPMENT

To develop a yield model which can be applied with confidence around the globe, it is necessary to obtain yield and associated weather data over a large range of climates. Climates over the U. S. Great Plains do not include all the variations that may be found but do cover a large proportion of those found in wheat-growing areas of the world.

2.1 Yield, phenological, and auxiliary data: source and type.

Throughout the U. S. Great Plains, experimental trials have been conducted yearly to substantiate yielding ability, and other characteristics, of popular wheat varieties and to test new varieties for potential acceptance. These varietal trials are conducted at branch agricultural stations (BAES) associated with land-grant universities. Annual reports from these branch stations flow into the universities and results of varietal trials are made available to the public in various forms.

Results of varietal trials were a primary data source and gave us information, though sometimes incomplete, on the following characteristics for each variety in the test:

a) average plot yields (over two to four replications)

b) planting date

c) heading date

d) amount of added nitrogen

e) cultural practice (fallow, continuous, irrigated).

When available, hail, severity of disease, and insect infestation were recorded but such data were used in an auxiliary capacity only and were not incorporated in the model. Ranges of yields, cultural practices, average planting and heading dates, at each location, are shown in Tables 2.1 and 2.2.

Yields in any given year were averages over three varietal yields, after adjusting each one for yielding ability. Varieties were chosen by examining USDA-SRS data from surveys, conducted within states, measuring percent acreage planted to each variety. The three most popular varieties in a particular time frame (five-year intervals prior to 1969) were selected. Some substitution was inevitable but the procedure reduced the number of varieties while maintaining those that accounted for a major portion of production.

Criteria for deleting a given season from the analysis were:

a) zero yields (drought, winterkill, etc.),

b) occurrence of hail,

c) excessive missing weather data.

Inclusion of zero yields for drought/winterkill for winter wheat would have increased our data by 44 observations. However, since zero yields do not always represent a "true" zero, they were eliminated to avoid distortions of reality.

2.2 Meteorological and climatological data: source and type.

Daily weather records, for stations near the BAES's, were secured from the National Weather Center at Asheville, North Carolina for stations outside of Kansas and from the Weather Data Library at Kansas State University for Kansas locations. Items read off the tapes were daily values of:

a) minimum temperature (°F)

b) maximum temperature (°F)

c) precipitation (inches).

Tables 2.1 and 2.2 show the weather stations and number of seasons used in yield model development for winter and spring wheat, respectively. Also tabled are long-term average daily temperature in January (ADTJ) and average annual precipitation (AAPR) for each location. Both ADTJ and AAPR play important roles in yield and crop calendar models.

Weather elements in the data sets represented climates ranging from cold to warm and dry to wet, with a multitude of combinations between these extremes. Consequently, a large range of values for weather-related variables, individually and jointly, was obtained. Locations in semi-arid regions included droughty years and years favorable to high yields. At some locations, moisture was almost always a limiting factor while at others it was never limiting.

The 1034 location-years used for winter wheat model development provided a wider range of climates than the 306 for spring wheat. In part, this reflects the fact that spring planted wheat is usually limited to areas where ADTJ < 20°F. This agrees with a statement by Hsieh (6) that the -6°C (21°F) January isotherm is a boundary between spring and winter wheat in China. Conversely, fall-planted wheats can be found at locations with ADTJ as low as 10°F and as high as 70°F. In the latter case varieties planted are genetically spring wheats, as vernalization is not required for flowering.

2.3 Application of model on regional basis - USDA yield data.

The experimental plot yields plus associated daily precipitation and temperatures formed the basic data set for developing our winter (spring) wheat yield models on an experimental plot basis. The plot-based models simulate both season-to-season and location-to-location variation. However, on a regional basis, an adjustment is necessary to account for management and productivity (MAP) factors which may have a long-term trend effect and vary with soil factors. In Section 7.0, we describe conversion of yields from a plot basis to yields specific to a given region (strata). For the U. S. Great Plains, this conversion was accomplished by using USDA-SRS yield estimates for a region to determine a mean-level adjustment to apply to the plot-based model estimates.

Table 2.1. Characteristics of locations used in winter wheat model development. (Locations are in descending order by ADTJ‡).

Location	N†	ADTJ‡ (°F)	AAPR§ inches	Range of Yields (bu/A)	Cultural¶ Practice	Ave.‖ PLD	Ave.†† HED
College Station, TX	7	51.3	38.7	6-30	F	10-29	4-13
Denton, TX	20	44.6	32.6	10-46	C	10-25	4-18
Vernon-Chillicothe, TX	12	42.5	25.3	9-35	F	11-1	4-20
Portageville, MO	8	39.3	46.7	14-41	C	9-30	5-1
Sikeston, MO	23	37.4	48.2	12-52	C	10-30	5-6
Stillwater, OK	18	36.9	32.8	6-59	F	10-8	4-30
Clovis, NM	17	36.7	17.9	4-35	F	10-5	5-5
Woodward, OK	22	35.9	25.1	15-52	F	10-9	5-1
Pierce City-Mt. Vernon, MO	21	35.7	44.4	7-47	C	10-7	5-4
Amarillo-Bushland, TX	13	35.3	21.1	5-48	F	10-12	5-8
Goodwell, OK	8	34.5	17.7	2-26	F	10-2	5-10
Columbus, KS	44	34.4	42.3	8-57	C	10-22	5-7
Ripley, OH	12	32.8	40.6	21-41	C	10-10	5-16
Springfield, OH	6	32.1	37.4	32-51	C	10-8	5-20

†N = number of years with useable data.

‡ADTJ = long-term average daily temperature in January.

§AAPR = average annual precipitation.

¶F = previous year fallow, C = previous year cropped.

‖PLD = planting date.

††HED = heading date.

Table 2.1 (continued)

Location	N[†]	ADTJ[‡] (°F)	AAPR[§] inches	Range of Yields (bu/A)	Cultural[¶] Practice	Ave.[‖] PLD	Ave.[††] HED
Vincennes, IN	15	32.0	43.0	24–50	C	10–6	5–16
Columbia, MO	20	31.0	39.4	15–56	C	10–2	5–20
Garden City, KS	38	30.9	18.8	3–46	F	10–2	5–20
Ottawa, KS	3	30.3	37.2	27–39	C	10–30	5–17
Hutchinson, KS	32	30.2	29.0	2–46	C	10–12	5–13
Hays, KS	52	29.5	23.0	5–57	F	10–4	5–21
Farmland, IN	8	29.3	38.9	40–58	C	9–24	5–20
Columbus	19	29.0	36.6	24–50	C	10–5	6–4
Colby, KS	42	28.8	18.6	3–67	F	9–23	5–23
Carpenter, OH	25	28.8	41.8	10–54	C	10–6	5–26
Tribune, KS	36	28.3	16.8	1–60	F	9–23	6–9
Manhattan, KS	61	28.1	31.7	12–56	C	10–7	5–16
Canfield, OH	22	27.5	34.0	18–59	C	10–6	5–30
Wooster, OH	28	27.4	38.1	21–51	C	10–2	6–10
Urbana, IL	38	27.1	36.6	18–61	C	9–27	5–21
Custar, OH	18	27.1	35.3	20–65	C	10–6	5–27
Vickery, OH	16	27.0	35.0	13–68	C	10–4	6–8
Yellow Jacket, CO	3	26.5	13.3	18–28	F	10–18	6–16
Julesburg, CO	5	26.4	16.8	23–48	F	9–23	5–30
Mankato, KS	12	25.9	24.9	12–41	C	10–6	5–25
Lafayette, IN	27	25.7	36.8	12–61	C	10–5	5–24
Lincoln, NE	29	25.5	27.3	15–53	C	10–1	5–18
Akron, CO	25	25.1	17.7	10–43	F	9–19	6–3

Table 2.1 (continued)

Location	N[†]	ADTJ[‡] (°F)	AAPR[§] inches	Range of Yields (bu/A)	Cultural Practice[¶]	Ave. PLD[‖]	Ave. HED[††]
Bethany-Spikard, MO	14	25.0	33.8	19-56	C	9-27	5-20
Wanatah, IN	15	24.7	36.0	36-70	C	9-29	5-27
North Platte, NE	21	24.0	20.7	20-61	F	9-22	5-29
Mead, NE	1	23.7	27.8	33-44	F	10-5	5-29
Archer, WY	10	23.1	14.7	10-37	F	9-12	6-13
Alliance, NE	13	22.9	16.7	8-53	F	9-13	6-7
Moccasin, MT	9	20.8	14.0	27-46	F	9-11	6-19
Ames, IA	18	19.5	31.8	10-62	C	9-24	5-31
Sheridan, WY	8	18.7	16.4	14-56	F	9-11	6-19
Beresford, SD	6	17.0	23.6	11-35	C	9-23	6-3
Presho, SD	4	17.0	16.5	26-37	F	9-16	6-5
Havre, MT	15	16.2	12.3	9-50	F	9-9	6-11
St. Paul, MN	20	14.6	24.7	17-46	C	9-13	6-4
Waseca, MN	19	13.6	28.3	17-49	C	9-12	6-11
Brookings, SD	9	13.4	19.8	5-42	C	9-16	6-13
Dickinson, ND	14	10.4	15.5	3-33	F, C	9-16	7-4
Williston, ND	8	10.0	14.1	9-34	F	9-11	6-20
Minot, ND	10	7.0	15.4	17-55	F	9-12	7-2
Grand Rapids, MN	15	6.1	25.7	6-46	C	9-13	7-13

Table 2.2. Characteristics of locations used in spring wheat model development. (Locations are in descending order by ADTJ‡).

Location	N†	ADTJ‡ (°F)	AAPR§ inches	Range of Yields (bu/A)	Cultural¶ Practice	Ave.‖ PLD	Ave.†† HED
Moccasin, MT	33	20.8	14.0	10–38	F	4–30	7–8
Beresford, SD	7	17.0	23.6	4–29	C	4–13	6–14
Havre, MT	32	16.2	12.3	7–35	F	4–23	6–25
Bison, SD	4	15.8	14.2	19–26	F	4–28	7–1
St. Paul, MN	8	14.6	24.7	24–37	C	4–23	6–20
Rosemount, MN	10	14.6	24.7	12–39	C	4–21	6–21
Waseca, MN	15	13.6	28.3	11–48	C	4–20	6–24
Brookings, SD	14	13.4	19.8	11–36	C	4–17	6–24
Dickinson, ND	32	10.4	15.5	1–48	F	5–2	7–4
Williston, ND	11	10.0	14.1	14–32	F	5–6	6–30
Eureka, SD	10	10.0	16.6	11–35	C	4–27	6–27
Morris, MN	23	8.0	22.3	19–41	C	4–27	6–22
Minot, ND	25	7.0	15.4	8–46	F	5–4	7–4
Grand Rapids, MN	14	6.1	25.7	6–54	C	5–5	7–6
Fargo, ND	14	5.5	18.3	9–52	F	4–26	6–25
Crookston, MN	24	4.0	20.2	15–53	C	4–27	6–26
Langdon, ND	30	1.0	17.6	17–58	F	5–6	7–7

†N = number of years with useable data.

‡ADTJ = long-term average daily temperature in January.

§AAPR = average annual precipitation.

¶F = previous year fallow, C = previous year cropped.

‖PLD = planting date.

††HED = heading date.

3.0 ADJUSTING ROBERTSON'S BMTS TO WINTER WHEAT

To bring yield and weather data from varied climates into a single model, it is necessary to measure the effect of weather-related variables (WRV's) in different stages of plant development rather than over fixed calendar periods. The most sophisticated approach to this problem was taken by Baier(1). The effects of a basic set of weather-related variables were considered to change daily and the magnitude of change was made dependent on the stage of development as measured by Robertson's Biometeorological Time Scale (BMTS) (10). To follow, in principle, Baier's approach to modeling, we investigated the applicability of Robertson's BMTS to winter wheat environments and varietal maturities. Methodology, statistical analysis, and rationale are discussed in Appendix A. Here, we present major findings.

3.1 Biases in application of an unadjusted BMTS.

Robertson's BMTS was developed from observations on Marquis spring wheat grown in Canadian climates. Two sources of biases (differences between observed and simulated results) might be anticipated when the model is applied to winter wheat. The first is due to differing maturation rates among winter wheat varieties. If the BMTS gives unbiased results for Turkey, a very late maturing variety, it would have to be biased for Triumph class varieties which mature 8 - 10 days earlier. The second source of bias relates to the wide range of climates in which winter wheat is grown. One might anticipate that if the BMTS were unbiased for a Texas climate, where a dormancy period is almost nonexistent, then it might well be biased when applied in North Dakota where the dormancy period is four to five months.

Our investigation began by programming Robertson's equations to simulate daily increments of development (DID) from planting to ripe stages. Application was made to selected locations using only those seasons when heading dates for both early and late maturing varieties were known. Results of applying the BMTS in an unadjusted (U_BMTS) mode are shown in Table 3.1.

With the exception of a few anomalies (e.g., Tribune, Kansas), magnitudes of the biases increase as one moves from colder/wetter to warmer/drier climates. The range of -15 to +7 days is based on differences between simulated and late maturing varieties. For early maturities the range would be -10 to +16 days. The two climatic variables chosen to help remove biases at specified locations were long-term average daily temperature in January (ADTJ) and average annual precipitation (AAPR). Arguments for use of these two variables are given in Appendix A.

3.2 Computation of adjustment factor.

Following our initial study of biases using the U_BMTS, we extended the computer program to simulate development from emergence (rather than planting) to heading for different rates of the DID.

Increased rates were simulated by multiplying DID's by factors greater than one and decreased rates by factors less than one.

In essence, the BMTS was accelerated or decelerated from emergence-to-heading till zero bias for the sample data was attained. At most, seven multipliers were obtained for a given location to attain zero bias for development rates associated with each of the following: early, mid-early, mid-late, late maturing varieties, and varieties popular in 1950, 1960, 1970. Seven regression equations were determined by regressing multipliers against ADTJ and AAPR. Details are given in Appendix A.

Table 3.1 Comparison of average heading dates for early maturing varieties, late maturing varieties, and a simulated crop calendar (U_BMTS).

Location	No. of Seasons	Ave. Heading Dates (Julian Day) Obs. (Early) (1)	Obs. (Late) (2)	U_BMTS (3)	Bias (Days) (3)-(2)
Waseca, MN	7	159	164	149	-15
Grand Rapids, MN	4	171	175	164	-11
Lincoln, NE	16	144	152	142	-10
Dickinson, ND	4	174	177	169	-8
Wanatah, IN	15	148	154	147	-7
Columbia, MO	7	135	144	137	-7
Tribune, KS	14	143	154	147	-7
Urbana, IL	6	137	147	141	-6
Manhattan, KS	11	133	142	137	-5
Lafayette, IN	15	143	152	148	-4
Wooster, OH	4	147	154	150	-4
Alliance, NE	8	157	163	161	-2
Colby, KS	16	139	147	145	-2
Columbus, KS	18	123	134	133	-1
Garden City, KS	11	135	146	145	-1
Amarillo, TX	18	126	137	137	0
North Platte, NE	9	152	157	158	+1
Hays, KS	33	135	144	145	+1
Woodward, OK	20	121	130	131	+1
Hutchinson, KS	22	126	137	139	+2
Akron, CO	12	147	157	160	+3
Goodwell, OK	15	131	138	141	+3
Denton, TX	15	107	117	120	+3
Hesperus, CO	7	165	171	177	+6
Ft. Collins, CO	10	151	160	167	+7

For application, in the U. S. Great Plains, we recommend use of the following equation to calculate a multiplier (M_{70}) to apply to a given location (region, strata):

$$M_{70} = .5684 + (.025081)\mathrm{ADTJ} - (.006139)\mathrm{AAPR},$$

where

M_{70} = a multiplier for a varietal maturity class defined by varieties popular in the U. S. Great Plains in 1970,

ADTJ = long-term average daily temperature in January,

AAPR = average annual precipitation.

Table A.1 in Appendix A exhibits values of M_{70} for a range of ADTJ and AAPR found in the Great Plains. The multiplier M_{70} was systematically used for all years and locations to derive weather-related variables (WRV's) specific to given phases of winter wheat development.

The most important contribution of the BMTS to yield model development was its usefulness in "standardizing" weather inputs from diverse climates so that a single model could be developed. Of secondary importance was simulation of season-to-season variation in development at a given location. Additional accuracy would have been welcome but it was not necessary to pinpoint major crop stages to within a day or two. Appendix A contains tables showing the precision of estimates of heading dates using the BMTS adjusted by M_{70} (A_BMTS). A test of the model for 186 location-years showed 83% of the simulated headings within ± 7 days of the observed heading dates.

3.3 Other adjustments to Robertson's BMTS.

In applying the BMTS to winter wheat, we found it necessary to make some minor modifications. The first involved the effect of maximum temperature (TX) from simulated emergence to jointing. In the original BMTS, the effect was quadratic with a concave upward graph. For TX < 23.6°F (-4.7°C) the BMTS gave positive increments of development. This was modified to give zero contribution from the terms involving TX if TX < 23.6°F.

The second adjustment also involved the simulated emergence to jointing phase. Occasional seasons arose when simulated jointing occurred prior to dormancy. Since this is physiologically impossible for winter wheat some adjustment was required. Accordingly, an algorithm was introduced into the program so that if BMTS $\geq$ 1.85 (BMTS = 2.0 at jointing) on any day prior to January 1, then the BMTS value was reset to 1.80 and continued to build up from that point. The effect of this modification is shown in Table 3.2.

3.4 Computations in Robertson's BMTS.

A daily increment of development (DID) in Robertson's BMTS (unadjusted) is computed as follows:

$$DID = V_1 * (V_2 + V_3),$$

where

$$V_1 = a_1(DL - a_0) + a_2(DL - a_0)^2,$$

$$V_2 = b_1(TX - b_0) + b_2(TX - b_0)^2,$$

$$V_3 = c_1(TN - b_0) + c_2(TN - b_0)^2,$$

with

DL = daylength, TX = maximum temperature, TN = minimum temperature, a_o and b_0 (threshold values), and a_1, a_2, b_1, b_2, c_1, c_2 vary from phenology phase to phase as shown in Table 3.3 in scientific notation ($.12E+02 = .12*10^2$).

The quantities V_1, V_2, and V_3 are forced to be zero or positive. If any one is negative, it is set equal to zero. If $V_1 = 0$, then DID = 0; but that is not necessarily true of V_2 or V_3.

The quantity DL may be read from tables but we have used an interpolation formula developed by Stuff (12). The formula reads as follows:

$$DL = 12.14 + [3.37 \tan(\pi X/180)] \cos(0.0172N - 1.95),\ 0 \le X \le 40°$$

$$= 12.25 + [1.6164 + 1.7643 \{\tan(\pi X/180)\}^2] \cos(0.0172N - 1.95),\ X > 40°,$$

where

X = latitude,

N = climatological day number (March 1 = 1).

The entries in Table 3.3 give DID values equivalent to those that would be obtained by using the coefficients shown in Robertson's paper (10, p. 211) even though the entries in the two tables differ. This is due to the multiplicative form of the model. This can be verified by multiplying out and comparing coefficients for like terms.

Table 3.2 Effect of altering† BMTS computer routine to force "jointing" to occur after January 1.

	Year	Jointing Date (Mo./Day) Before	After	Heading Date (Mo./Day) Before	After
Colby, KS	1938	11/10	3/13	5/11	5/12
	1954	11/16	2/26	5/16	5/16
	1955	10/21	4/1	5/9	5/13
	1963	12/7	3/25	5/8	5/9
	1964	10/30	4/11	5/18	5/20
	Range††		3/15 to 4/30		
Columbia, MO	1962	10/21	3/9	5/10	5/10
	1963	10/19	3/13	5/6	5/7
	1964	11/18	3/3	5/7	5/7
	1972	1/11	3/11	5/12	5/13
	Range		3/9 to 4/13		
Pierce City, MO	1955	1/4	2/26	4/27	4/28
	1963	12/28	3/4	4/25	4/25
	1965	1/23	2/15	5/2	5/2
	1966	11/21	3/9	5/5	5/5
	1971	1/21	2/27	5/3	5/4
	Range		2/2 to 4/4		

† If BMTS $\geq$ 1.85 (Robertson scale) before January 1 then BMTS reset to 1.80. On January 1 it will have between 0.15 and 0.20 units of development before it reaches 2.00 (jointing).

†† Range of simulated jointing dates for years at station when correction in BMTS was not needed.

Table 3.3 Coefficients for Robertson's BMTS.

	Phases of Development[†]				
	P to E	E to J	J to H	H to D	D to R
a_0	.1000E+20	.8413E+01	.1093E+02	.1094E+02	.2438E+02
a_1	-.1419E-19	.5581E-01	.2613E-01	.2021E-01	-.2165E-01
a_2	0	0	-.1701E-02	-.1192E-02	0
b_0	.4437E+02	.2364E+02	.4265E+02	+.4218E+02	.3767E+02
b_1	.7652E-01	-.6324E-01	.1047E-01	.1688E-01	.3543E-02
b_2	-.1571E-02	.9050E-03	0	0	0
c_1	.6857E-01	.6601E-02	.1396E-01	.2136E-02	.1811E-01
c_2	-.1597E-02	-.7710E-04	0	0	0

†P = planting, E = emergence, J = jointing, H = heading, D = dough, R = ripe.

4.0 SOIL MOISTURE BUDGETS

A soil moisture budget is a necessary tool to model yields. The precipitation-evapotranspiration sequence, when adequately simulated, provides a means of detecting when plant stress occurs due to lack of soil moisture. In general, one expects that yield expressed as a function of soil moisture stress would be more universally applicable than yield expressed as a function of precipitation.

4.1 Baier and Robertson's VSMB

Our search for a soil moisture budget, which could be operated with daily meteorological inputs of precipitation and minimum and maximum temperatures (PR, TN, TX), led to one developed by Baier and Robertson (3) and known as the versatile soil moisture budget (VSMB). The VSMB has a number of appealing characteristics not the least of which is a potential for universal application. Input requirements were sufficiently unrestrictive to allow us to simulate historical moisture conditions.

The most recent description of the VSMB is given in a technical bulletin by Baier, et al. (5). To operate the VSMB, it is necessary to assume values for some of the parameters (e.g., water-holding capacity of soil in the root zone). Values we have assumed together with the main formulas in the VSMB are shown in Appendix B. Discussion to follow will be limited to general characteristics of the VSMB.

4.1.1 Potential evapotranspiration (PE). Estimation of PE in the VSMB is based on work by Baier and Robertson (2) and Baier (4). Different formulas are given for estimating PE, dependent on amount of input data available. We chose to use one requiring minimal daily meteorological measurements, namely, TN, TX, and Q_o where Q_o = total solar radiation in cal cm^{-2} falling on a horizontal surface at the top of the atmosphere during one day. Tabled values of Q_o are readily available (11).

4.1.2 Actual evapotranspiration (AE). Daily AE values are a sum of AE values over six moisture zones. The AE values for each zone are functions of: (1) a crop coefficient, (2) a ratio of plant-available soil moisture to capacity of available water in the zone, (3) an adjustment factor for availability of moisture under various dryness conditions, (4) an adjustment factor accounting for effects of varying PE rates on the AE/PE ratio, and (5) the value of PE itself. The first four factors take on values specific to each zone while daily values for the last one are constant for all zones.

4.1.3 Precipitation losses. Not all precipitation becomes a part of the budget. Precipitation losses are of three types. One is from run-off and this is simulated by allowing only a portion of the moisture from rainfall to infiltrate the soil. The amount of loss is made to depend on total amount of rainfall for the day and the ratio of plant-available water to capacity of available water in the top zone as derived by Linsley, Kobler, and Paulus (8). The second type of loss simulates drainage when the 24-hour precipitation exceeds the total of AE, runoff, and the sum of moisture deficits over all zones. The third type of loss, due to losses of moisture from a snow pack, is simulated by a snow budget.

4.1.4 Fill and withdrawal algorithms. The algorithm for moisture entering the soil profile specifies that the top zone is first filled to field capacity before water infiltrates to the second zone. The same procedure is followed for succeeding zones. There is a provision for modifying this algorithm to allow for some infiltration into a lower zone before the zones above it reach field capacity but we have not used this latter option in operating the VSMB.

Increases to the VSMB from snow are simulated by a separate snow budget. The snow budget simulates gains in soil moisture when snow melts and losses of potential gains due to blowing and evaporation of snow and runoff.

For withdrawal, AE values are calculated for each zone as indicated in Section 4.1.2. One adjustment, not discussed in 4.1.2, simulates larger rates of absorption of water by roots in the lower zones in periods of drought when the lower zones may still be quite moist relative to the top layers. The adjustment involves a redistribution of the crop coefficients.

4.1.5 Stored moisture. The VSMB is divided into six zones for budgeting purposes. Simulated evapotranspiration is restricted to the top three zones in the planting-to-jointing phase and when the land is idle. The bottom three zones simulate a reservoir for storage of water to be used in the jointing-to-ripe phases of development when roots are deep enough to draw on moisture reserves. In our yield model we use the contents of zones 4 and 5 to define variables related to lack of stored moisture at various stages of development.

4.1.6 Continuous cropping and fallowing. The VSMB simulates soil moisture levels not only during the growing season but also while the land is idle. Consequently, during the growing season one can simulate either continuous cropping or fallow cropping or both and we have programmed the VSMB accordingly. Our computer program carries three budgets simultaneously, two related to fallowing and one for continuous cropping.

Two budgets are necessary to simulate fallowing because during a growing season one of the budgets simulates conditions under a crop while the other simulates the fallow period. During fallowing, no water is removed from the bottom three zones of the VSMB so there is additional opportunity to increase stored moisture for the next season. Contents of the two fallow-related budgets are switched at planting time.

4.1.7 Initial soil moisture levels. To apply the VSMB it is necessary to specify contents for each of the six zones as of the beginning date of processing which is usually, but need not be, a simulated planting date. Contents of the lower three zones are seldom at capacity at planting time in semi-arid regions. For the U. S. Great Plains, the problem is minimal since we have already processed many years at over 60 locations and, with the aid of continuous weather records, new processing can begin on the date when our previous processing terminated.

One solution for areas outside the U. S. Great Plains is to begin processing two years (where fallowing is practiced) or one year (for continuous cropping) prior to the season for which a yield estimate is to be made. The effect of this is to reduce the contents of the lower three zones due to cropping the first year and, for fallowing, to allow the lower zones to refill or stay at low levels if dry conditions prevailed.

Where prior weather data are unavailable, it will be necessary to estimate initial contents on the basis of average annual precipitation and any precipitation information available on the year prior to the season of interest. Experience with Great Plains data will be helpful in this regard.

4.2 Tanner, Ritchie, Kanemasu (T-R-K) Model

Kanemasu applied the work of Tanner and Jury (13), Priestley and Taylor (9), and Jury and Tanner (7) to winter wheat and estimated parameters in the various models using lysimetric data (see Appendix C). In the T-R-K model, evapotranspiration is decomposed into its two components: evaporation and transpiration and each component is estimated separately.

An important element in the T-R-K model is the use of leaf area index (LAI) to estimate both evaporation and transpiration. Complementary to this work, Kanemasu has related LAI to multispectral scanner (MSS) band ratios (4/5, 4/6, 4/7, 5/6) using data generated from Landsat I and II (see Appendix D).

Kanemasu's work has resulted in a method of simulating actual and potential evapotranspiration under winter wheat using daily inputs of (a) solar radiation, (b) minimum and maximum temperature, (c) precipitation, and (d) MSS band ratio values from Landsat satellites. This work provides (a) an alternative to the VSMB for estimating the AE/PE ratio used in the yield models presented in Section 7.0, and (b) a direct input into growth and yield models now under development by Kanemasu.

4.3 Comparison of VSMB and T-R-K

(a) For potential evapotranspiration, both the VSMB and T-R-K require daily minimum and maximum temperature; but the VSMB, as we have applied it, uses tabled daily values of solar radiation at the edge of the atmosphere; the T-R-K requires daily values of measured solar radiation at ground level.

(b) For actual evapotranspiration, both models use a measure of reduced transpiration due to soil dryness as measured by the ratio of plant-available water to water-holding capacity and both measure actual evapotranspiration as a proportion of potential. However, the method of measuring this proportion is different. The VSMB makes the proportion a function of crop coefficients, the ratio of contents to capacity, and ($PE-\overline{PE}$) while the T-R-K makes the proportion a function of leaf area index (LAI).

4.4 Agreement of soil moisture budgets

Kanemasu applied the T-R-K model to a Finney County, Kansas and a Riley County, Kansas site, the former in a semi-arid climate, the latter in a sub-humid climate. The VSMB was applied over the same period. Cumulative evapotranspiration values are plotted against calendar dates, from planting through ripe, in Figure 4.1.

The agreement between the two budgets is good, giving credence to the use of the VSMB in winter wheat environments and to use of the T-R-K model as an alternative to the VSMB for soil moisture budgeting.

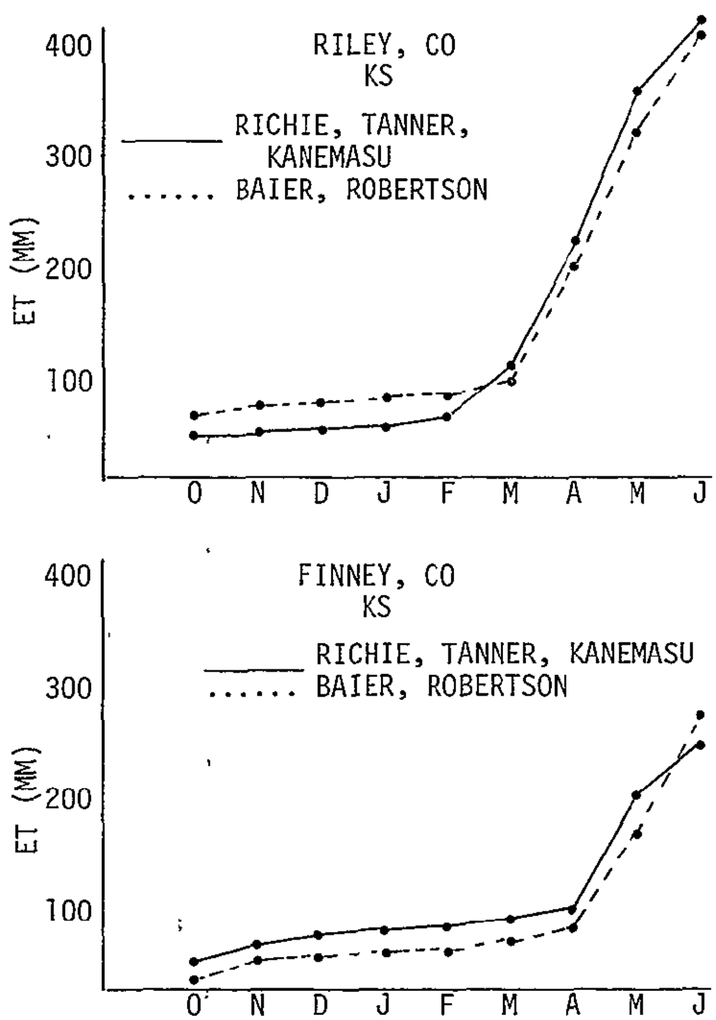

Figure 4.1 Comparison of VSMB and R-T-K for Riley and Finney Counties, KS.

5.0 VARIETAL YIELDING ABILITY

One of the first problems encountered in using yield data over many seasons and locations is variation due to differences in varietal yielding ability (VYA). One could restrict the data set to a single variety but that limits the number of observations severely. The other alternative is to assign each variety, used in model development, a VYA factor which measures its yielding ability against that of some standard (check) variety. The latter alternative also provides a basis for determining the contribution of varietal improvement to yield increases over time thus isolating this component of technology. We have chosen the second alternative and in this section we describe the procedure used to determine the VYA's shown in Table 5.1 (winter wheat) and Table 5.2 (spring wheat).

Data, for determining VYA's, were the same as used for model development; namely, yields from varietal trials at BAES's. For winter wheat, we found that the varieties, Pawnee and Comanche, appeared in more seasons at more locations than other varieties and were generally equally adaptive and productive. They were given VYA values of 1.00. For spring wheat and durums the VYA for Thatcher was set equal to 1.00.

Table 5.1. Winter wheat yielding ability (VYA) factors.

Variety Name	Code	VYA	Year Released	Released by
Turkey	TURK	.85	1875	
Kharkof	KHAR	.86	1900	
Fulcaster	FULC	.86	1830-71	
Fultz	FULT	.87	1871	
Early Premium	E_PR	.87	1830-71	
Michigan Amber	MI_A	.88	1830	
Trumbull	TRUM	.89	1916	Kansas
Kanred	KANR	.91	1917	Kansas
Blackhull	BLAC	.91	1917	Kansas
Parkoff	PARF	.93	1915	Indiana
Tenmarq	TENM	.93	1932	Kansas
Vigo	VIGO	.97	1946	Indiana
Fairfield	FAIR	.97	1942	Indiana
Yogo	YOGO	.98	1932	Montana
Ponca	PONC	.99	1951	Kansas
Pawnee	PAWN	1.00	1943	Kansas
Comanche	COMA	1.00	1942	Kansas
Chiefkan	CHFK	1.01	1935	Kansas
Karmont	KARM	1.02	1921	Montana
Wichita	WICH	1.02	1944	Kansas, Texas
Kaw 61	KW61	1.02	1965	Kansas
Triumph	TRIU	1.02	1940	Oklahoma
Early Blackhull	E_BL	1.03	1933	Kansas

Table 5.1 (continued) Winter wheat.

Variety Name	Code	VYA	Year Released	Released by
Clarkan	CLAR	1.03	1934	Kansas
Super Triumph	S_TR	1.03	1957	Oklahoma
Thorne	THOR	1.04	1938	
Westar	WEST	1.04	1944	Texas
Agent	AGEN	1.04	1967	oklahoma
Cheyenne	CHEY	1.05	1933	Nebraska
Nebred	NEBR	1.05	1938	Nebraska
Warrier	WARR	1.05	1960	Nebraska
Concho	CONC	1.06	1954	Oklahoma
Bison	BISO	1.06	1956	Kansas
Kiowa	KIOW	1.06	1950	Kansas
Tascosa	TASC	1.07	1959	Texas
Guide	GUID	1.07	1967	Nebraska
Omaha	OMAH	1.07	1960	Nebraska
Parker	PARK	1.08	1966	Kansas
Ottawa	OTTA	1.09	1960	Kansas
Seneca	SENE	1.09	1950	Ohio
Kaw	KAW	1.10	1960	Kansas, Oklahoma
Improved Triumph	I_TR	1.10	1944	Oklahoma
Sturdy	STUR	1.10	1966	Texas
Butler	BUTL	1.10	1947	Ohio
Hume	HUME	1.11	1967	South Dakota
Knox	KNOX	1.12	1953	Indiana

Table 5.1 (continued) Winter wheat.

Variety Name	Code	VYA	Year Released	Released by
Triumph 64	TR 64	1.13	1964	Oklahoma
Monon	MONO	1.14	1959	Indiana
Caddo	CADD	1.14	1963	Texas
Eagle	EAGL	1.14	1971	Kansas
Minter	MINT	1.15	1948	Minn. S. Dakota
Winalta	WINA	1.15	1961	Canada
Gage	GAGE	1.15	1963	Nebraska
Lancer	LANC	1.15	1963	Nebraska
Winoka	WINO	1.15	1968	South Dakota
Danne (D129-16)	DANN	1.15	1971	Oklahoma
Pronto	PRON	1.15	1970	Kansas
Scout	SCOU	1.16	1963	Nebraska
Scout 66	SC66	1.17	1967	Nebraska
Knox 62	KX62	1.19	1962	Indiana
Benhur	BENH	1.21	1966	Indiana
Dual	DUAL	1.23	1955	Indiana
Sage	SAGE	1.23	1973	Kansas
Centurk	CENT	1.23	1971	Nebraska
Redcoat	REDC	1.24	1960	Indiana
Fulton	FULT	1.28	1964	Ohio
Arthur 71	AR71	1.34	1971	Indiana
Arthur	ARTH	1.36	1968	Indiana

Table 5.2. Spring wheat and durum varietal yielding ability (VYA) factors.

Variety Name	Code	VYA	Year Released
Marquis	MARQ	.89	1907
Reward	REWD	.92	1928
Pentad	PNTD	.93	1911
Rescur	RSCU	.94	1947
Ceres	CERS	.97	1926
Conley	CNLY	.97	1960
Thatcher	TCHR	1.00	1934
Pilot	PILT	1.00	1939
Regent	RGNT	1.00	1939
Chinook	CHNK	1.01	1964
Carleton	CRLT	1.01	1943
Mindum	MNDM	1.03	1917
Justin	JSTN	1.03	1963
Mida	MIDA	1.05	1944
Renown	RENN	1.06	1939
Hercules	HERC	1.07	1968
Rival	RIVL	1.08	1939
Cadet	CDET	1.08	1946
Pembina	PEMB	1.09	1959
Ramsey	RMSY	1.09	1956
Premier	PREM	1.10	1938
Leeds	LEDS	1.10	1966

Table 5.2 (continued) Spring wheats and durums.

Variety Name	Code	VYA	Year Released
Polk	POLK	1.12	1968
Kubanka	KUBK	1.12	1909
Steward	STEW	1.13	1943
Redman	RDMN	1.13	1945
Chris	CRIS	1.13	1965
Fortuna	FORT	1.13	1966
Selkirk	SELK	1.13	1955
Rushmore	RUSH	1.14	1949
Lee	LEE_	1.14	1951
Langdon	LANG	1.14	1956
Canthatch	CANT	1.15	1959
Crim	CRIM	1.15	1963
Rolette	ROLT	1.15	1972
Bounty 208	BNTY	1.17	1973
Waldron	WALD	1.17	1969
Ward	WARD	1.18	1972
Wells	WELL	1.18	1960
Sentry	SNTY	1.19	1965
Manitou	MANT	1.19	1965
Lark	LARK	1.23	1971
Lakota	LKTA	1.24	1960
Era	ERA	1.26	1970

5.1 Comparison of pairs of varieties

The first step in computing VYA's involved comparing each winter (spring) wheat variety with every other winter (spring) wheat variety. Results are shown in Table E.1 (winter wheat) and Table E.2 (spring wheat) in Appendix E. The entries in the table are values of V_{ij} (i = row, j = column):

$$V_{ij} = n_{ij}^{-1} \sum_{h=1}^{n_{ij}} (Y_{ih}/Y_{jh})$$

where

V_{ij} = average of ratio of yields of variety i to variety j computed over n_{ij} location-years,

Y_{ih} = yield of variety i in location-year h,

Y_{jh} = yield of variety j in location-year h,

n_{ij} = number of location-years in which variety i and variety j appeared in the same varietal test.

No ratios were included in calculating V_{ij} for which either yield was less than 1.0 bushel/acre. Entries in Tables E.1 and E.2 were limited to the cases where $n_{ij} \geq 20$ and/or the standard error of V_{ij} was less than or equal to 0.05 and $n \geq 4$. Both restrictions were aimed at reducing the variance of our estimates of VYA's.

Ratios of yields were preferred to differences as an expression of the superiority of one variety over another. Inspection of raw data suggested that the difference between presently used varieties and older varieties (e.g. Turkey) were larger in good yielding years than in poor years.

5.2 Procedure for Estimating VYA

Let s denote a standard variety. We considered two different estimates of VYA for variety i. The first was V_{is} itself. The second was

$$\bar{V}_{is} = n_i^{-1} \sum_{k=1}^{n_i} V_{ik} * V_{ks},$$

where

n_i = number of cases for which both V_{ik} and V_{ks} satisfied one of both the following conditions: (a) the sample size was $\geq$ 20, (b) the standard error of V values was $\leq$ 0.05 and the sample size was $\geq$ 4.

The quantity, $\bar{V}_{is}$ provided a means of estimating VYA for variety i without the benefit of varietal tests that contained both varieties i and s.

As an example, from Table E.1 we have

$$\begin{aligned}
\bar{V}_{FULZ,\ PAWN} &= V_{FULZ,\ TRUM} * V_{TRUM,\ PAWN} \\
&+ V_{FULZ,\ TENM} * V_{TENM,\ PAWN} \\
&+ V_{FULZ,\ VIGO} * V_{VIGO,\ PAWN} \\
&+ V_{FULZ,\ FAIR} * V_{FAIR,\ PAWN} \\
&+ V_{FULZ,\ SENE} * V_{SENE,\ PAWN} \\
&+ V_{FULZ,\ REDC} * V_{REDC,\ PAWN}, \\
\bar{V}_{BULZ,\ PAWN} &= (.94)(.94) + (.93)(.88) + (1.00)(1.00) \\
&+ (.88)(.97) + (.79)(1.21) + (.88)(1.03) \\
&= 0.90.
\end{aligned}$$

Other considerations led to a final assignment of VYA = .87 for FULZ = Fultz as shown in Table 5.1.

Final assignment of VYA values involved some subjective judgment. First, VYA values were established for varieties with large sample sizes (Turkey, Triumph, Scout, Arthur for winter wheat; Marquis, Selkirk, Mindum, Lee, Wells, Era for spring wheat and durums). Second, all other varieties had to have VYA values that fit between the values previously established. Third, values for V_{is} and $\bar{V}_{is}$ helped to establish an initial ordering; and this was followed by rearrangements to make results consistent (if V_{ij} was significantly greater than 1.00, then the VYA for variety i should be greater than that for variety j).

Finally, since the rows and columns of Tables E.1 and E.2 are ordered by VYA values, the V_{ij} values should tend to increase as you read down columns, decrease as you read across rows, and elements near the diagonal should be close to 1.00.

6.0 VARIABLES IN YIELD MODELS

In this section, we define the symbols, mathematical forms, and threshold values for the variables which appear in our winter and spring wheat yield models.

6.1 Definitions of Variables

Symbols for variables have been chosen to designate both a variable and either a stage, or phase between stages, of crop development to which the given variable applies. Thus, SSM_s, for s = J, would be stored soil moisture deficits at simulated jointing and SM_rs for r = F, s = H is a measure of soil moisture deficits between simulated flag leaf and heading stages.

Symbols (letters used) for particular points on Robertson's BMTS are given below. The names (letters) for the stages designated by 1.5, 2.5, and 3.5 were not a part of the BMTS. They have been chosen more for ease of communication than for the closeness of the relation between the BMTS values and physiological occurrences.

Robertson's BMTS	Approximate Stage (r or s)	Robertson's BMTS	Approximate Stage (r or s)
0.0	Planting	3.0	Heading
1.0	Emergence	3.5	Milk
1.5	Tillering	4.0	Dough
2.0	Jointing	5.0	Ripe
2.5	Flag Leaf		

Main Effects

1)	Stored soil moisture deficits at stage s	SSM_s
2)	Square of SSM_s	SSMSQ_s
3)	Soil moisture deficit between stages r and s	SM_rs
4)	Square of SM_rs	SMSQ_rs
5)	Average daily minimum temperature between stages r and s	ATN_rs
6)	Average daily maximum temperature between stages r and s	ATX_rs
7)	Average daily minimum temperature degree-days over 50°F between stages r and s	T50_rs
8)	Average daily maximum temperature degree-days over 86°F between stages r and s	T86_rs
9)	Precipitation between stages r and s	PR_rs
10)	Excessive precipitation between stages r and s	XPR_rs
11)	Average daily range of temperatures between stages r and s	RT_rs
12)	Long-term average daily temperature during January	ADTJ
13)	Square of ADTJ	ADTJSQ

14) Amount of added nitrogen — NI

15) Wheat planted on fallowed soil — FL (= 0 or 1)

Interactions

16) T50_rs * PR_rs — T50PR_rs

17) ADTJ * SM_rs — JTSM_rs

18) ADTJ * SMSQ_rs — JTSMQ_rs

19) FL * ADTJ — FLJT

20) FL * ADTJSQ — FLJTSQ

21) NI * XPR_rs — NIXPR_rs

22) ADTJ * NI * XPR_rs — JNIXP_rs

Other Basic Variables

23) Julian day (D) when stage s is reached — D_s

24) Number of calendar days from stage r up to stage s = (D_r) - (D_s) — D_rs

25) Combined contents of zone 4 and 5 in VSMB at stage s — CNTNS_s

26) Minimum and maximum temperature and precipitation on day d — TN_d, TX_d, PR_d

27) Simulated actual and potential evapotranspiration on day d — AE_d, PE_d

6.2 Mathematical forms and threshold values.

All sums (Σ) in the formulas to follow indicate a summation of values over Julian days (d) from stage r to one day before stage s where r and s are designated in the symbol used to specify the variable of interest. Thus SM_JF involves a summation of AE and PE values over the days involved in simulated jointing (BMTS = 2.0) to simulated flag leaf (BMTS = 2.5).

Another symbol, $(\ )^+$ or $[\ ]^+$, is used frequently to designate that the function inside the parentheses (brackets) can take on values that are zero or positive. Thus

$(F_d)^+ = F_d, \quad \text{if } F_d > 0$

$\quad\;\; = 0 \quad \text{if } F_d \leq 0.$

Formulas for calculating AE_d and PE_d, which appear below are in Appendix B.

(1) $SM\_rs = [1 - (\Sigma AE_d/\Sigma PE_d)/\alpha_1]^+$

Stages (rs):	PE	ET	TJ	JF	FH	FH	HM	MR
Threshold (α_1):	0.5	0.6	0.7	0.8	0.8	0.9	0.9	(Winter and Spring Wheat)

(2) $SSM\_s = [1 - (CNTNS\_s)/\alpha_2]^+$

Stage (s):	P	E	T	J	F	H	M	D	R	
Winter Wheat Threshold (α_2):	5	5	5	5	4	3	2	2		(Inches)
Spring Wheat Threshold (α_2):	3.5	3.5	3.5	3.5	3.0	2.5	2.0	1.25	0.75	(Inches)

(3) $XPR\_rs = [(\Sigma PR_d) - \alpha_3]^+$ (inches)

Stages (rs):	PE	PT	PJ	PF	PH	HM	HD	
Winter Wheat Threshold (α_3):	2	4	6	7	8	2	4	(Inches)
Spring Wheat Threshold (α_3):	2	3	4	6	8	2	4	(Inches)

(4) $ATN\_rs = (\Sigma TN_d)/D\_rs$ (°F)

(5) $ATX\_rs = (\Sigma TX_d)/D\_rs$ (°F)

(6) $RT\_rs = ATX\_rs - ATN\_rs$ (°F)

(7) $T50\_rs = \Sigma(TN_d - 50)^+/D\_rs$ (°F)

(8) $T86\_rs = \Sigma(TX_d - 86)^+/D\_rs$ (°F)

Threshold values were used to define all soil moisture and some temperature variables. Ideally, the threshold values would have been estimated, along with other parameters of the model, by mathematical techniques. However, the literature on nonlinear estimation does not include functions of the type we used. At the same time, it is important to represent effects of variables over their total range of values as accurately as possible.

Inspection of preliminary results relating yields to AE/PE values indicated that AE/PE values were limiting "up to a point" beyond which decreases in yields were not detectable. One could fit a quadratic function but the danger is that a small yield may be associated with a large AE/PE value, not because large values of the AE/PE decrease yields, but because some other variable, which should be a part of the model, "caused" the decreased yield. Thus, adoption of thresholds can limit variables to their effective ranges and leave the explanation of yield variation to other variables. These same concepts were applied to other variables using threshold values.

In the absence of analytical procedures to determine threshold values for AE/PE we looked at 40 to 50 years of data at each of five locations in semi-arid areas of Kansas. For each phase of development we pick a pair of potential threshold values and used both to define SM values. Variables using each of thresholds were put in the regression run and the stepwise algorithm picked the ones we used in the final analysis. For SSM values, thresholds were picked so that SSM was close to zero if contents of zones involved were close to capacity before draw-down and close to maximum possible contents as draw-down proceeded from jointing-to-ripe.

Thresholds used in temperature-related variables were based on judgments of a number of agronomists and a plant pathologist. Here again, the stepwise algorithm picked these variables, when they entered, ahead of other forms such as average minimums or average maximums.

7.0. WINTER AND SPRING WHEAT YIELD MODELS

For our yield models (winter and spring), the following mathematical form is used to express a regional yield as a function of the major variables affecting yield:

$$\hat{Y}_R = MAP * VYA * \hat{Y}_p \qquad [7.1]$$

and

$$\hat{Y}_p = B_0 + B_1X_1 + B_2X_2 + \cdots + B_rX_r, \qquad [7.2]$$

where

$\hat{Y}_R$ = estimated yield (bu./acre) for a specified region (strata),

$\hat{Y}_p$ = estimated yield (bu./acre) on an experimental plot basis (standard variety, average productivity over plots at agricultural experiment fields in the U. S. Great Plains),

MAP = management and productivity factor used to adjust from an experimental plot productivity level to productivity on a regional level for a given level of management,

VYA = varietal yielding ability (a mean level for varieties popular at a particular time),

$B_0, B_1, \cdots, B_r$ are parameters (coefficients, constants) associated with the variables in the model,

$X_1, X_2, \cdots, X_r$ are the quantities which vary from season to season [weather-related variables (WRV's), nitrogen amounts, cultural practices (fallow or continuous)].

For a specified region, the quantity VYA can vary from season to season as higher yielding varieties are introduced. The factor MAP shows some increase in time but may be quite stable over a five-to-ten year period. The B-values give the model its universal character in that they are expected to remain constant over regions.

In the early stages of our work, an exponential multiplicative form (linear in log Y_R) was used jointly with the form shown in [7.2]. No particular advantage was evident for either form so the simpler additive model was retained for use.

7.1 Yields on an experimental plot basis.

The plot-based models (winter and spring) were derived by regressing agricultural experiment station average plot yields (adjusted to a standard variety) on WRV's, nitrogen amounts, and cultural practices (fallow or continuous). The B-values (equation [7.2]) for the winter and spring wheat models are shown in Tables 7.1 and 7.2, respectively.

7.1.1 Coefficients and variables. Entries in Tables 7.1 and 7.2 are the coefficients for the respective variables shown on the right-hand side. Coefficients of equation [7.2] for prior-to-harvest yield predictions are given at the specified BMTS values. End-of-harvest estimates for winter wheat use the equation generated from entries at BMTS = 4.0 since no variables observed after that point in the crop calendar were statistically significant. Thus, an estimated plot yield for winter wheat on fallow at Garden City, KS, for the year 1976 was calculated as:

$$
\begin{aligned}
\hat{Y}_p = {} & 50.84 - 7.25(.656) - 16.55(.95) + 0.386(29.36) \\
& -0.373(0) - 0.154(1.78) - 6.40(.084) \\
& -0.062(73.8) - 0.172(52.6) - 1.008(.29) \\
& -0.233(1.17) - 0.402(1.12) - 0.598(.71) \\
& -0.473(5.30) + 0.1727(16) + 0.01647(0)
\end{aligned}
$$

$$-0.00068(0) - 1.051(0) + 0.365(30.9) - 0.00947\ (954.8)$$

$$= 28.3 \text{ bu/A}$$

This is an "end-of-harvest" estimate. Predictions can be made on any date during the season using the most recent "prior-to-harvest" equation. Thus, if current weather is available to April 1 and the BMTS value is 2.2 on that date, then the winter wheat equation with coefficients under 2.0(J) in Table 7.1 would be used.

7.1.2 Estimates based on cultural practice. Our models allow the option of estimating yields for dryland wheat planted on either fallowed land or land which was cropped the previous year. With a few assumptions one can also estimate yields for irrigated wheat.

Two steps are necessary to differentiate between fallowed and previously cropped land for yield purposes. They are:

(a) Values for stored soil moisture deficit (SSM) and soil moisture deficit (SM) variables are chosen from one of the VSMB budgets for fallowing and from another budget for continuous (previously cropped) cropping. (See Section 4.1.6).

(b) For winter wheat only, the variable FL = 1.0 if fallowed and FL = 0.0 if previously cropped.

We have not developed special models for irrigated wheat. Rather we simply use the dryland models with the following alterations:

(a) Coefficients for SSM and SM variables are set equal to zero (this assumes that no moisture deficits, as defined by our variables, occur).

(b) For winter wheat only, FL = 0.0, and six inches of precipitation are added to PR_JF (this assumes moist conditions because of irrigation during this period contribute to deleterious effect of high nighttime temperatures).

Table 7.1. Coefficients for KSU winter wheat yield model. (Entries are standardized to varieties Pawnee/Commanche and "average" experimental plot yield levels).

Model at BMTS:				
0.0 (P)	1.0 (E)	1.5 (T)	2.0 (J)	Variables
32.67	33.01	38.90	49.95	1
-10.69				SSMSQ_P
	-10.02			SSMSQ_E
		-10.37		SSMSQ_T
			-10.29	SSM_J
	-3.09			SMSQ_PE
		-4.33	-11.57	SM_ET
			+0.163	ADTJ * SM_ET
		+0.512		ATN_ET
		-0.418	-0.074	ATX_ET
			-0.252	ATX_TJ
+0.1310	+0.1369	+0.1448	+0.1589	NI
	-0.002641			NI * ADTJ * XPR_PE
		+0.04464		NI * XPR_PT
		-0.001677		NI * ADTJ * XPR_PT
			+0.03183	NI * XPR_PJ
			-0.001205	NI * ADTJ * XPR_PJ
+0.255	+0.293	+0.640	+0.572	ADTJ * FL
-0.01066	-0.01141	-0.01879	-0.01577	ADTJ * ADTJ * FL
.175	.187	.242	.275	R^2 (Plot Basis)
11.6	11.5	11.1	10.9	STD. DEV.

Table 7.1 (continued)

Model at BMTS: 2.5 (F)	3.0 (H)	3.5 (M)	4.0 (D)	Variables
51.31	52.03	51.01	50.84	1
-6.73				SSM_F
	-7.10			SSM_H
		-5.11		SSM_M
			-7.25	SSMSQ_D
-16.82	-17.05	-16.88	-16.55	SM_ET
+0.385	+0.392	+0.385	+0.386	ADTJ * SM_ET
-0.528	-0.346	-0.373	-0.373	ADTJ * SMSQ_JF
	-0.250	-0.162	-0.154	ADTJ * SMSQ_FH
		-7.69	-6.40	SMSQ_HM
-0.079	-0.073	-0.064	-0.062	ATX_ET
-0.231	-0.221	-0.189	-0.172	ATX_TJ
-0.999	-0.865	-0.906	-1.008	T50_JF
-0.210	-0.2381	-0.2360	-0.233	PR_JF * T50_JF
	-0.426	-0.421	-0.402	T50_FH
		-0.764	-0.598	T86_HM
			-0.473	T86_MD
+0.1801	+0.1811	+0.1796	+0.1727	NI
+0.01988				NI * XPR_PF
-0.000816				NI * ADTJ * XPR_PF
	+0.01618	+0.01650	+0.01647	NI * XPR_PH
	-0.000681	-0.000691	-0.000680	NI * ADTJ * XPR_PH
		-1.013		XPR_HM
			-1.051	XPR_HD
+0.425	+0.327	+0.331	+0.365	ADTJ * FL
-0.01154	-0.00871	-0.00865	-0.00947	ADTJ * ADTJ * FL
.310	.323	.339	.350	R^2 (Plot Basis)
10.64	10.55	10.44	10.36	STD. DEV.

Table 7.2. Coefficients for KSU spring wheat yield model (entries are standardized to the variety Thatcher and average experimental plot yield levels).

Model at BMTS:					
0.0 (P)	1.0 (E)	1.5 (T)	2.0 (J)	2.5 (F)	Variables
27.05	26.90	27.10	27.94	54.90	1
-11.09	-8.50	-5.69	-6.04		SSM_P
				-7.50	SSMSQ_F
	+9.92				SSM_PE
	-0.99				ADTJ * SM_PE
		+9.73	+9.31	+10.74	SM_ET
		-1.154	-1.125	-1.253	ADTJ * SM_ET
			-0.0142	-0.0186	ATN_TJ * PR_TJ
				-0.364	ATX_JF
+0.0708	+0.0704	+0.0711	+0.0732	+0.0861	NI
.077	.108	.136	.140	.170	R^2 (plot basis)
10.247	10.109	9.948	9.940	9.781	STD. DEV.

Table 7.2 (continued)

Model at BMTS: 3.0 (H)	3.5 (M)	4.0 (D)	5.0 (R)	Variables
84.66	134.10	186.41	203.59	1
-6.18				SSMSQ_H
	-5.97			SSMSQ_M
		-0.287	-0.314	ADTJ * SM_PE
+9.18	+8.22	+7.64	+7.69	SM_ET
-1.127	-1.036	-0.763	-0.681	ADTJ * SM_ET
+10.63	+8.58	+9.56	+8.56	SM_FH
-1.491	-1.650	-1.7667	-1.6567	ADTJ * SMSQ_FH
-0.0129	-0.0249	-0.0236	-0.0246	ATN_TJ * PR_TJ
-0.309	-0.367	-0.327	-0.350	ATX_JF
-0.451	-0.203	-0.285	-0.274	ATX_FH
	-0.757	-0.481	-0.472	ATX_HM
	-0.024	-0.026	-0.025	ATX_HM * PR_HM
		-0.884	-0.769	ATX_MD
		+0.507	+0.539	T56_MD
			-0.321	ATX_DR
+0.0874	+0.0904	+0.0949	+0.0968	NI
.219	.307	.386	.401	R^2 (plot basis)
9.539	9.012	8.513	8.424	STD. DEV.

7.1.3 Statistical properties. Values of the coefficient of determination (R^2) and the standard deviation of the deviations of observed plot yields from the regression plane are included in Tables 7.1 and 7.2. The values of $R^2 = 0.35$ and STD. DEV. = 10.36 at BMTS = 4.0 in Table 7.1 and $R^2 = 0.40$, STD. DEV. = 8.4 at BMTS = 5.0 in Table 7.2 are reminders that estimation of a plot yield in a designated year at a designated location based solely on knowledge of applied nitrogen and WRV-values calculated from meteorological data collected, say 1 to 10 miles away, is subject to considerable error. Well-controlled wheat experiments commonly have standard deviations of 2 to 4 bushels per acre for plot-to-plot variability and this increases as the plots are separated in space and time. The 1034 plot yields, used to develop our winter wheat model, had a standard deviation of 12.8 bu./A and the 306 for spring wheat, a standard deviation of 10.6 bu./A. The main purpose of using plot yields for model development was to choose WRV's whose effects were of sufficient magnitudes to be statistically significant in spite of large variation in observed yields. Further, the WRV's had to be effective over a wide range of environments in order to come into the model. Almost all coefficients shown in Tables 7.1 and 7.2 exceeded their standard errors by an amount sufficient to declare them statistically significant at the 5% level.

7.1.4 What the models say. Growth and development of roots, green matter, and grain are biological processes and we have not attempted to model them. Moisture and temperature provide a substantial part of the environment in which the growth occurs, and it is their effects we have tried to measure in our models.

A model must first and foremost produce results consistent with known phenomena. Our discussion, relative to the results shown in Tables 7.1 and 7.2, will indicate what the "model says" and critical judgment can then be brought to bear on the results by agronomists, meteorologists, and any others who have studied some of the phenomena under consideration. Due to repeated use of the terms, we will use (WWM) for winter wheat model, and (SWM) for spring wheat model, and abbreviations for variables and crop stages given in Section 6.1. Bear in mind that WWM was developed for climates with $10° \leq$ ADTJ $\leq 50°F$ and SWM for $0° <$ ADTJ $\leq 20°F$. Almost all the discussion will be relative to WWM at BMTS = 4.0 (D) in Table 7.1 and SWM at BMTS = 5.0 (R) in Table 7.2.

Both WWM and SWM show deleterious effects of high temperatures, in almost all phases of development.

For WWM, terms measuring temperature effects directly (ATX, T50, T86) appear with minus signs from E to D; for SWM from T to R. For WWM, the deleterious effect is enlarged by precipitation from J to F and for SWM from T to J and H to M and suggests conditions favorable to plant diseases. Terms which reduce the deleterious effects of high temperatures are: (a) T56_MD in SWM, which may help insure maturity before freezing weather, and (b) the combination ATX_ET and ATX_TJ in WWM. The combined effect of the latter terms is least when it is relatively warm in the fall so that BMTS gets to 1.5 (T) before winter and ATX_ET is greater than ATX_TJ because the low winter temperatures are included in computing ATX_TJ. This effect is shown more explicitly in the WWM for BMTS = 1.5 where ATN_ET has a positive influence and ATX_ET a negative influence.

The magnitude of effects of soil moisture deficits (SM-terms) depend on a climatic factor (ADTJ).

Dependence of effects of SM-terms on ADTJ are pronounced both in the WWM and the SWM. The WWM says, "the larger the value of ADTJ, the more pronounced the effect of a prescribed level of a soil moisture deficit" during the phases JF and FH, and SWM says the same for phases PE, ET, and FH. For WWM, in the ET phase, the effect of an SM-value is less pronounced for larger values of ADTJ. Geographically, a soil moisture deficit in the fall is more serious in Montana than in Texas, whereas in the springtime, the situation is reversed. It should also be noted that if we compare the SWM with ADTJ = 5°F and the WWM with ADTJ = 30° in relatively arid climates, that from season to season, temperature swings will dominate yield variation in the SWM whereas soil-moisture deficits, along with temperatures, will cause yield variation in the WWM.

<u>Excessive precipitation during certain phases reduces yields.</u>

For the WWM, precipitation in excess of four inches in the HM phase reduced yields by a bushel per inch and for the SWM, any precipitation in the same phase increases losses due to high maximum temperatures. Consequences of excess moisture during the HM phase could include disease losses, poor pollination and lodging. Any precipitation during the JF phase of winter wheat or during the TJ phase for spring wheat increased the effect of high nighttime temperatures. Increased severity of disease problems seems a likely result.

<u>Beneficial effects of added nitrogen are partially offset by too much precipitation, especially in climates with high ADTJ.</u>

In the humid wheat-growing areas, the leaching of nitrogen from the root zone is well-known and the WWM shows how benefits from a pound of nitrogen are reduced by excess precipitation. For example, with no excess precipitation, and assuming nitrogen is added on a "need" basis, it takes about 6 pounds/acre to increase yields by a bushel per acre. However, in a year with about 26 inches of precipitation (18 inches excess) from planting to heading, it takes about 10 pounds of nitrogen to produce a bushel. For spring wheat the model indicates that it takes about 10 pounds of nitrogen to produce a bushel. Leaching is usually not a problem in spring wheat areas of the Great Plains.

Gains from fallowing depend in part on a climatic factor (ADTJ).

Gains from fallowing appear as a direct effect in the WWM in addition to the indirect effect of smaller deficits in stored moisture and soil moisture and larger values of the AE/PE ratio. Direct gains depend on ADTJ with gains increasing with decreasing ADTJ's. Fallowing increases time available for natural processes to create nitrate nitrogen for succeeding crops and the benefit of this increased time increases as ADTJ decreases.

7.1.5 Some shortcomings of the models. A couple factors whose effects are deleterious and are not included in WWM are freezing temperatures at anthesis and winterkill due to very cold temperatures when the wheat is unprotected by snow. Variables to represent these factors were included in the model development stage but neither situation occurred often enough and/or had sufficient influence on plot yields in the varietal trials to be statistically significant.

Just as freezes at anthesis become part of the random error term of the models, so also do severe epidemics of diseases and major outbreaks of insect infestation. These factors (freezes, diseases, insects) are usually localized and responses vary from field to field but, in severe cases, they can reduce yields by 5 to 10 bushels per acre over several million acres.

A shortcoming of the SWM is lack of breadth in climates over which the model was developed. Plot yields were available for climates with $0° < ADTJ \leq 20°F$. It would have been advantageous to have yields and weather data from climates with ADTJ as low as -10°F to see if interaction terms containing ADTJ would retain the same coefficients.

7.2 Estimating regional yields

Equations [7.1] shows the relation between our plot-based estimate ($\hat{Y}_p$) and a regional estimate ($\hat{Y}_R$). In application, one needs values for VYA and MAP factors.

7.2.1 Regional values for VYA. In the U. S. Great Plains, most state offices of the USDA-SRS publish information on the percentage of wheat planted to different varieties of winter and spring wheat and durums. In many states, these are published on a CRD basis. To determine a VYA value for a CRD for a particular year, we calculated a weighted average of five VYA values from Table 5.1 (winter wheat) or Table 5.2 (spring wheat and durums). The five VYA values were those for the five most popular varieties and the weight for a VYA value was the ratio of its proportion to the sum of the proportions for the five.

Table 7.3 shows regional VYA values for CRD's in Kansas over the past 22 years. These data were prepared for "bootstrap" testing of our model so that the VYA value for a specified year was computed on the basis of percentages planted in the previous year. Table 7.4 shows comparable values for North Dakota.

7.2.2 Regional values of MAP. As the name implies, we consider the MAP (management and productivity) factor as heavily dependent on the productivity of the soil (its type, slopes, and a myriad of other factors) and management

Table 7.3 Regional VYA values for CRD's in Kansas. (Values based on varieties planted in the previous year).

Harvest Year	NW	NC	NE	WC	C	EC	SW	SC	SE
1956	0.99	1.00	1.00	1.02	1.01	1.00	1.03	1.01	1.01
1957	0.99	1.00	1.00	1.02	1.01	1.00	1.03	1.01	1.02
1958	0.99	1.00	1.00	1.02	1.00	1.00	1.03	1.02	1.01
1959	1.01	1.00	1.00	1.02	1.00	1.01	1.03	1.01	1.01
1960	1.03	1.00	1.00	1.02	1.00	1.01	1.03	1.01	1.02
1961	1.03	1.00	1.00	1.02	1.00	1.02	1.03	1.01	1.02
1962	1.05	1.03	1.01	1.05	1.04	1.03	1.05	1.03	1.02
1963	1.04	1.04	1.01	1.04	1.03	1.03	1.04	1.03	1.02
1964	1.04	1.04	1.02	1.05	1.04	1.05	1.04	1.03	1.02
1965	1.05	1.08	1.03	1.06	1.04	1.07	1.05	1.03	1.03
1966	1.06	1.08	1.04	1.07	1.05	1.07	1.05	1.04	1.03
1967	1.07	1.09	1.05	1.08	1.06	1.07	1.06	1.04	1.04
1968	1.09	1.11	1.08	1.08	1.07	1.08	1.07	1.05	1.04
1969	1.11	1.15	1.08	1.12	1.08	1.10	1.10	1.07	1.06
1970	1.12	1.14	1.10	1.12	1.10	1.10	1.11	1.08	1.06
1971	1.14	1.15	1.12	1.12	1.13	1.11	1.12	1.10	1.07
1972	1.15	1.15	1.11	1.14	1.12	1.09	1.13	1.10	1.06
1973	1.15	1.13	1.12	1.15	1.12	1.12	1.14	1.10	1.05
1974	1.16	1.13	1.08	1.16	1.13	1.08	1.15	1.11	1.05
1975	1.17	1.13	1.13	1.16	1.13	1.08	1.16	1.12	1.06
1976	1.16	1.16	1.14	1.16	1.15	1.10	1.16	1.12	1.06

Table 7.4 Regional VYA values for CRD's in North Dakota. (Values based on varieties planted in the previous year).

Harvest Year	NW	NC	NE	WC	C	EC	SW	SC	SE
1956	1.11	1.10	1.10	1.12	1.10	1.10	1.13	1.13	1.12
1957	1.12	1.10	1.10	1.12	1.10	1.10	1.13	1.13	1.12
1958	1.13	1.10	1.10	1.12	1.10	1.10	1.13	1.13	1.12
1959	1.13	1.10	1.10	1.12	1.10	1.10	1.13	1.13	1.12
1960	1.13	1.10	1.10	1.12	1.10	1.10	1.13	1.13	1.12
1961	1.13	1.10	1.10	1.12	1.10	1.10	1.13	1.13	1.12
1962	1.13	1.10	1.10	1.12	1.10	1.10	1.13	1.13	1.12
1963	1.13	1.10	1.10	1.12	1.10	1.10	1.13	1.13	1.12
1964	1.13	1.10	1.10	1.12	1.10	1.10	1.13	1.13	1.12
1965	1.12	1.10	1.10	1.12	1.10	1.09	1.13	1.13	1.12
1966	1.12	1.10	1.11	1.12	1.10	1.10	1.13	1.12	1.12
1967	1.13	1.11	1.12	1.12	1.11	1.11	1.12	1.12	1.12
1968	1.13	1.12	1.13	1.11	1.12	1.12	1.12	1.11	1.13
1969	1.14	1.13	1.14	1.11	1.13	1.13	1.12	1.11	1.13
1970	1.14	1.13	1.14	1.11	1.13	1.15	1.12	1.10	1.13
1971	1.15	1.15	1.15	1.11	1.15	1.15	1.12	1.12	1.14
1972	1.16	1.15	1.15	1.14	1.15	1.16	1.14	1.14	1.16
1973	1.15	1.14	1.14	1.14	1.15	1.15	1.15	1.15	1.15

factors. Management factors have played an important role in yield increases, especially in semi-arid regions. Unfortunately, we do not, at this time, have data to independently estimate effects of certain management practices (larger machines, soil conservation measures, etc.) as we have the application of nitrogen, cultural practices (fallowing and irrigation) and varietal improvement. Nor do we have the necessary data to show the difference in yields between sand and clay soils and the effect of slope on yields.

In terms of equation [7.1], MAP is simply a value to relate regional yields to plot-based estimates. As such, it can be estimated, for a given region, by using historical estimates of Y_R and calculating $\hat{Y}_p$ with corresponding historical input data. Various statistical estimators may be used to calculate MAP. We suggest the simple form

$$MAP(R, W, y) = [\sum_{h=y-1}^{y-10} Y(R, h)]/[\sum_{h=y-1}^{y-10} VYA(R, h) * \hat{Y}_p(W, h)] \qquad [7.3]$$

where

MAP(R, W, y) = MAP value for estimating a yield for region R, using weather from station W, in harvest year y,

Y(R, h) = historical yield for region R in harvest year h,

VYA(R, h) = value of VYA for region R in harvest year h,

$\hat{Y}_p(W, h)$ = plot-based estimate of yield, using weather from station W, in harvest year h.

For the U. S., USDA-SRS generated yields can be used for Y(R, h) values. The CRD is the most likely choice of region. MAP values for CRD's in Kansas and North Dakota are given in Tables 7.5 and 7.6, respectively.

Clearly, Equation [7.3] could be calculated using less than 10 years of historical data. Based on our experience to date, the 10 years is a compromise between a series so long that it conceals a trend or so short that year-to-year sampling variation is not adequately removed when no trend is present.

Table 7.5. Regional MAP values for CRD's in Kansas for specified weather station locations.†

	Crop Reporting Districts and Weather Locations								
Year	NW CBY	NC MKO	NE MAN	WC TRI	C HAY	EC OTT	SW GNC	SC HUT	SE CUS
1967	.81	.70	.79	.97	.77	.78	.77	.71	.74
1968	.80	.71	.80	1.00	.77	.78	.76	.72	.76
1969	.80	.71	.80	.95	.78	.79	.72	.71	.78
1970	.81	.73	.81	.99	.79	.77	.75	.74	.78
1971	.82	.73	.86	.98	.82	.77	.75	.76	.79
1972	.87	.75	.88	.96	.84	.78	.74	.76	.80
1973	.86	.75	.88	.96	.85	.80	.76	.77	.84
1974	.90	.78	.87	.96	.84	.81	.77	.79	.86
1975	.89	.75	.84	.95	.79	.78	.75	.78	.84
1976	.90	.75	.83	.94	.77	.78	.74	.76	.82

†CBY = Colby, MKO = Mankato, MAN = Manhattan, TRI = Tribune, HAY = Hays, OTT = Ottawa, GNC = Garden City, HUT = Hutchinson, CUS = Columbus.

Table 7.6 Regional MAP values for CRD's in North Dakota for specified weather station locations.†

	Crop Reporting Districts and Weather Locations											
Crop	NW 1		NC 2		NE 3	WC 4		C 5	EC 6	SW 7	SC 8	SE 9
Year	MNT	CRB	SNH	GVL	LGN	WLN	DCN	JAM	FGO	DCN	MND	EDG
1964	.64	.71	.55	.69	.76	.61	.73	.74	.82	.65	.56	.63
1965	.66	.73	.57	.74	.77	.63	.76	.76	.83	.67	.56	.64
1966	.68	.74	.59	.75	.79	.65	.78	.75	.83	.68	.57	.65
1967	.72	.80	.62	.81	.81	.70	.81	.78	.87	.74	.60	.70
1968	.71	.80	.64	.84	.80	.71	.82	.77	.88	.75	.60	.71
1969	.74	.86	.66	.87	.81	.76	.85	.77	.89	.77	.64	.72
1970	.78	.89	.68	.92	.81	.79	.89	.78	.93	.79	.65	.73
1971	.78	.90	.67	.93	.81	.82	.89	.81	.95	.80	.66	.76
1972	.83	.96	.72	1.00	.82	.89	.92	.88	.98	.82	.67	.80
1973	.81	.93	.68	.98	.80	.86	.89	.87	.96	.82	.66	.78

†MNT = Minot, CRB = Crosby, LGN = Langdon, WLN = Williston, DCN = Dickenson, JAM = Jamestown, FGO = Fargo, MND = Mandan, EDG = Edgeley, SNH = San Haven, GVL = Granville

7.2.3 Regional values of added nitrogen (NI). When estimating a regional yield, values for NI to compute plot-based yield estimates ($\hat{Y}_p$) should be an "averages" for the region of interest. No figures are available for nitrogen applied to wheat on a CRD basis. However, data are, and have been, generated by the USDA-SRS on a state level. From these data we calculated the following regression equation to estimate dryland nitrogen use in a region R in harvest year y.

$$NI(R, y) = -151 + 1.84\ (AAPR)_R + 1.81\ y; \qquad y = 55, 56, \ldots, 73 \tag{7.4}$$

$$= -151 + 1.84\ (AAPR)_R + 1.81\ (73); \qquad y = 74, 75, 76,$$

and R = CRD's in winter wheat areas in the following states: CO, NE, KS, OK, TX, MO, IL, IN, OH.

In Equation [7.4], NI(R, y) is in pounds per acre and

AAPR = average annual precipitation for region R in inches.

Equation [7.4] was developed using AAPR values for the states shown above with the exception of Texas. For the other states, AAPR values were averages over the main wheat-growing CRD's rather than over the entire state. Results of applying Equation [7.4] in Kansas are shown in Table 7.7.

Models, such as Equation [7.4], developed for a given size unit (a state) sometimes give misleading results when applied to a smaller unit (a CRD). As a further test of the model, two agronomists at Kansas State University were asked to estimate nitrogen use per acre on a CRD. Using sales data and their many years of experience, they provided estimates which are summarized in Table 7.8. The data attests to the adequacy of the model for Kansas where the range in amount applied from CRD to CRD is as great as one would find in any state because of the range in AAPR values. We have assumed that the rate

Table 7.7 Estimated amount of nitrogen (lbs./A) applied under dryland conditions in Kansas by crop reporting district.

Harvest Year	NW	NC	NE	WC	C	EC	SW	SC	SE
1956	0	0	10	0	0	14	0	0	16
1957	0	0	12	0	0	16	0	0	18
1958	0	0	14	0	1	18	0	0	19
1959	0	1	16	0	3	20	0	3	21
1960	0	3	18	0	5	21	0	4	23
1961	0	5	19	0	7	23	0	6	25
1962	0	6	21	0	8	25	0	7	27
1963	0	8	23	0	10	27	0	9	28
1964	0	10	25	0	12	29	0	11	30
1965	1	12	27	0	14	30	0	13	32
1966	3	14	28	2	16	32	0	15	34
1967	5	16	30	4	17	34	2	16	36
1968	6	18	32	5	19	36	4	18	38
1969	8	20	34	7	21	38	5	20	39
1970	10	22	36	9	23	39	7	22	41
1971	12	23	37	11	25	41	9	24	43
1972	14	25	39	13	26	43	11	25	45
1973	15	27	41	14	28	45	13	27	47
1974	17	33	43	16	30	47	14	29	48
1975	19	33	45	18	32	48	16	31	50
1976	19	33	45	18	32	48	16	31	50

Table 7.8 Comparison of estimates of amount of applied nitrogen on dryland wheat in Kansas (entries are pounds per acre).

				Independent Estimates[2]	
Year	Sectors	CRB USDA-SRS	Model[1]	Agronomist "A"	Agronomist "B"
1960	Western		0	2	0
	Central		7	4	6
	Eastern		22	28	11
	State	8	6	6	4
1965	Western		1	5	1
	Central		16	12	14
	Eastern		31	47	21
	State	11	12	13	10
1970	Western		10	12	3
	Central		25	25	25
	Eastern		40	47	36
	State	24	21	23	18
1975	Western		19	14	5
	Central		34	30	30
	Eastern		49	51	40
	State	32	30	26	22

[1]Model based on Crop Reporting Board, USDA-SRS, data reported on a state-wide basis. (See Eq. 7.4)

[2]Based, in part, on fertilizer sales data plus knowledge and experience.

of application has remained constant since 1973. Actually, it may have dropped somewhat in 1974, the year of a large price increase.

Table 7.9 shows estimated amounts of applied nitrogen for North Dakota. The estimates were based largely on two sources of information: (1) USDA-SRS estimates of amount of nitrogen applied to spring wheat in North Dakota, (2) a special survey conducted by North Dakota State University in 1971 which gave estimates of amount of nitrogen applied in various regions of the state. Based on these surveys, we set up the following algorithm to apportion a statewide estimate to western, central, and eastern tiers of crop reporting districts:

(a) Let X = (pounds of nitrogen applied per acre on fields receiving N) times (proportion of fields receiving N) = pounds/acre of N on a statewide basis

(b) Assign (3/8)X to the western tier, (6/8)X to the central tier, and (15/8)X to the eastern tier.

7.2.4 Regional values for cultural practices. As indicated in Section 7.1.2, values for $\hat{Y}_p$ can be calculated for dryland wheat grown on fallowed and continuously cropped land and for wheat grown under irrigation. Regional estimates should be a weighted average of these three values where the weights are the percent of land under each cultural practice. These percents are available through some of the state USDA-SRS offices. Percents of wheat acreage planted under each of the three cultural practices in Kansas and North Dakota are shown in Tables 7.10 and 7.11, respectively. Since the tabled values were used in a "bootstrap" test, they are actually the proportions for the previous year.

This completes our discussion of the type of data needed to apply our models on a regional basis. Though the discussion centered on winter wheat, the same procedures and data are needed for spring wheat and durums.

Table 7.9 Estimated amount of nitrogen (lbs./A) applied under dryland conditions in North Dakota by crop reporting district.

Year	NW	NC	NE	WC	C	EC	SW	SC	SE
1956	0	0	5	0	0	5	0	0	5
1957	0	0	5	0	0	5	0	0	5
1958	0	0	5	0	0	5	0	0	5
1959	0	0	5	0	0	5	0	0	5
1960	0	0	5	0	0	5	0	0	5
1961	0	0	5	0	0	5	0	0	5
1962	0	0	5	0	0	5	0	0	5
1963	0	0	5	0	0	5	0	0	5
1964	0	0	5	0	0	5	0	0	5
1965	1	3	7	1	3	7	1	3	7
1966	1	3	7	1	3	7	1	3	7
1967	2	3	8	2	3	8	2	3	8
1968	2	4	9	2	4	9	2	4	9
1969	2	4	11	2	4	11	2	4	11
1970	3	7	17	3	7	17	3	7	17
1971	4	8	19	4	8	19	4	8	19
1972	4	8	21	4	8	21	4	8	21
1973	5	9	23	5	9	23	5	9	23

Table 7.10 Percentages of fallowed (F), continuous cropped (C) and irrigated (I) wheat in Kansas by CRD[†]. (Values based on previous year's percentages).[††]

Harvest	NW			NC		WC			C		SW			SC	
Year	F	C	I	F	C	F	C	I	F	C	F	C	I	F	C
1956	84	16	0	20	80	70	30	0	15	85	65	35	5	12	88
1957	85	15	0	24	76	74	26	0	20	80	67	27	6	20	80
1958	87	13	0	32	68	69	25	6	24	76	57	19	24	18	82
1959	86	14	0	38	62	83	15	2	35	65	78	16	6	33	67
1960	88	12	0	34	66	82	15	3	26	74	69	24	7	21	79
1961	87	12	1	33	67	81	16	3	25	75	68	25	7	19	81
1962	89	11	0	31	69	80	17	3	22	78	68	25	7	17	83
1963	90	9	1	45	55	86	11	3	32	68	75	18	7	25	75
1964	92	7	1	45	55	84	12	4	34	66	75	17	8	27	73
1965	88	11	1	45	55	86	10	4	35	65	77	15	8	28	72
1966	87	11	1	44	56	86	11	3	35	65	74	16	10	27	73
1967	93	6	1	46	54	85	12	3	36	64	73	17	10	27	73
1968	89	10	1	39	61	83	14	3	29	71	70	20	10	22	78
1969	91	8	1	36	64	85	10	5	28	72	71	18	11	20	80
1970	93	6	1	43	57	86	10	4	34	66	71	18	11	22	78
1971	94	5	1	49	51	88	8	4	41	59	78	12	12	30	70
1972	94	5	1	52	48	90	6	4	42	48	78	12	12	29	71
1973	94	5	1	52	48	89	7	4	41	59	77	11	11	28	72
1974	97	2	1	55	45	93	3	4	41	59	82	8	10	27	73
1975	95	4	1	39	61	89	5	5	36	64	78	11	11	20	80
1976	95	4	1	35	65	92	3	5	28	72	73	12	15	20	80

[†]The NE, EC, and SE CRD's were 100% continuous cropping (C).

[††]Source: Annual Reports. Kansas State Board of Agriculture.

Table 7.11 Percentages of fallowed (F) and continuous cropped (C) wheat in North Dakota by CRD. (Values based on previous year's percentages).†

Year	NW		NC		NE		WC		C		EC		SW		SC		SE	
	F	C	F	C	F	C	F	C	F	C	F	C	F	C	F	C	F	C
1956	81	19	43	57	34	66	58	42	34	66	39	61	57	43	26	74	15	85
1957	78	22	44	56	41	59	49	51	35	65	48	52	65	35	22	78	13	87
1958	87	13	57	43	54	46	58	42	46	54	54	46	71	29	27	73	20	80
1959	92	8	75	25	63	37	61	39	55	45	61	39	62	38	32	68	24	76
1960	92	8	78	22	70	30	59	41	58	42	57	43	59	41	31	69	23	77
1961	92	8	74	26	71	29	61	39	58	42	59	41	64	36	26	74	23	77
1962	96	4	80	20	77	23	69	31	64	36	64	36	68	32	41	59	24	76
1963	96	4	82	18	75	25	73	27	72	28	71	29	72	28	45	55	37	63
1964	98	2	87	13	90	10	81	19	80	20	79	21	86	14	55	45	44	56
1965	97	3	87	13	88	12	80	20	75	25	72	28	82	18	51	49	45	55
1966	96	4	88	12	82	18	82	18	78	22	73	27	86	14	51	49	42	58
1967	96	4	85	15	79	21	81	19	75	25	74	26	86	14	50	50	42	58
1968	93	7	81	19	75	25	79	21	70	30	64	36	85	15	46	54	39	61
1969	93	7	80	20	72	28	78	22	67	33	65	35	84	16	45	55	36	64
1970	96	4	88	12	80	20	85	15	80	20	75	25	93	7	61	39	47	53
1971	97	3	93	7	83	17	92	8	86	14	76	24	96	4	71	29	63	37
1972	95	5	86	14	78	22	89	11	77	23	67	33	94	6	68	32	56	44
1973	96	4	87	13	74	26	89	11	75	25	57	43	96	4	74	26	55	45

†Source: North Dakota Wheat Historic Estimates, 1955-70, and North Dakota Crop and Livestock Statistics - annual summaries compiled by North Dakota Crop and Livestock Reporting Service.

8.0 APPLICATIONS

Bootstrap tests of the winter and spring wheat yield models were applied to Kansas and North Dakota, respectively. Results are shown in Tables 8.1 and 8.2. Non-weather input data can be found in Tables 7.7 and 7.9 (applied nitrogen); 7.3 and 7.4 (VYA values); 7.5 and 7.6 (MAP values); and 7.10 and 7.11 (mix of cropping practices). Daily values for precipitation, minimum and maximum temperatures were recorded at the weather stations shown in Tables 7.5 and 7.6.

In a bootstrap test, data used in development of a model are not used to test the model. Accordingly, MAP values were calculated for the ten-year period prior to a test year. VYA values, nitrogen values and the mix of cropping practices (F, C, and I) were calculated from information available for the year prior to the test year.

Entries in Tables 8.1 and 8.2 give model-estimated "end of harvest" yields that can be compared with USDA-SRS estimates for each crop reporting district and for each state as a whole. For this test, MAP values were computed and final comparisons made with USDA-SRS yields per harvested acre.

Table 8.1 Comparison of model (KSU) and USDA (SRS) yields for Kansas using one weather station[†] per CRD (Bootstrap Test). Entries are bushels per acre.

		Crop Reporting District and Percent Acreage									
Crop Year		NW 10% CBY	NC 12% MKO	NE 3% MAN	WC 11% TRI	C 15% HAY	EC 4% OTT	SW 17% GNC	SC 23% HUT	SE 5% CUS	State
1967	KSU	27.9	22.3	20.9	23.7	21.3	21.6	22.9	16.5	25.2	21.7
	SRS	23.0	21.0	26.7	20.4	17.5	25.0	15.5	17.6	30.1	20.0
1968	KSU	16.6	27.5	34.2	22.4	23.5	31.9	26.7	29.3	28.8	26.0
	SRS	20.9	30.3	38.7	13.3	27.1	36.4	14.5	28.1	34.3	26.0
1969	KSU	26.9	32.7	32.7	27.6	31.4	34.8	25.2	29.4	30.7	29.3
	SRS	29.1	33.5	31.0	30.3	29.0	28.2	32.1	32.2	29.5	31.0
1970	KSU	24.7	32.8	24.9	33.3	25.7	28.0	29.6	26.9	30.8	28.6
	SRS	33.7	33.6	33.0	35.6	30.9	31.1	33.3	32.5	33.0	33.0
1971	KSU	28.0	33.4	37.8	35.1	31.2	35.2	27.9	30.7	32.6	31.3
	SRS	37.1	40.4	45.2	30.7	33.5	39.3	31.4	32.9	39.1	34.5
1972	KSU	27.4	33.2	39.7	18.7	31.0	33.3	24.2	28.6	33.3	28.3
	SRS	32.7	34.9	38.2	29.6	33.9	36.1	32.6	34.1	36.7	33.5
1973	KSU	33.0	35.7	40.7	34.0	39.6	33.9	32.7	33.3	31.4	34.6
	SRS	39.0	43.3	34.7	34.6	39.1	35.1	33.6	36.5	34.8	37.0
1974	KSU	39.8	38.1	39.4	35.6	37.3	35.8	29.8	32.5	30.4	34.7
	SRS	32.7	28.4	30.7	31.8	23.1	28.3	26.6	25.8	27.6	27.5
1975	KSU	29.4	31.6	37.1	29.2	33.9	32.5	26.5	34.1	32.9	31.4
	SRS	32.3	29.9	31.4	30.1	29.5	30.0	27.1	28.0	25.9	29.0
1976	KSU	37.5	28.8	36.6	21.0	29.3	35.5	25.7	30.4	32.9	29.4
	SRS	32.0	35.0	31.0	30.0	30.0	25.0	26.0	28.0	26.0	29.5

[†] See Table 7.5 for weather locations.

Table 8.2 Comparison of model (KSU) and USDA (SRS) yields for North Dakota using one or two weather stations† per CRD (Bootstrap Test). Entries are bushels per acre.

		Crop Reporting District and Percent Acreage												
		NW 17%		NC 12%		NE 19%	WC 9%		C 10%	EC 10%	SW 9%	SC 6%	SE 8%	
		CRB	MNT	SNH	GVL	LGN	WLN	DCN	JAM	FGO	DCN	MND	EDG	State
1964	KSU	20.9	19.1	19.3	15.9	25.3	17.0	15.8	21.5	22.2	14.9	17.1	15.6	20.0
	SRS	25.4		26.4		29.3	21.6		25.5	25.7	18.7	17.3	17.5	23.8
1965	KSU	23.4	22.9	20.7	21.8	25.2	19.4	19.3	24.1	28.0	17.8	19.5	20.2	22.6
	SRS	27.0		26.2		31.2	25.3		22.8	28.9	21.7	21.7	22.6	26.0
1966	KSU	17.6	18.3	17.7	15.2	25.3	13.3	18.0	15.6	20.3	15.9	14.7	11.7	18.1
	SRS	25.3		24.6		26.4	22.1		21.1	24.8	22.1	19.2	19.6	23.4
1967	KSU	19.7	20.7	20.7	19.2	32.8	18.7	19.2	22.9	28.7	17.8	16.8	20.3	23.2
	SRS	17.9		20.7		28.9	20.4		20.2	29.7	24.5	17.2	21.5	22.6
1968	KSU	19.8	24.1	23.6	25.1	32.5	19.0	21.9	28.7	28.5	21.2	20.3	26.8	25.7
	SRS	23.3		24.5		31.4	23.6		29.0	33.6	23.6	22.9	27.1	26.8
1969	KSU	29.1	27.3	28.8	26.7	34.4	23.6	26.8	28.9	25.1	25.1	20.4	27.1	28.0
	SRS	31.7		30.2		33.8	27.7		30.8	32.4	23.9	23.1	26.0	29.8
1970	KSU	20.6	23.9	23.6	21.3	26.1	17.7	21.4	14.0	26.4	20.1	16.5	15.8	21.3
	SRS	24.0		22.2		28.1	21.1		23.7	26.7	20.8	16.5	21.2	23.6
1971	KSU	26.0	25.4	29.0	23.9	39.9	19.1	23.4	24.2	33.0	21.8	23.5	22.0	27.9
	SRS	29.7		30.7		35.8	27.7		33.4	36.4	27.8	26.5	32.0	31.8
1972	KSU	39.4	38.3	40.0	36.9	39.5	38.2	38.8	25.5	33.2	35.0	25.1	29.0	35.0
	SRS	29.6		28.5		31.3	30.0		27.0	30.6	28.3	23.8	25.8	28.9
1973	KSU	26.4	26.2	26.2	27.3	34.3	21.5	21.7	15.5	31.0	19.8	17.6	22.1	25.4
	SRS	29.9		29.4		30.3	26.4		22.0	30.0	28.8	19.7	23.7	27.5

†See Table 7.6 for location names.

9.0 REFERENCES

1. Baier, W. 1973. Crop-weather analysis model: Review and model development. Jour. Appl. Meteor. 12: 937-947.

2. Baier, W. and G. W. Robertson. 1965. Estimation of latent evaporation from simple weather observations. Can. J. Plant Sci. 45: 276-284.

3. Baier, W. and G. W. Robertson, 1966. A new versatile soil moisture budget. Can. J. Plant Sci. 46: 299-314.

4. Baier, W., 1971. Evaluation of latent evaporation estimates and their conversion to potential evaporation. Can. J. Plant Sci. 51: 255-266.

5. Baier, W., D. Z. Chaput, D. A. Russello, W. R. Sharp, 1972. Soil moisture estimator program system. Tech. Bull. 78 Agrometeorology Section, Agriculture Canada, Ottawa.

6. Hsieh, C., 1973. Atlas of China, p. 32, McGraw-Hill, New York.

7. Jury, W. A. and C. B. Tanner, 1975. Advection modification of the Priestley and Taylor evapotranspiration formula. Agron. Jour. 67: 840-842.

8. Linsley, R. K., M. A. Kohler, and J. L. H. Paulhus, 1949. Applied hydrology. McGraw-Hill Book Co., Inc., New York.

9. Priestley, C. H. B. and R. J. Taylor, 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Mon. Wea. Rev. 100: 81-92.

10. Robertson, G. W., 1968. A biometeorological time scale for a cereal crop involving day and night temperatures and photoperiod. Intern. J. Biometeor. 12: 191-223.

11. Smithsonian Institute, 1951. Smithsonian meteorological tables, 6th ed., Washington, D.C.

12. Stuff, R. J., 1975. Preliminary evaluation of phenological models for spring wheat. Tech. Memo. #6134, Lockheed Electronics Co., Johnson Space Center, June.

13. Tanner, C. B. and W. A. Jury, 1976. Estimating evaporation and transpiration from a row crop during incomplete cover. Agron. Jour. 68; 239-243.

APPENDIX A

ADJUSTING ROBERTSON'S BIOMETEOROLOGICAL TIME SCALE TO WINTER WHEAT CLIMATES AND VARIETAL MATURITIES

1. Recommendations

For winter wheat in the Great Plains region, we recommend that the daily increments of development (DID), produced by direct application of Robertson's biometeorological time scale (BMTS), be modified by multiplying each DID, by

(1) $M_{70} = .5684 + (.025081)ADTJ - (.006139)AAPR$,

where

M_{70} = a multiplier for a varietal maturity class defined by varieties popular in the Great Plains region in 1970,

ADTJ = long-term average daily temperature for the month of January for a specified location or region (e.g. a CRD),

AAPR = Average annual precipitation for a specified location or region.

The scalar multiplier should be applied from <u>simulated emergence to heading only</u>. Values of M_{70} for various combinations of ADTJ and AAPR are shown in Table A.1.

For LACIE areas, other than the Great Plains, we do not have information on popular varieties (and hence varietal maturities) in our data bank. Two possible courses of action for regions in the <u>Northern hemisphere</u> are:

a. Assume the popular varieties have maturities similar to those found in the Great Plains for the same combination of values of ADTJ and AAPR and use M_{70} from Equation 1.

or

b. If information is available within a region, on varietal maturities relative to U. S. varietal maturity classes, then the following set of equations can be used to estimate a multiplier value:

(2) $M_{early} = .7037 + (.023445)ADTJ - (.006735)AAPR,$

(3) $M_{mid\text{-}early} = .7613 + (.018766)ADTJ - (.007251)AAPR,$

(4) $M_{mid\text{-}late} = .7905 + (.012568)ADTJ - (.005733)AAPR,$

(5) $M_{late} = .7243 + (.009613)ADTJ - (.003536)AAPR.$

Equations (2) through (5) were established using varieties, or varieties similar to those, shown in Table A.2.

The remainder of this report deals with methodology used to establish Equations (1)-(5), a test of the results for the Great Plains area, and comments on potential for improved models.

2. Methodology and Statistical Analysis

To estimate the increase or decrease in calendar days from emergence to heading associated with a given scalar multiplier, a computer program was written to systematically apply a range of multiplier values to DID's given by the BMTS over as few as four and as many as 56 seasons at Branch Agricultural Experiment Station (BAES) locations in the Great Plains. Multiplier values, over a range of 0.55 units, in increments of 0.05, were applied at each location. The BMTS was started each fall with either a known planting date or the average of planting dates for a BAES location. A computer printout showed, for each multiplier value, the average Julian day when the adjusted BMTS (A-BMTS) reached 3.0 (heading on the BMTS scale). The average was computed over seasons. A portion of the results are shown graphically in Figure A.1.

The next step was to determine, for each location, a multiplier value that would equalize average simulated headings with average observed heading dates for specified maturity classes. Two approaches were applied to the problem of defining maturity classes.

Approach #1. Varieties for which considerable heading data were available from varietal trials at BAES were singled out to represent early, mid-early, mid-late, and late maturities (see Table A.2). For a given location, average heading dates were computed for varieties belonging to the various maturity classes. Graphs similar to those in Figure A.1 were used to associate a multiplier value with an average observed heading date for a maturity class. The selected multiplier values are shown in Table A.3. For example, the average heading date for Scout (mid-early maturity) at Garden City, Kansas was day number 136.6 and from Figure A.1, this corresponds to the multiplier 1.23, recorded in Table A.3. Approach #1 was used in deriving Equations (2)-(5).

Approach #2. For each season, at each BAES, three popular varieties were singled out to provide yield and phenology data. Popular varieties were chosen by examining USDA-SRS data. The average of the average observed heading dates of the three varieties was computed and referred to Figure A.1, and similar graphs, to select a multiplier value. Multiplier values, so selected, changed from year to year only if the selected popular varieties changed. Multipliers for the harvest years of 1950, 1960, 1970 are shown in Table A.3. There is a clear movement toward planting earlier varieties in Oklahoma and Texas during the 1950 to 1970 time frame. If we take the column headed "Late" maturity to represent the period before 1940, then a movement toward planting earlier maturing varieties in the 1940's, throughout the Great Plains, is even more apparent.

By following the values of multipliers in Table A.3 from the Late maturity class, through 1950, 1960, and 1970, and then to the Early maturity class one concludes that the movement by farmers toward adopting earlier maturing varieties has peaked. For many locations there has been little or no change from 1960 to 1970. This is the basis for the recommendation that Equation (1) derived for varieties popular in 1970 can be used at the present time.

The variation in multiplier values from location-to-location shown in Table A.3 suggested that factors existed causing variation in the length of time from emergence-to-heading not accounted for by air temperature and daylength alone (factors of the BMTS). First it was noted that variation in multipliers was related to latitude and elevation of the BAES. (See December Monthly Progress Report for Contract NAS9-14282). While such a relation would help to determine multipliers for points between the BAES's in the Great Plains, it became clear that the formulas would not be applicable in other LACIE regions.

Two factors not included in Robertson's BMTS are soil temperature and soil moisture. Soil temperature lags behind air temperature both in the period of declining temperatures leading to dormancy and in the period of increasing temperatures coming out of dormancy. The amount of lag coming out of dormancy is dependent on the severity and duration of a cold spell. The more heat that is taken out of the soil, the more that must be restored following dormancy. Hence one might expect to find in the Northern hemisphere that some of the location-to-location variation in multiplier values is associated with long-term average daily temperatures for January (ADTJ).

Lack of soil moisture can induce an increased rate of maturity since biological functions are accelerated. Excess soil moisture acts together with sub-freezing temperatures to cause a larger lag between soil and ambient air temperatures than under drier moisture conditions and results in slower plant development in the post-dormancy period. Average annual precipitation

(AAPR) has been chosen to represent the soil moisture effect at a location. Better explanatory variables can probably be found but values for ADTJ and AAPR are readily available for not only the Great Plains but also other LACIE areas.

Values for ADTJ and AAPR are given in Table A.3 for BAES locations in the Great Plains. Regression analyses were performed using multipliers for a maturity class as a dependent variable and ADTJ and AAPR as independent variables. Allowance was made for testing models other than those linear in ADTJ and AAPR. For maturities represented by "1970 varieties", a model which included an interaction term gave a statistically better fit than that with linear terms only but this model is not being recommended in place of (1) because:

a. The reduction in the standard error of estimate from $\hat{\sigma} = .092$ to $\hat{\sigma} = .085$ did not appear large enough to warrant dropping the simpler linear model in favor of a model that may give misleading results under extrapolation.

b. The models for "1950 and 1960 varieties" were linear in ADTJ and AAPR as were those for Early, Mid-Early, Mid-Late, and Late Varieties.

c. There is no apparent physical explanation to account for an interaction term.

d. The interaction term may have been a result of the particular combination of locations and varieties used and may not be present with some additional strategically located data points.

e. Frequency distributions of differences between observed and model estimated heading dates, for 168 location-years between 1965 and 1973, were almost identical for both models.

Table A.4 summarizes the major statistical results relative to prediction equations for multipliers. Small standard errors for the coefficients and large values of R^2 (square of the multiple correlation coefficient) show the importance of ADTJ and AAPR in explaining variation in multiplier values among locations.

3. A Test of the Model

To test the power of our model to determine a multiplier which will produce simulated headings that are close to actual heading dates, for diverse climates, the multipliers (M_{70}) produced by Equation (1) were applied to DID's produced by the BMTS for the years 1965 to 1973 at each location where heading dates were available in our data bank. The results are shown in Table A.5 which give the average observed heading day for three popular varieties, the Julian day when the adjusted BMTS (A-BMTS) reached simulated heading, and the day when simulated heading would have been reached if no adjustment (U-BMTS were applied (multiplier = 1.0).

Results from Table A.5 are partially summarized in Table A.6 which shows the frequency distribution of absolute differences between observed headings and A-BMTS simulated headings and between observed and U-BMTS simulated headings. Results in Table A.6 indicate that 83% of the simulated headings would be within ± 7 days of the average observed heading date of three varieties. A detailed look at the 10 cases for which the absolute difference between observed and model exceeded 11 days showed no particular geographical or temporal pattern.

The consequences of not adjusting Robertson's BMTS to winter wheat varieties and conditions is shown rather explicitly in Table A.6. Forty-six percent of the differences are greater than seven days with deviations, as large as 30 days occurring. Clearly, use of equation (1) and application of M_{70} to DID's, while not as precise as might be achieved with further work, provides a marked improvement over use of an unadjusted BMTS for Winter Wheat.

4. Potential for Improvement

An obvious approach to improvement is to look for variables other than the average daily temperature in January (ADTJ) and average annual precipitation (AAPR) to more accurately reflect location-to-location variation in the crop calendar. However, it should be noted that the root mean square for differences between observed and A-BMTS heading dates, shown in Table A.5, is 6 days which compares with about 4 days for Robertson's BMTS applied to a single variety of spring wheat. Part of the difference in the root mean squares is due to (a) sets of three varieties used in some location-years had maturities different from those used to estimate M_{70}, (b) variation in observer's definition of heading dates (many different observers provided heading dates at the BAES's) and (c) variation in planting dates between observation and model.

For general application of results, one seeks explanatory variables which are available for all LACIE areas and/or simple to calculate from historical data. A search for other explanatory variables may provide some improvement but may not be worth the effort.

Relative to year-to-year effects we ran one test which gave negative results. In this test we ran the A-BMTS, season-by-season, using M_{70}, with ADTJ and AAPR inputs from emergence to February 1.

On February 1, M_{70} was recomputed by replacing ADTJ (the average daily temperatures for many seasons) by the average daily temperature for January for that particular season. The simulation from February 1 to heading was completed using this new multiplier. The results for six locations in Kansas for the harvest years 1965 to 1973 showed larger discrepancies (differences between observed and model-generated heading dates) than those in Table A.5 where the same value of M_{70} is used season after season. With hindsight, this result should have been premeditated. While the average daily temperature in

January (ADTJ), computed over many years, may be a reasonable measure of the average heat loss at a location, relative to other locations, and accounts for some of the spacial variation in multipliers for the daily increments of developments (DID's); it does not follow that the average daily January temperature for a particular year is a precise measure of the heat loss for that year relative to other years.

Sizeable improvement in the accuracy of measuring the development rate of winter wheat probably involves going back to the fundamental ideas used by Robertson in developing the BMTS for spring wheat. Our work suggests that some measure of soil temperature and soil moisture should be incorporated into the DID's so that the effects of these factors would be included in simulating both year-to-year and location-to-location variation in the crop calendar.

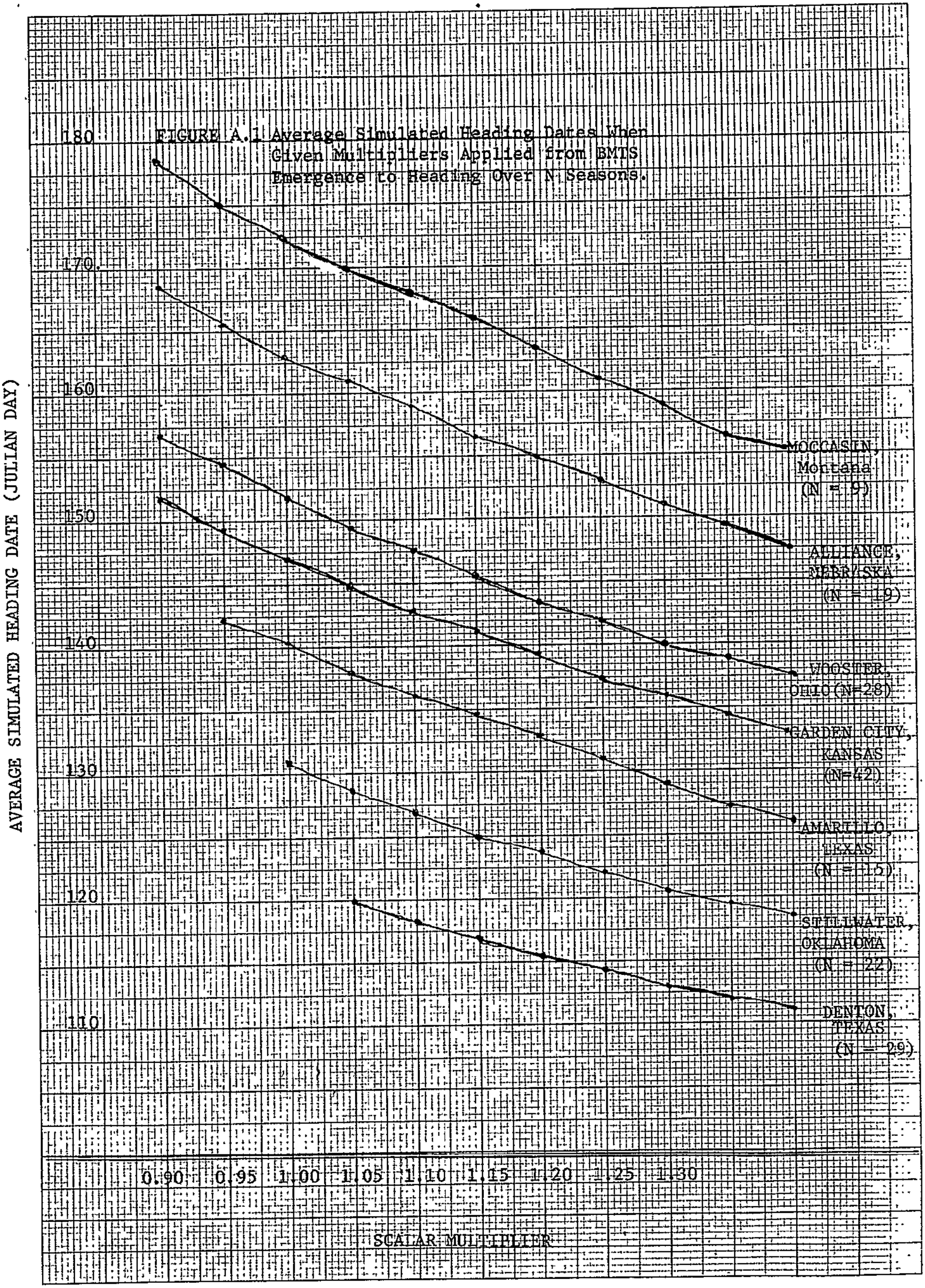

FIGURE A.1 Average Simulated Heading Dates When Given Multipliers Applied from BMTS Emergence to Heading Over N Seasons.

Table A.1 Scalar multiplier for adjusting Robertson's biometeorological time to winter wheats.

Annual Precip. (Inches)	January Average Temperature (Fahrenheit Degrees)																	
	7.5	10.0	12.5	15.0	17.5	20.0	22.5	25.0	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	50.0
10	0.70	0.76	0.82	0.88	0.95	1.01	1.07	1.13	1.20	1.26	1.32	1.38	1.45	1.51	1.57	1.64	1.70	1.76
15	0.66	0.73	0.79	0.85	0.92	0.98	1.04	1.10	1.17	1.23	1.29	1.35	1.42	1.48	1.54	1.60	1.67	1.73
20	0.63	0.70	0.76	0.82	0.88	0.95	1.01	1.07	1.14	1.20	1.26	1.32	1.39	1.45	1.51	1.57	1.64	1.70
25	0.60	0.67	0.73	0.79	0.85	0.92	0.98	1.04	1.10	1.17	1.23	1.29	1.36	1.42	1.48	1.54	1.61	1.67
30	0.57	0.64	0.70	0.76	0.82	0.89	0.95	1.01	1.07	1.14	1.20	1.26	1.32	1.39	1.45	1.51	1.58	1.64
35	0.54	0.60	0.67	0.73	0.79	0.86	0.92	0.98	1.04	1.11	1.17	1.23	1.29	1.36	1.42	1.48	1.54	1.61
40	0.51	0.57	0.64	0.70	0.76	0.82	0.89	0.95	1.01	1.08	1.14	1.20	1.26	1.33	1.39	1.45	1.51	1.58
45	0.48	0.54	0.61	0.67	0.73	0.79	0.86	0.92	0.98	1.04	1.11	1.17	1.23	1.30	1.36	1.42	1.48	1.55
50	0.45	0.51	0.57	0.64	0.70	0.76	0.83	0.89	0.95	1.01	1.08	1.14	1.20	1.26	1.33	1.39	1.45	1.52

Table A.2 Winter wheat varieties used to define maturity classes.

	ADTJ < 20°F	ADTJ > 20°F	
Maturity	Hard Wheats	Hard Wheats	Soft Wheats
Early	Lancer, Warrier, Hume	Triumph class	Monon, Benhur, Knox
Mid-Early	Nebred, Winoka, Winalta	Scout class	Arthur
Mid-Late	Minter	Comanche, Pawnee	Dual, Fairfield
Late	Kharkof, Yogo, Cheyenne	Turkey, Kharkof	Trumbull, Redcoat

Table A.3 BMTS multipliers which equate average observed heading dates for maturity classes to average simulated heading dates and values of explanatory variables.

Location	Maturity Classes: Varieties Popular in: 1970	1960	1950	Late	Mid-Late	Mid-Early	Early	Explanatory Variables: ADTJ	AAPR
Grand Rapids, MN	--	.81	.81	.76	.80	.81	.84	6.1	25.7
Minot, ND	.73	.70	--	.65	.70	.75	.79	7.0	15.4
Williston, ND	.77	--	--	.76	.77	.80	.82	10.0	14.1
Dickinson, ND	.82	.86	.85	.78	.83	.83	.90	10.4	15.5
Brookings, SD	--	.78	--	.76	.78	.80	.81	13.4	19.8
Waseca, MN	.74	.73	.72	.69	.72	.76	.78	13.6	28.3
St. Paul, MN	.70	.73	.75	.65	.73	.75	.78	14.6	24.7
Havre, MT	.88	.90	.87	.85	.90	.96	1.04	16.2	12.3
Ames, IA	--	.88	.94	.81	.85	.93	1.00	19.5	31.8
Moccasin, MT	.96	.92	--	.84	.90	.96	.99	20.8	14.0
Alliance, NB	1.10	1.04	1.04	.97	1.08	1.05	1.12	22.9	16.7
Mead, NB	.93	--	--	.83	1.01	1.03	1.15	23.7	27.8
North Platte, NB	1.05	1.00	1.04	.97	1.09	1.02	1.15	24.0	20.7
Wanatah, IN	.96	.89	--	.82	.85	.93	.98	24.7	36.0
Akron, CO	1.21	1.22	1.17	.96	1.07	1.24	1.28	25.1	17.7
Lincoln, NB	--	.84	.84	.78	.87	.95	1.00	25.5	27.3
Lafayette, IN	1.05	1.03	.88	.86	.91	1.04	1.10	25.7	36.8
Fort Collins, CO	--	--	--	.97	1.08	1.20	1.24	26.0	14.5
Julesburg, CO	1.17	--	--	.97	1.10	1.20	1.22	26.4	16.8
Yellow Jacket, CO	1.20	1.18	--	1.08	1.17	1.22	1.24	26.5	13.3
Vickery, OH	--	--	--	.83	--	--	1.01	27.0	35.0
Urbana, IL	.90	.92	.88	.71	.83	.97	1.06	27.1	36.6
Custar, OH	.93	--	--	.84	--	--	.98	27.1	35.3
Wooster, OH	1.03	1.05	1.01	.96	1.00	1.04	1.10	27.4	38.1

Table A.3 (continued)

Location	Varieties Popular in: 1970	1960	1950	Late	Mid-Late	Mid-Early	Early	ADTJ	AAPR
			Maturity Classes					Explanatory Variables	
Canfield, OH	--	--	--	1.03	--	--	1.11	27.5	34.0
Manhattan, KS	1.00	1.01	1.03	.88	.97	.99	1.09	28.1	31.7
Tribune, KS	1.02	1.03	1.05	.88	--	--	1.09	28.3	16.8
Colby, KS	1.27	1.18	1.18	.90	1.14	1.31	1.39	28.8	18.6
Farmland, IN	--	--	--	.80	.96	1.01	1.04	29.3	38.9
Hays, KS	1.19	1.21	1.17	.97	1.14	1.22	1.33	29.5	23.0
Hutchinson, KS	1.29	1.28	1.27	1.04	1.14	1.33	1.45	30.2	29.0
Ottawa, KS	1.11	--	--	.96	1.02	1.08	1.24	30.3	37.2
Garden City, KS	1.18	1.22	1.15	.93	1.10	1.23	1.29	30.9	18.8
Columbia, MO	1.00	1.01	.95	.86	.91	.94	1.07	31.0	39.4
Springfield, OH	.99	--	--	.90	.92	1.04	1.12	32.1	37.4
Ripley, OH	--	--	--	.93	--	--	1.12	32.8	40.6
Columbus, KS	1.25	1.19	1.11	.93	1.06	1.25	1.33	34.4	42.3
Goodwell, OK	1.21	1.21	1.15	.91	.95	1.16	1.29	34.5	17.7
Amarillo, TX	1.31	1.25	1.17	1.00	1.02	1.25	1.44	35.3	21.1
Woodward, OK	--	--	--	.91	.99	1.28	1.43	35.9	25.1
Stillwater, OK	1.47	1.27	1.21	.96	1.10	1.26	1.56	36.9	32.8
Clovis, NM	1.26	1.16	1.16	1.08	1.18	1.28	1.32	36.7	17.9
Portageville, MO	1.31	1.20	--	.97	1.04	1.11	1.33	39.3	46.7
Chillicothe, TX	1.37	1.36	1.22	.92	1.11	1.28	1.47	42.5	25.3
Denton, TX	1.65	1.30	1.20	.97	1.03	1.30	1.60	44.6	32.6
College Station, TX	1.70	1.58	--	--	--	--	--	51.3	38.7

Table A.4 Coefficients, standard errors, and related statistics for models to adjust the BMTS to winter wheat environments and varietal maturities.

Varietal Maturity		Coefficients (COEF) and Their Standard Errors (S.E.) Constant	ADTJ	AAPR	$\hat{\sigma}$	R^2	N
1970	COEF.	.5684	.025081	-.006139	.092	.855	37
	S.E.	.0526	.001826	.001779			
1960	COEF.	.6522	.019478	-.004599	.086	.838	35
	S.E.	.0492	.001547	.001718			
1950	COEF.	.7760	.014825	-.005730	.085	.731	28
	S.E.	.0660	.001815	.002033			
Late	COEF.	.7243	.009613	-.003536	.073	.546	44
	S.E.	.0402	.001368	.001291			
Mid-Late	COEF.	.7905	.012568	-.005733	.084	.635	40
	S.E.	.0462	.001569	.001542			
Mid-Early	COEF.	.7613	.018766	-.007251	.081	.804	40
	S.E.	.0449	.001526	.001500			
Early	COEF.	.7037	.023455	-.006735	.095	.811	44
	S.E.	.0522	.001776	.001676			

Table A.5 Comparison of observed (obs.)[†], adjusted BMTS (A-BMTS)[††], and unadjusted BMTS (U-BMTS)[§] heading dates (Julian day).

Location	Multiplier		Year 65	66	67	68	69	70	71	72	73
Havre, MT		OBS.	168		173	161	158	168		162	164
	.90	A-BMTS	168		170	166	159	161		158	163
	1.00	U-BMTS	163		166	160	155	158		154	158
Moccasin,		OBS.		170	182	171		175	171	165	174
MT	1.00	A-BMTS		171	179	171		172	173	162	168
	1.00	U-BMTS		171	179	171		172	173	162	168
Minot, ND		OBS.	194	183	177	174			174		165
	.65	A-BMTS	187	185	187	192			180		183
	1.00	U-BMTS	164	169	167	168			162		161
Williston,		OBS.			169	166	162	178		167	
ND	.73	A-BMTS			178	175	168	174		165	
	1.00	U-BMTS			162	156	151	161		154	
Dickinson,		OBS.		173	178	177					
ND	.73	A-BMTS		184	185	189					
	1.00	U-BMTS		171	168	172					
St. Paul,		OBS.	172	170			154		156		
MN	.78	A-BMTS	163	166			158		162		
	1.00	U-BMTS	152	156			147		153		
Waseca,		OBS.					162				
MN	.74	A-BMTS					164				
	1.00	U-BMTS					150				
Alliance,		OBS.	168	156	164						
NB	1.04	A-BMTS	161	162	161						
	1.00	U-BMTS	163	154	164						
North		OBS.			157	154	146		157	153	
Platte,	1.04	A-BMTS			159	158	149		161	154	
NB	1.00	U-BMTS			161	159	150		163	154	
Mead, NB		OBS.							152	152	
	.99	A-BMTS							155	150	
	1.00	U-BMTS							155	149	

Table A.5 (continued)

Location	Multiplier	65	66	67	68	69	70	71	72	73
		Year								
Akron, CO	OBS.			153	155	146	153	157	146	159
	1.09 A-BMTS			155	158	148	156	161	150	158
	1.00 U-BMTS			158	162	154	160	164	154	161
Julesburg, CO	OBS.		149	149		147				
	1.13 A-BMTS		147	150		146				
	1.00 U-BMTS		151	157		150				
Yellow Jacket, CO	OBS.	172	162		163					
	1.15 A-BMTS	172	162		169					
	1.00 U-BMTS	179	168		174					
Colby, KS	OBS.	140		138		144	141	144		
	1.18 A-BMTS	140		151		149	144	153		
	1.00 U-BMTS	148		158		156	149	159		
Hays, KS	OBS.	136	138	131	137	140	139	137	140	142
	1.17 A-BMTS	135	139	142	151	138	140	147	142	141
	1.00 U-BMTS	141	146	146	155	147	144	154	148	146
Hutchinson, KS	OBS.	129	130	123	124	132	130	125	121	136
	1.15 A-BMTS	131	131	132	135	133	135	138	132	136
	1.00 U-BMTS	137	137	139	144	139	140	144	137	141
Tribune, KS	OBS.				149	143	143			
	1.18 A-BMTS				135	139	136			
	1.00 U-BMTS				151	147	140			
Garden City, KS	OBS	138	140		145	138	138	138	136	
	1.23 A-BMTS	134	135		146	138	140	145	137	
	1.00 U-BMTS	142	144		155	147	147	153	145	
Columbus, KS	OBS.	124	123	120	128		126	126		
	1.18 A-BMTS	122	125	122	127		128	131		
	1.00 U-BMTS	127	133	131	134		133	138		
Manhattan, KS	OBS.	134	137	142	137	151	135	136	139	137
	1.08 A-BMTS	129	135	133	133	142	134	135	136	135
	1.00 U-BMTS	133	138	138	137	146	138	138	138	138
Ottawa, KS	OBS					139	137			
	1.10 A-BMTS					136	140			
	1.00 U-BMTS					140	143			

Table A.5 (continued)

Location	Multiplier		65	66	67	68	69	70	71	72	73
Columbia,		OBS.	136					138		135	
MO	1.10	A-BMTS	131					133		132	
	1.00	U-BMTS	134					138		135	
Portage-		OBS.			118	125	122			114	
ville,	1.27	A-BMTS			113	122	125			122	
MO	1.00	U-BMTS			122	128	130			128	
Urbana,		OBS.		153							
IL	1.02	A-BMTS		147							
	1.00	U-BMTS		147							
Lafayette,		OBS	141			144		142		143	
IN	.99	A-BMTS	140			151		144		147	
	1.00	U-BMTS	140			150		144		147	
Wanatah,		OBS.	146			149		144		149	
IN	.97	A-BMTS	141			150		144		149	
	1.00	U-BMTS	140			149		143		148	
Spring-		OBS.							147		156
field,	1.14	A-BMTS							144		147
OH	1.00	U-BMTS							153		152
Wooster,		OBS.	146			150					
OH	1.02	A-BMTS	147			154					
	1.00	U-BMTS	147			155					
Stillwater,		OBS.	121	118		116	119	117	113	105	116
OK	1.29	A-BMTS	114	122		117	123	122	123	113	126
	1.00	U-BMTS	123	131		126	131	131	137	126	137
Goodwell,		OBS.	141	130	120	127		127		119	136
OK	1.33	A-BMTS	128	122	118	129		128		116	140
	1.00	U-BMTS	141	136	132	148		140		127	154
Woodward,		OBS.	122	117		117	124	122			
OK	1.31	A-BMTS	119	122		118	128	125			
	1.00	U-BMTS	126	129		127	139	132			
Clovis,		OBS.				126	125	126	128	120	137
NM	1.38	A-BMTS				127	122	130	123	117	131
	1.00	U-BMTS				144	140	144	142	134	148

Table A.5 (continued)

Location	Multiplier		Year 65	66	67	68	69	70	71	72	73
Chillocothe,		OBS.	128	124	104			115		99	122
TX	1.48	A-BMTS	110	107	99			115		102	118
	1.00	U-BMTS	125	126	116			128		113	131
Amarillo,		OBS.		120			130				137
TX	1.32	A-BMTS		127			123				132
	1.00	U-BMTS		138			136				141
Denton,		OBS.		108				111	102		
TX	1.49	A-BMTS		106				111	108		
	1.00	U-BMTS		119				120	118		
College		OBS.	109	106	96			105			
Station,	1.62	A-BMTS	102	102	95			107			
TX	1.00	U-BMTS	114	116	108			117			

†Based on average of three popular varieties planted in given year.

††Based on Equation (1) - Maturity class based on varieties popular in 1970.

§Based on BMTS without adjustments.

Table A.6 Frequency and relative frequency of absolute differences between observed and BMTS heading dates shown in Table A.5.

	Observed Minus A-BMTS		Observed Minus U-BMTS	
Class Interval	Frequency	Relative Frequency	Frequency	Relative Frequency
0-3 days	83	.494	43	.256
4-7 days	56	.333	48	.286
8-11 days	19	.113	33	.196
12 or greater	10[†]	.060	44[††]	.262
Total	168	1.000	168	1.000

[†] Largest difference was 18

[††] Largest difference was 30

FORMULAS AND ASSIGNED PARAMETER VALUES FOR THE VSMB

In this section we document the pertinent formulas used from Baier and Robertson's versatile soil moisture budget (VSMB). A more detailed description is given in Baier, et. al. (5).

Potential evapotranspiration

Potential evapotranspiration is simulated on a daily basis by calculating:

$$PE = 0.0037[0.933\ (TX-TN) + 0.928\ TX + 0.0486\ Q_0 - 87.03] \quad \text{if } [\quad] > 0$$
$$= 0 \quad \text{if } [\quad] \leq 0$$

where

PE = potential evapotranspiration (inches),

TX = maximum daily temperature (°F),

TN = minimum daily temperature (°F),

Q_o = solar radiation at the edge of the atmosphere (cal cm^{-2} day^{-1}).

The quantity Q_o was linearly interpolated from Smithsonian tables (11).

Actual evapotranspiration

Actual evapotranspiration is simulated for a particular day in month m (m = 1, 2,..., 12) by:

$$AE = (PE) \sum_{j=1}^{6} (S_j'/S_j)(K_j')(Z_j)\exp\{[7.91 - 11.0 * (S_j'/S_j)][PE - \overline{PE}_m]\}$$

where

AE = actual evapotranspiration (inches),

S_j' = plant-available soil moisture in zone j at the end of the previous day (inches),

S_j = capacity of zone j for plant-available water (inches) (see Table B.1),

K'_j = adjustable crop coefficient for zone j, which varies with stage of development and dryness of zone j according to the formula

$$K'_j = K_j \{1 + \sum_{i=1}^{j-1} K_i[1 - (S'_i/S_i)]\}$$

where values of $K_j (j = 1, 2, \ldots 6)$ are given in Table B.2,

Z_j = adjustment factor for zone j using soil dryness curve F, (product of S'_j/S_j and associated entry in Table B.3)

$\overline{PE}_m$ = long-term average daily PE for month m (m = 1, 2, ..., 12), where $\overline{PE}_m$ may be approximated by the quantity

$0.0037[0.933\ (\overline{TX}_m - \overline{TN}_m) + 0.928\ \overline{TX}_m + 0.0486\overline{Q}_{om} - 87.03]$, if $[\ ] \geq 0$ or zero if $[\ ] < 0$.

where

$\overline{TX}_m$, $\overline{TN}_m$, $\overline{Q}_{om}$ are long-term means for month m.

Runoff and Infiltration

The amount of water infiltrating the soil from 24-hour precipitation amounts is simulated by the formula:

$$I = 0.9177 + [1.811 - 0.97(S'_1/S_1)] * \log_{10} PR, \text{ if } PR > 1.0,$$

$$= PR \qquad \text{if } PR \leq 1.0,$$

where

I = amount infiltrating soil (inches),

PR = amount of precipitation (inches),

S'_1, S_1 have been previously defined.

Snow budget

The main decisions to be made in the snow budget are choices of snow coefficients and temperature thresholds for classifying precipitation as snow. For snow coefficients we chose to use 0.65 for the fallow period for winter wheat and the same for the first winter of fallowing for spring wheat. The second snow coefficient was set at 0.10 for simulating conditions either under a crop for winter wheat or for the second winter under fallow for spring wheat or between crops for continuous spring wheat.

Threshold values for differentiating rain from snow were chosen to be 33.8°F, both before and after January 1, for all locations in the U. S. Great Plain

Table B.1 Values chosen for capacities for VSMB zones.

	Zones						
	1	2	3	4	5	6	Totals
			Percent of total capacity				
	5.0	7.5	12.5	25.0	25.0	25.0	100%
			Capacities (inches)				
Winter Wheat	0.50	0.75	1.25	2.50	2.50	2.50	10 inches
Spring Wheat	0.35	0.525	0.875	1.75	1.75	1.75	7 inches

Table B.2 Crop coefficients (K) for VSMB zones.

		Zones					
Development Stage	BMTS	1	2	3	4	5	6
Planting-emergence	0-1	.60	.15	.05			
Emergence-jointing	1-2	.55	.25	.05			
Jointing-heading	2-3	.40	.25	.10	.10	.05	
Heading-soft dough	3-4	.45	.25	.10	.10	.05	.05
Soft dough-ripe	4-5	.45	.25	.10	.10		
Fallow	---	.60	.15	.05			

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Table B.3 Table F for computing Z values in VSMB (Entries are functions of Z_j'/Z_j from .01 (.01)1.00 in lexicographical order).

1.00	0.75	0.66	0.50	0.60	0.66	0.85	1.12	1.44	1.66
1.82	2.33	2.69	3.00	3.33	3.43	3.70	3.89	4.00	4.00
4.00	4.00	4.00	3.91	3.80	3.69	3.59	3.50	3.41	3.33
3.20	3.10	3.00	2.92	2.85	2.77	2.69	2.60	2.55	2.50
2.45	2.37	2.30	2.26	2.22	2.16	2.10	2.07	2.04	2.00
1.95	1.90	1.86	1.83	1.80	1.77	1.75	1.72	1.69	1.66
1.63	1.60	1.58	1.56	1.53	1.51	1.49	1.47	1.45	1.42
1.40	1.38	1.36	1.34	1.32	1.30	1.28	1.27	1.26	1.25
1.23	1.21	1.19	1.18	1.17	1.15	1.14	1.13	1.12	1.11
1.10	1.09	1.08	1.06	1.05	1.04	1.03	1.02	1.01	1.00

APPENDIX C

Estimating Evapotranspiration from Winter Wheat

Edward T. Kanemasu

INTRODUCTION

One of the most important factors influencing wheat growth and subsequent grain yield is soil water availability. In attempts to predict wheat production over a large region, the daily estimates of evapotranspiration is desirable. Several evapotranspiration (ET) models have been proposed (Jensen, 1973; Baier and Robertson, 1966; Ritchie, 1972; Tanner and Ritchie, 1975) with varying degrees of complexity as to input data. On a regional basis, many models are not acceptable because of type of meteorological data required. Data requirements become critical when such models are applied to countries or locations where meteorological data are minimal. Therefore, it would appear advantageous to develop a model for daily ET based upon parameters that can or have the potential for being estimated by spacecraft. Tanner and Ritchie's approach appears to have that application.

METHODS AND MATERIALS

On October 16, 1974 winter wheat [<u>Triticum aestivum</u> (L.) cv. Cloud] was planted on two 1-ha plots at the Evapotranspiration Research Field, 14 km southeast of Manhattan, Kansas. Wheat was planted in 17.8-cm north-south rows. A weighing lysimeter was located in the center of each plot; however, one of the plots had been planted to sorghum and showed atrazine carryover. Meteorological and physiological measurements have been described by Brun, Kanemasu, and Powers (1972). Leaf area index was determined weekly except during dormancy when monthly samples were sufficient.

In addition, we maintained 3 test areas in Riley (96°37'W,39°8'N), Ellsworth (98°17.5'W, 38°43'N), and Finney counties (101°5.9'W,38°9.6'N). In each test area, 3 large winter wheat fields (> 40 ha) were periodically monitored (usually on clear Landsat overpass dates) for leaf area index and soil moisture estimates.

Near the lysimeter area, five recommended winter wheat varieties were planted (33 m x 120 m). Soil moisture and leaf area index were estimated every 7 to 10 days except during dormancy when monthly samples were taken.

MODEL

Maximum evapotranspiration (ET_{max}) is the energy-limited ET occurring from a well-watered surface. Several investigations (Tanner and Ritchie, 1975, Davies and Allen, 1973; Jury and Tanner, 1975; and Priestley and Taylor, 1972) have successfully shown that the Priestley-Taylor formula estimates ET for conditions of adequate water and leaf area index ≥ 2.5:

$$ET_{max} = \alpha[s/(s+\gamma)]Rn \quad [1a]$$

where α is a proportionality constant for a particular crop and climate; γ is the psychrometer constant (mb/°K); s is the slope of the saturation vapor pressure curve (mb/°K) at mean temperature; and Rn is the 24-hr net radiation (mm water/day). Priestley and Taylor (1972), in evaluating eleven climatic situations (non-advective conditions), found a mean $\alpha = 1.26$; α will increase with advection (Jury and Tanner, 1975). We evaluated α by rearranging [1]

$$\alpha = \frac{ET_{max}}{[s/(s+\gamma)]Rn} \quad [1b]$$

where ET_{max} was estimated by lysimetric observations during periods of full canopy cover and wet soil surface (0-5 cm). Using 24-hour Rn in [1b], we evaluated an α of 1.35. In situations in which we did not ~~measure 24-hour Rn, we used:~~

$$Rn = .868\ Rs - 2.81 \qquad [2a]$$

from planting to jointing growth stage and for the remainder of the season

$$Rn = .926\ Rs - 2.70 \qquad [2b]$$

where Rs is the solar radiation (mm day^{-1}). Therefore, ET_{max} may be determined by [1] and [2] from mean air temperature and solar radiation.

Evaporation. Our method of estimating evaporation from the soil surface was identical to that of Ritchie (1972). Briefly, when the soil surface is wet, the amount of energy at the surface is limiting evaporation; thus,

$$Eo = (\tau/\alpha)ET_{max} \qquad [3]$$

where Eo is the evaporation from the soil surface during stage 1 evaporation. Ritchie (1972) found the empirical relationship for sorghum to be:

$$\tau = Rns/Rn = exp\ (-.398\ LAI) \qquad [4]$$

where Rns is the net radiation of the soil surface and LAI is the leaf area index. Our data would support equation [4] for winter wheat until heading stage then $\tau = .25$. We propose that leaf area index can be determined from spacecraft. Evaporation, according to [3], continues until Eo = U where U is the upper limit of stage 1 evaporation. Evaporation, when limited by the transmitting properties of the soil (stage 2), is given as

$$E = ct^{1/2} - c(t-1)^{1/2} \qquad [5]$$

where c (mm day$^{-1/2}$) is dependent upon the hydraulic properties of the soil and t is time (days) after stage 1 evaporation. Ritchie (1972) reported values for U and c for several soils. From lysimeter observations on Muir silt loam, U and c were evaluated to be 10mm and 3.5mm day$^{-1/2}$, respectively.

Transpiration. Ritchie (1973) reported that transpiration from sorghum or corn is not affected by soil-water deficit until the available water in the root zone is less than 0.3 of the maximum available moisture content (θ_{max}). Thus, when the available water content in the root zone is between 1 and .3 of the maximum, transpiration (T) is estimated, as suggested by Tanner and Ritchie (1975), for crop cover <50% as

$$T = \alpha v(1-\tau)[s/(s+\gamma)]Rn \qquad [6a]$$

and for crop cover >50% as

$$T = (\alpha-\tau)[s/(s+\gamma)]Rn \qquad [6b]$$

where $\alpha v = (\alpha-.5)/.5$.

When available soil water content (θ_a) is less than .3 of the maximum avialable soil-water content, equations [6a] and [6b] are multiplied by K_s, given as

$$K_s = \frac{\theta_a}{.3\theta_{max}} \qquad [7]$$

Tanner and Ritchie (1975), in surveying the literature, found that $.3\theta_{max}$ represented the critical moisture level for nearly all data. Davies and Allen (1973) suggested using only the surface soil moisture content (depth not reported) in assessing the effect of water deficit on evapotranspiration for bare soil and shallow rooting crops but recognized the limitations of such an approach to deeply rooted crops.

We consistently underestimated the lysimetric observations on the very warm days (>27C) during full canopy cover. To account for those conditions, we added A to [6], where

$$A = .1\ T \text{ when } T_{max} > 27C \qquad [8]$$

Evapotranspiration (ET) was estimated by summing E (or Eo), T, and A (Table 1). We have no theoretical explanation for [8] except Linacre (1964) found that well-water leaves in bright sunshine are warmer than air when the ambient temperature is cool, and, at high temperatures, leaves are cooler than ambient.

RESULTS AND DISCUSSION

Figure 1 shows the comparison of lysimeter to model estimates of evapotranspiration [ET] for winter wheat. The seasonal cumulative ET for the lysimeter and model was 336 mm (13.2 in) and 321 mm (12.6 in), respectively. Daily model values of ET were usually within 1 mm of lysimeter values. The greater ET estimated by the lysimeter during November and December (15 mm) could be attributed to the additional energy the lysimeter receives from the soil due to its metal framework. Transpiration accounted for 66 percent of the total ET. While the advective corrective term, A, accounted for only 3 percent.

From effective precipitation and model evapotranspiration estimates, the soil moisture in the 150 cm profile was calculated. Figure 2 shows the comparison of soil moisture between the model estimates and those observed from gravimetric samples for the lysimeter area.

Table 1 shows the monthly ET for the five varieties of winter wheat as estimated by the model. The average seasonal ET was 432 mm (17.0 in) and was nearly identical for all varieties. During the same time period, the model predicted a seasonal ET of 420 mm (16.5 in), 335 mm (13.2 in) and 248 mm (9.8 in) for winter wheat in Riley, Ellsworth, and Finney counties, respectively (Table 2). The difference in ET across the Kansas (east to west) is due to the difference in leaf area index (Fig. 3). The greatest difference in ET occurs during March, April and May. That time corresponds to the period when leaf area indices are rapidly increasing.

LITERATURE CITED

1. Baier, W. and G. W. Robertson. 1966. A new versatile soil moisture budget. Can. J. Plant Sci. 46:299-315.
2. Brun, L. J., E. T. Kanemasu, and W. L. Powers. 1972. Evapotranspiration from soybean and sorghum fields. Agron. J. 64:145-148.
3. Chin Choy, E. W. and E. T. Kanemasu. 1974. Energy balance comparisons of wide and narrow row spacings in sorghum. Agron. J. 66:98-100.
4. Davies, J. A. and C. D. Allen. 1973. Equilibrium, potential and actual evaporation from cropped surfaces in Southern Ontario. J. App. Meteorol. 12:649-657.
5. Heilman, J. and E. T. Kanemasu. 1975. Testing a resistance form of the energy balance to estimate evapotranspiration. Agron. J. (submitted).
6. Heilman, J., Kanemasu, E. T., Rosenberg, N. J., and Blad, B. 1975. Using thermal scanner measurements of crop temperatures to estimate evapotranspiration. Remote Sens. Env. (submitted).
7. Jensen, M. E., D. C. N. Robb, and C. Eugene Franzoy. 1970. Scheduling irrigations using climate-crop-soil data. J. Irrg. and Drain Div. Proc. Amer. of Civil Eng. 96(IR 1):25-38.
8. Jury, W. A. and C. B. Tanner. 1975. A modification of the Priestley and Taylor evapotranspiration formula. Agron. J. (submitted).
9. Kanemasu, E. T., G. W. Thurtell, and C. B. Tanner. 1969. Design, calibration and field use of a stomatal diffusion porometer. Plant Physiol. 44:881-885.

10. Linacre, E. T. 1964. A note on a feature of leaf and air temperature. Agric. Meteorol. 1:66-72.

11. Priestley, C. H. B. and R. J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weath. Rev. 100:81-92.

12. Ritchie, J. T. 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8:1204-1213.

13. Ritchie, J. T. 1973. Influence of soil water status and meteorological conditions on evaporation from a corn canopy. Agron. J. 65:893-897.

14. Saxton, K. E., H. P. Johnson, and R. H. Shaw. 1974. Modeling evapotranspiration and soil moisture. Trans. Amer. Soc. Agric. Engr. 17:673-677.

15. Tanner, C. B. and J. T. Ritchie. 1975. Evapotranspiration empiricisms and modeling. Agron. J. (submitted).

16. Teare, I. D. and E. T. Kanemasu. 1972. Stomatal diffusion resistance and water potential of soybean and sorghum leaves. New Phytol. 71:805-810.

17. Thom, A. S. 1972. Momentum, mass and heat exchange of vegetation. Q. J. Roy. Meteorol. Soc. 98:124-134.

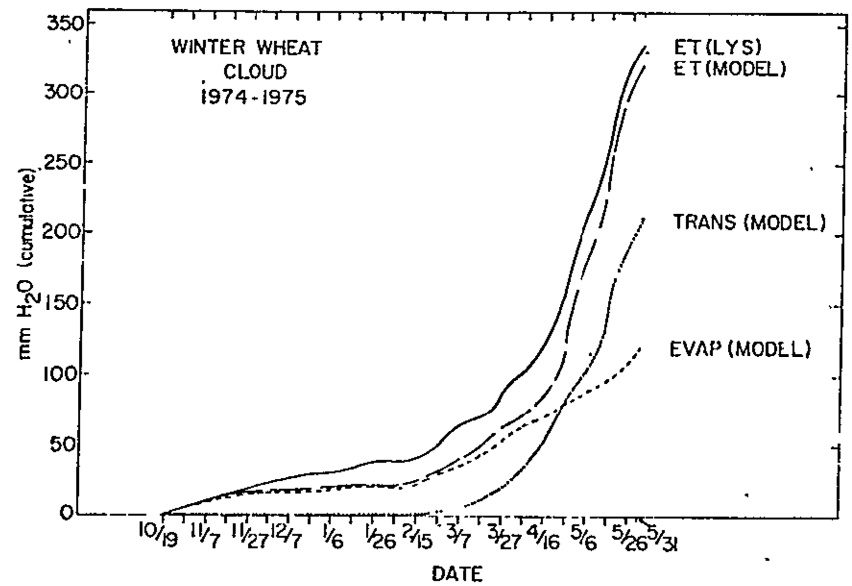

Fig. C.1 Lysimetric and model estimates of evapotranspiration (ET) and model estimates of transpiration (Trans.) and evaporation (Evap.) for winter wheat during the 1974-75 growing season at Manhattan, Kansas.

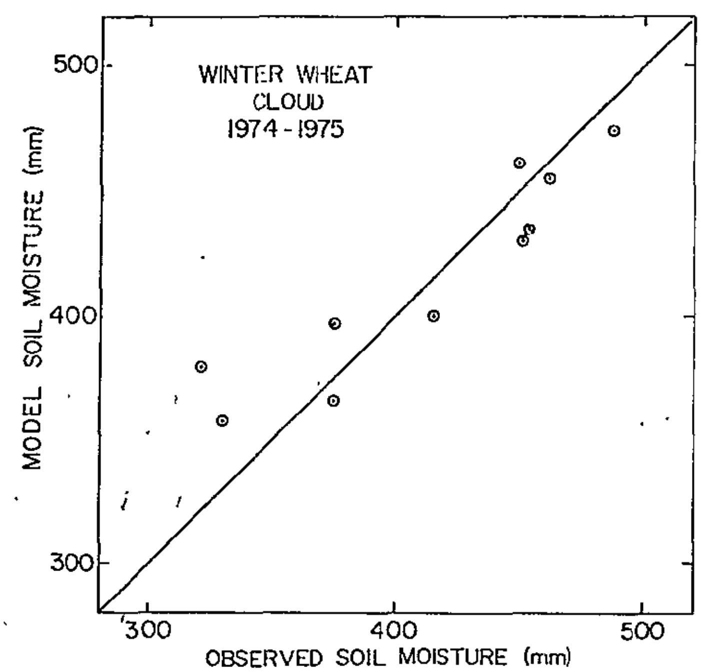

Fig. C.2 Soil moisture (mm water in the 150 cm profile) estimated by the evapotranspiration model compared to observed values.

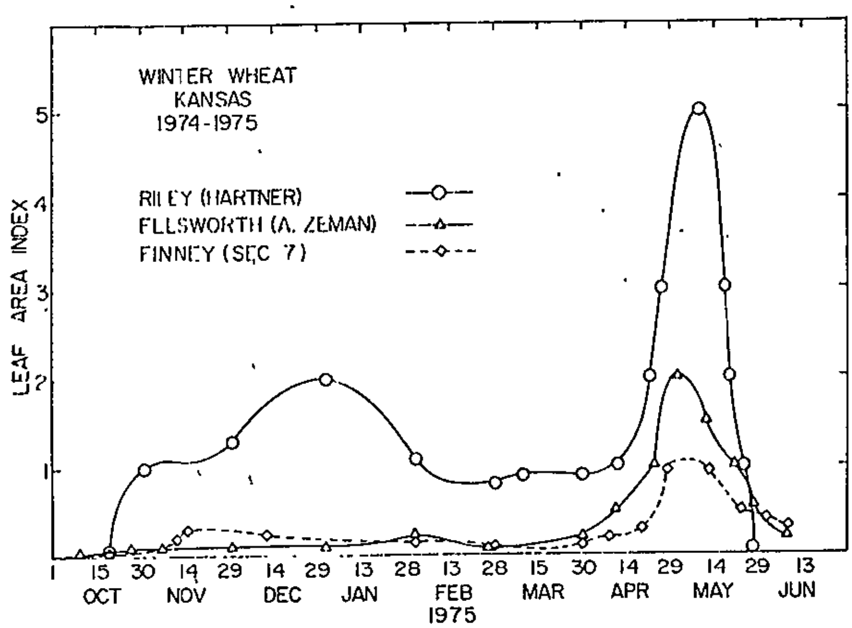

Fig. C.3 Measured leaf area indices (LAI) on three winter wheat fields in Kansas for 1974-1975 growing season.

Table C.1 Model evapotranspiration estimates for 5 winter wheat varieties at Manhattan, Kansas (planted 10/4/74).

	EVAPOTRANSPIRATION (mm)				
Date	Centurk	Trison	Arthur 71	Sage	TAM wheat 101
10/30/74	25.1	25.1	25.1	25.1	25.1
11/30/74	7.8	8.4	8.4	7.8	7.8
12/31/74	1.9	1.9	1.9	1.8	1.9
1/31/75	4.3	4.5	4.5	4.3	4.3
2/28/75	21.1	19.8	19.8	21.0	21.0
3/31/75	44.7	51.9	50.1	47.8	49.3
4/30/75	96.1	94.3	89.3	92.5	98.3
5/31/75	176.7	172.3	178.4	173.3	174.9
6/21/75	54.7	55.7	54.8	55.5	50.0
Total (mm)	432.4	434.0	432.3	429.1	432.6
(in)	17.0	17.1	17.0	16.9	17.0

Table C.2 Model estimates of average monthly evapotranspirational loss (mm) from commercial winter wheat fields (Scout variety) in Riley, Ellsworth, and Finney counties.

Month	Riley	Ellsworth	Finney
October, 1974	29.9	29.8	32.7
November	7.7	7.1	12.7
December	1.9	1.8	2.0
January, 1975	4.4	3.9	2.3
February	21.0	17.8	2.8
March	48.2	32.5	12.1
April	93.3	62.2	29.5

ESTIMATING LEAF AREA INDICES OF WINTER WHEAT FROM LANDSAT

E. T. Kanemasu, D. Lenhert, and J. Heilman

ABSTRACT

Leaf area index (LAI), ratio of green leaf area to ground area, is an important parameter in both the process of evapotranspiration and crop growth. Plants were collected and LAI was estimated on nine commercial winter wheat fields in Kansas throughout the winter wheat growing season. Multispectral scanner (MSS) bands 4, 5, 6, and 7 from Landsat I and II were correlated with LAI. Landsat predicted LAIs were used in an evapotranspiration (ET) model which predicted seasonal ET in close agreement with those using observed LAIs.

Leaves are one of the most important plant organs; they are the sites of photosynthesis and transpiration. Most agronomic crops obtain large leaf area indices (ratioof leaf area to soil area) which enables the plant community to absorb photosynthetic active radiation (visible wavelengths). In general, maximum photosynthesis of a row-crop canopy is reached near a leaf area index (LAI) of 3 while for wheat, presumably because of its higher planting rate and tillering capability, obtains maximum photosynthesis at about a LAI of 1.35. Because of the energy demanding nature of evaporation, maximum evapotranspiration rates are obtained at those same LAIs. Therefore after a critical LAI is obtained, mutual shading by the addition of new leaves does not significantly affect photosynthesis (growth) or evapotranspiration. Thus, it is not as important to differentiate between a LAI of 4 or 5 as it is to discriminate between LAI of 1 and 2.

MATERIALS AND METHODS

The study areas were 3 commercial wheat fields at each of 3 different locations. During the 1973-74 and 1974-75 winter wheat growing season, the fields were located in Riley, Ellsworth and Finney counties. Except for snow and extreme cold weather, plants were sampled at 3 locations in each field at each Landsat overpass date. Leaf area was determined at the Ellsworth and Finney sites by measuring the length and breadth of each leaf and converted to area by Teare and Peterson's (1971) equation

$$LA = .813\ X - .64 \qquad [1]$$

where LA is leaf area (cm^2) and X is product of maximum length times breadth. At Riley, the leaf area was measured with an optical planimeter

Landsat imagery and computer compatible tapes (CCT) were received for cloud free dates (Table 1). Because of the poor satellite coverage at the Ellsworth and Finney county sites during the 1973-74 growing season, only the Riley county fields were analyzed. All fields and CCTs were considered for the 1974-75 season except for Riley county site for which CCTs have not been received.

RESULTS

As part of an ERTS-1 study on winter wheat, we reported four linear regression equations relating LAI to each of the multispectral scanner (MSS) band ratios - 4/5, 4/6, 4/7, and 5/6. Using those equations we predicted LAI for the current data set. Early in the analysis is became clear that the regression equations using MSS 4/5 and 4/6 when summed and divided by two predicted the more reasonable results. The resulting equation was

$$\mathrm{LAI} = 1.653(\mathrm{MSS}\ 4/5) - 1.698(\mathrm{MSS}\ 4/6) + .093$$

Using [2], we predicted the LAI for the test fields (Fig. 1 and 2). The evapotranspiration model was run using the Landsat predicted LAIs (Table 2). In general, the seasonal ET values obtained were within 50 mm (2 in) of the ET values using measured LAI values. Therefore, it appears that Landsat can estimate LAIs for use in an evapotranspiration model.

Further refinement in equation [2] will provide improvement in ET estimates. We are waiting for the 1974-75 CCT for Riley county before revising [2].

Table D.1 Computer compatible tapes from Landsat for 1973-74 and 1974-75 winter wheat.

Riley County		Finney County		Ellsworth County	
Date	Tape No.	Date	Tape No.	Date	Tape No.
20 Oct. 1973	1454	18 Oct. 1974	1817	10 Sept 1974	1779
31 Mar. 1974	1616	23 Nov. 1974	1853	28 Sept 1974	1797
18 Apr. 1974	1634	29 Dec. 1974	1889	16 Oct. 1974	1815
24 May 1974	1670	20 Mar. 1975	2057	21 Nov. 1974	1851
29 June 1974	1706	29 Mar. 1975	1979	9 Dec. 1974	1869
17 July 1974	1724	15 Apr. 1975	1996	18 Mar. 1975	2055
4 Aug. 1974	1742	3 May 1975	5014	5 Apr. 1975	2073
9 Sept 1974	1778	4 May 1975	5015	23 Apr. 1975	2091
15 Oct. 1974	1814	18 June 1975	2147	20 May 1975	5031
20 Nov. 1974	1850	27 June 1975	5069	16 June 1975	2145
7 Dec. 1974	1867			25 June 1975	5067

Table D.2 Comparison of evapotranspiration estimated by using observed LAI and Landsat-derived LAI for winter wheat (1974-75).

Month	ELLSWORTH (mm) Observed	ELLSWORTH (mm) Landsat	FINNEY Observed	FINNEY Landsat
Oct.	29.9	30.9	35.0	35.5
Nov.	7.3	7.7	15.0	14.6
Dec.	1.8	1.9	8.1	8.8
Jan.	4.0	4.2	5.4	6.2
Feb.	18.0	22.0	4.7	7.2
Mar.	33.7	46.2	8.9	15.8
Apr.	58.7	56.1	20.1	29.8
May	106.2	109.2	97.2	106.5
June	41.4	60.6	60.0	63.0
	301 mm	338.8mm	254.4mm	287.4mm

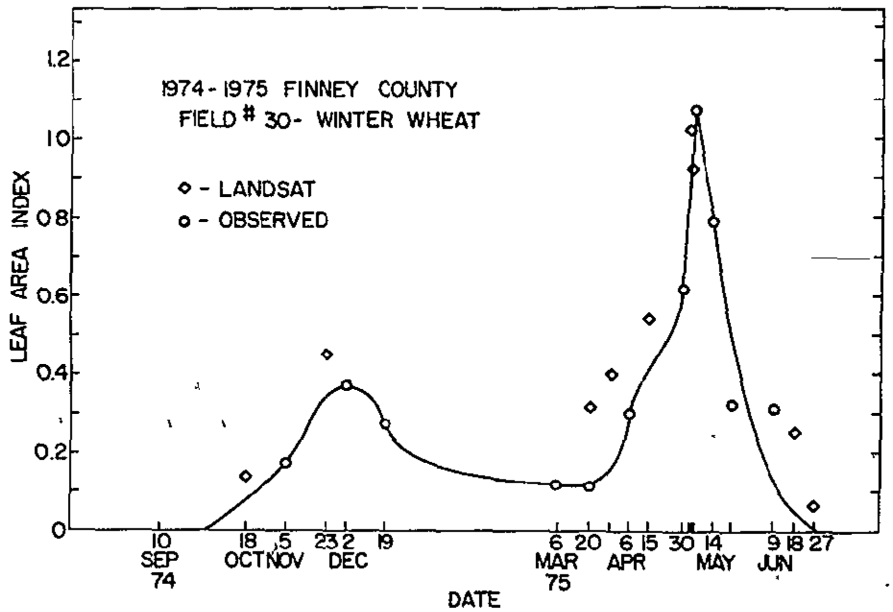

Fig. D.1 Seasonal trends in observed (o) and Landsat-predicted (◊) leaf area index in Finney county test field.

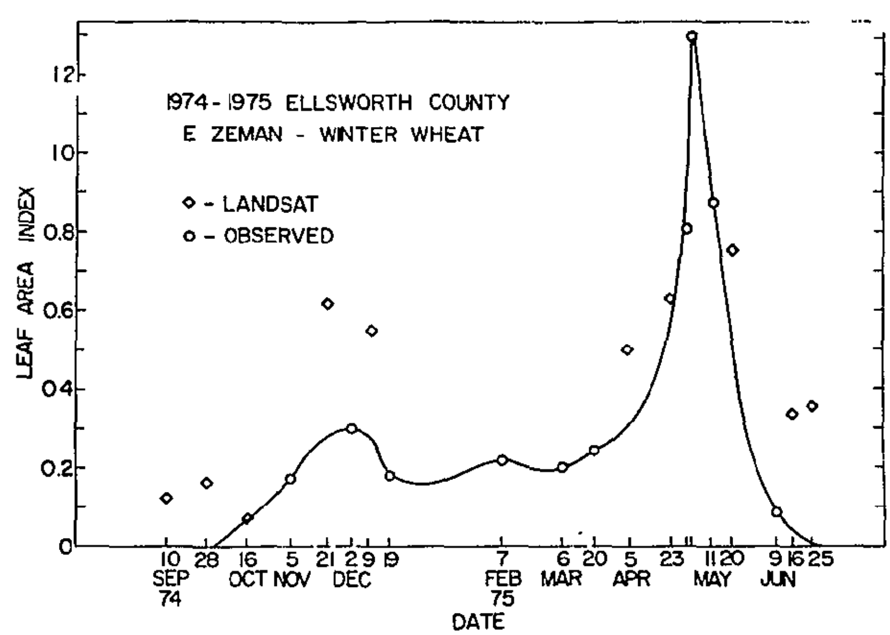

Fig. D.2 Seasonal trends in observed (o) and Landsat-predicted (◇) leaf area index in Ellsworth county test field.

APPENDIX E

COMPARATIVE YIELDING ABILITY OF WINTER (SPRING) WHEATS

Table E.1 Comparative yielding ability of winter wheat varieties.

Code Name	TURK	KHAR	FULC	FULZ	E_PR	MI_A	TRUM	KANR	BLAC
TURK	[.85]†	1.00	1.04			1.02		.92	.90
KHAR	1.00	[.86]						.94	.96
FULC	.96		[.86]	1.01		.94	.98	1.12*	.95
FULZ			.99	[.87]		1.06	.94		
E_PR					[.87]				
MI_A	.98		1.06	.94		[.88]	1.04		.95
TRUM			1.02	1.06		.96	[.89]	.84	
KANR	1.09	1.06	.89*				1.19	[.91]	.98
BLAC	1.11	1.04	1.08			1.05		1.02	[.91]
PARF									
TENM	1.12	1.00	1.20*	1.08		1.14		1.12	1.03
VIGO	1.11		.99	1.00			1.07		
FAIR	1.09		1.07	1.13			1.05		
YOGO		1.04							
PONC	1.16	1.06							1.18*
PAWN	1.22	1.09					1.06	1.21*	1.15
COMA	1.17	1.10	.96				1.01	1.20*	1.10
CHFK	1.23*	1.28*						1.29*	1.10
KARM									
WICH	1.18	1.02	.88					1.15*	1.10
KWGI	1.11								
TRIU	1.15	1.01						.97*	1.06
E_BL	1.19*	1.20						1.12	1.06
CLAR			1.14*		1.15				
S_TR									
THOR			1.12	1.17			1.09		
WEST		1.11							1.12*
AGEN									
CHEY	1.08	1.10				1.06		1.06	1.04
NEBR	1.10	1.12						1.12	1.07
WARR	1.26	1.02							
CONC		1.09							1.07
BISO	1.22	1.11							
KIOW	1.19	1.09							1.13

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*n $\geq$ 20 but S.E. > .05.

Table E.1 (continued) Winter wheat.

Code Name	PARK	TENM	VIGO	FAIR	YOGO	PONC	PAWN	COMA	CHFK
TURK		.89	.90	.92		.86	.82	.85	.81*
KHAR		1.00			.96	.94	.92	.91	.78*
FULC		.83*	1.01	.93				1.04	
FULZ		.93	1.00	.88					
E_PR									
MI_A		.88							
TRUM			.93	.95			.94	.99	
KANR		.89					.83*	.83*	.78*
BLAC		.97				.85*	.87	.91	.91
PARF	[.93]†								
TENM		[.94]		.95	1.11	.88	.88	.93	.94
VIGO			[.97]	.98			1.00		
FAIR		1.05	1.02	[.97]			.97	1.01	
YOGO		.90			[.98]			.79	
PONC		1.14				[.99]	.98	.98	1.06
PAWN		1.14	1.00	1.03		1.02	[1.00]	.99	1.03
COMA		1.08		.99	1.27	1.02	1.01	[1.00]	1.00
CHFK		1.06				.94	.97	1.00	[1.01]
KARM									
WICH		1.17	1.01	1.04	1.47	1.04	1.02	1.03	.88*
KWGI						1.05		1.04	
TRIU		1.09	1.00	1.03		1.04	1.04	1.02	
E_BL		1.08			1.02	1.00	.98	1.01	.81*
CLAR						1.06	1.05	1.01	.99
S_TR									
THOR			.96*	1.03					
WEST		1.17				1.00	1.01	1.03	1.10
AGEN						1.01		1.08	
CHEY		1.12*			1.05	1.09*	1.04	1.03	.91
NEBR		1.18*			1.01	1.13*	1.01	1.06	1.00
WARR					.99*		1.01	.95	
CONC		1.17*				1.05	1.08	1.08	
BISO		1.14				1.05	1.08*	1.06	
KIOW		1.24*				1.10*	1.11	1.06	

† [ ] means numbers on diagonal are values for VYA for the specified varieties.

* $n \geq 20$ but S.E. > .05.

Table E.1 (continued) Winter wheat.

Code Name	KARM	WICH	KWGI	TRIU	E_BL	CLAR	S_TR	THOR	WEST
TURK		.85	.90	.87	.84*				
KHAR		.98		.99	.83				.90
FULC		1.13				.88*		.89	
FULZ								.85	
E_PR						.87			
MI_A									
TRUM								.92	
KANR		.87*		1.03*	.89*				
BLAC		.91		.94	.94				.89*
PARF									
TENM		.85		.92	.93				.85
VIGO		.99		1.00				1.04*	
FAIR		.96		.97				.97	
YOGO		.68			.98				
PONC		.96	.95	.96	1.00	.94			1.00
PAWN		.98		.96	1.02	.95			.99
COMA		.97	.96	.98	.99	.99			.97
CHFK		1.14*			1.23*	1.01			.91
KARM	[1.02]†								
WICH		[1.02]	1.02	1.01	1.00	1.05			.94
KWGI		.98	[1.02]	1.00			.98		
TRIU		.99	1.00	[1.02]	.97	.98	.99		.89
E_BL		1.00		1.03	[1.03]				1.03
CLAR		.95		1.02		[1.03]			
S_TR			1.02	1.01			[1.03]		
THOR								[1.04]	
WEST		1.06		1.12	.97				[1.04]
AGEN		.97		1.02					
CHEY	1.01	1.17*	1.15	1.21*	.96				.98
NEBR		1.13*			1.27*				
WARR	1.00	1.01	1.14	.99*	.96*	.84			
CONC		1.02	1.12	1.10	.97				1.09
BISO		1.03	1.05	1.02	.90*				
KIOW		1.06		1.04	1.05				.97

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*n ≥ 20 but S.E. > .05.

Table E.1 (continued) Winter wheat.

Code Name	AGEN	CHEY	NEBR	WARR	CONC	BISO	KIOW	TASC	GUID
TURK		.93	.91	.79		.82	.84		.71*
KHAR		.91	.89	.98	.92	.90	.92	.89	
FULC									
FULZ									
E_PR									
MI_A		.94							
TRUM									
KANR		.94	.89						
BLAC		.96	.93		.93		.88		
PARF									
TENM		.89*	.85*		.85*	.88	.81*		
VIGO									
FAIR									
YOGO		.95	.99	1.01					
PONC	.99	.92*	.88*		.95	.95	.91*	.93*	
PAWN		.96	.99	.99	.93	.93*	.90	.88	
COMA	.93	.97	.94	1.05	.93	.94	.94	.88	
CHFK		1.10	1.00						
KARM		.99		1.00					
WICH	1.03	.85*	.88*	.99	.98	.97	.94	.98	.89
KWGI		.87		.88	.89	.95		.93	.94
TRIU	.98	.83*		1.01*	.91	.98	.96	1.00	.85*
E_BL		1.04	.79*	1.04*	1.03	1.11*	.95	1.04	
CLAR				1.19					
S_TR								1.14	
THOR									
WEST		1.02				.92		1.03	
AGEN	[1.04]†					.93		.95	.97
CHEY		[1.05]	.99	.96	1.07*	.99	1.00		
NEBR		1.01	[1.05]	.91	1.01*	1.05			
WARR		1.04	1.10	[1.05]		1.03			1.00
CONC	1.07	.93*	.99*		[1.06]	.98	1.05*	.95	
BISO		1.01	.95*	.97	1.02	[1.06]	.99	.92	
KIOW		1.00			.95*	1.01	[1.06]		

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*n ≥ 20 but S.E. > .05.

Table E.1 (continued) Winter wheat.

Code Name	OMAH	PARK	OTTA	SENE	KAW	I_TR	STUR	BUTL	HUME
TURK	.73*	.79	.75		.77				
KHAR			.90		.81*	.83			
FULC				.80				.81	
FULZ				.79					
E_PR									
MI_A									
TRUM				.88				.86	
KANR									
BLAC					.77*				
PARF									
TENM			.94			1.19			
VIGO				.91				.93	
FAIR				.93				.94	
YOGO			.65						
PONC	1.05	1.03	.93		.88				
PAWN	1.00	.90	.93	.83	.86				
COMA		.93	.90		.85	.90			
CHFK									
KARM									
WICH	.93	.99	1.00		.97	.94			
KWGI		.93	1.01		1.02	.90			
TRIU	.93*	.93	.97		.92	.91	.95		
E_BL					.92	.96			
CLAR			1.07*		.91				
S_TR						.95			
THOR				.96				.94	
WEST									
AGEN						.92	1.00		
CHEY	.76*		.82		.91				
NEBR	.85		.81		.87				
WARR	.90		.83		.90			.72	
CONC		1.09*	.97*		.92	.88*			
BISO	.79*	1.01	.97		.97				
KIOW									

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*n ≥ 20 but S.E. > .05.

Table E.1 (continued) Winter wheat.

Code Name	KNOX	TR64	MONO	CADD	EAGL	MINT	WINA	GAGE	LANC
TURK		.85			.75			.72	.65*
KHAR				.79		.83*	.78*		.69*
FULC									
FULZ									
E_PR									
MI_A									
TRUM	.88		.83						
KANR									
BLAC								.86	
PARF									
TENM									
VIGO	.88		.82						
FAIR	1.00								
YOGO						.73*	.74*		.93*
PONC	.92		.89				.90		
PAWN	.88	.85	.88					.89	.83*
COMA		.88		.91				.89	.99
CHFK									
KARM	1.07						1.03	——	.98
WICH		.99	.99	.99				.90	.87
KWGI		.95		.89	.88			.91	.91
TRIU	.93	.90	.93	.90				.83	.85*
E_BL		.92		.93		.63*		.99	
CLAR	.89		.80*						
S_TR		.97		.86					
THOR	.99								
WEST									
AGEN		.86		.94*	.87				
CHEY						.89*	.88*	.83*	.75*
NEBR						.85	.67	.76	.65
WARR			.72		1.06	.76*	.93	.92	.98
CONC		.96		.98					1.00
BISO		1.01			.91			.89	.72*
KIOW									

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*n $\geq$ 20 but S.E. > .05.

Table E.1 (continued) Winter wheat.

Code Name	WINO	DANN	PRON	SCOU	SC66	KX62	BENH	DUAL	SAGE
TURK				.74	.76				.69*
KHAR	1.02			.76	.85				
FULC									
FULZ									
E_PR									
MI_A									
TRUM						.79	.76	.79	
KANR									
BLAC									
PARF									
TENM									
VIGO						.84	.76	.83	
FAIR								.92	
YOGO	.98								
PONC				.88				.93	
PAWN				.88	.93	.84	.77	.94	
COMA				.84	.85				
CHFK									
KARM									
WICH				.87	.90				.82
KWGI				.89	.87				
TRIU	1.37	.88		.79*	.81	.90		.92	
E_BL				.87					
CLAR									
S_TR				.79					
THOR									
WEST									
AGEN		.83		.94	.94				
CHEY				.86					
NEBR				.81*	.85				
WARR	.97*			.90	.98				
CONC				.94	.93		.94		
BISO				.86	.88				.92
KIOW									

† [ ] means numbers on diagonal are values for VYA for the specified varieties.

* n ≥ 20 but S.E. > .05.

Table E.1 (continued) Winter wheat.

Code Name	CENT	REDC	FULT	AR71	ARTH
TURK	.71				
KHAR	.82				
FULC					
FULZ		.88			
E_PR					
MI_A					
TRUM		.77			
KANR					
BLAC					
PARF					
TENM					
VIGO		.77		.70	.64
FAIR					
YOGO	.83				
PONC					
PAWN	.85	.97			
COMA					
CHFK					
KARM					
WICH					
KWGI	.82				
TRIU					
E_BL					
CLAR					
S_TR					
THOR					
WEST					
AGEN					
CHEY					
NEBR	.73				
WARR	.90				
CONC	.85				
BISO					
KIOW					

† [ ] means numbers on diagonal are values for VYA for the specified varieties.

* $n \geq 20$ but S.E. > .05.

Table E.1 Comparative yielding ability of winter wheat varieties.

Code Name	TURK	KHAR	FULC	FULZ	E_PR	MI_A	TRUM	KANR	BLAC
TASC		1.12							
GUID	1.40*								
OMAH	1.37*								
PARK	1.26								
OTTA	1.33	1.11							
SENE			1.25	1.26			1.13		
KAW	1.30	1.23*							1.30*
I_TR		1.20							
STUR									
BUTL			1.23	1.23			1.16		
HUME									
KNOX							1.14		
TR64	1.18								
MONO							1.20		
CADD		1.27							
EAGL	1.33								
MINT		1.20*							
WINA		1.28							
GAGE	1.38								1.16
LANC	1.53*	1.45*							
WINO		.98							
DANN									
PRON									
SCOU	1.36	1.32							
SC66	1.32	1.18							
KX62							1.26		
BENH							1.32		
DUAL							1.27		
SAGE	1.44*								
CENT	1.40	1.22							
REDC				1.14			1.30		
FULT									
AR71									
ARTH									

† [ ] means numbers on diagonal are values for VYA for the specified varieties.

* n ≥ 20 but S.E. > .05.

Table E.1 (continued) Winter wheat.

Code Name	PARK	TENM	VIGO	FAIR	YOGO	PONC	PAWN	COMA	CHFK
TASC						1.08*	1.14	1.13	
GUID									
OMAH						.95	1.00		
PARK						.97	1.11	1.08	
OTTA		1.06			1.54	1.08	1.07	1.11	
SENE			1.10	1.07			1.21		
KAW						1.14	1.16	1.18	
I_TR		.84						1.11	
STUR									
BUTL			1.08	1.06					
HUME									
KNOX			1.14	1.00		1.09	1.14		
TR64							1.18	1.13	
MONO			1.22			1.12	1.14		
CADD								1.10	
EAGL									
MINT					1.38*				
WINA					1.36*				
GAGE						1.11	1.12	1.12	
LANC					1.07*		1.20*	1.01	
WINO					1.02				
DANN									
PRON									
SCOU						1.14	1.13	1.19	
SC66							1.08	1.18	
KX62			1.19				1.19		
BENH			1.32				1.30		
DUAL			1.21	1.09		1.07	1.06		
SAGE									
CENT					1.20		1.17		
REDC			1.30				1.03		
FULT									
AR71			1.40						
ARTH			1.56						

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*n $\geq$ 20 but S.E. > .05.

Table E.1 (continued) Winter wheat.

Code Name	KARM	WICH	KWGI	TRIU	E_BL	CLAR	S_TR	THOR	WEST
TASC		1.02	1.07	1.00	.96		.88		
GUID		1.12	1.06	1.18*					
OMAH		1.07		1.07*					
PARK		1.01	1.07	1.07					
OTTA		1.00	.99	1.03		.93*			
SENE								1.04	
KAW		1.03	.98	1.08	1.08	1.10			
I_TR		1.06	1.11	1.10	1.04		1.05		
STUR				1.05					
BUTL								1.06	
HUME	.93			1.49					
KNOX	.93			1.08		1.12		1.01	
TR64		1.01	1.05	1.11	1.09		1.03		
MONO		1.01		1.08		1.25*			
CADD		1.01	1.12*	1.11	1.07		1.16		
EAGL			1.14						
MINT					1.58*				
WINA	.97								
GAGE		1.11	1.10	1.20	1.01				
LANC	1.02	1.15	1.10	1.18*					
WINO				.73					
DANN				1.13					
PRON									
SCOU		1.15	1.12	1.27*	1.15		1.27		
SC66		1.11	1.15	1.23					
KX62				1.11					
BENH									
DUAL				1.09					
SAGE		1.22							
CENT			1.22						
REDC									
FULT									
AR71									
ARTH									

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*n ≥ 20 but S.E. > .05.

Table E.1 (continued) Winter wheat.

Code Name	AGEN	CHEY	NEBR	WARR	CONC	BISO	KIOW	TASC	GUID
TASC	1.05				1.05	1.09*		[1.07]†	
GUID	1.03			1.00					[1.07]
OMAH		1.32*	1.17	1.11		1.26*			
PARK					.92*	.99		1.04	.99
OTTA		1.21	1.23	1.08	.95*	1.03		1.03	.97
SENE									
KAW		1.10	1.15	1.11	1.09	1.03		1.05	
I_TR	1.09				1.13*			1.04	1.02
STUR	1.00								
BUTL				1.39					
HUME									.96
KNOX									
TR64	1.16				1.04	.99		1.19	1.10
MONO				1.38					1.15
CADD	1.06*				1.02			1.05	1.04
EAGL	1.15			.94		1.10			
MINT		1.12*	1.18	1.31*					
WINA		1.13*	1.49	1.08					
GAGE		1.20*	1.32	1.09		1.12		1.09	1.10
LANC		1.33*	1.54	1.02	1.00	1.38*			1.08
WINO				1.03*					1.08
DANN	1.20								
PRON									
SCOU	1.06	1.16	1.23*	1.11	1.06	1.16		1.08	1.06
SC66	1.06		1.18	1.02	1.07	1.14		1.07	1.10
KX62								1.10	1.20
BENH					1.06				1.17
DUAL									
SAGE						1.09			
CENT			1.36	1.11		1.17			1.14
REDC									
FULT									
AR71									
ARTH									

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*n ≥ 20 but S.E. > .05.

Table E.1 (continued) Winter wheat.

Code Name	OMAH	PARK	OTTA	SENE	KAW	I_TR	STUR	BUTL	HUME
TASC		.96	.97		.95	.96			
GUID		1.01	1.03			.98			1.04
OMAH	[1.07]†		.94		.97				
PARK		[1.08]	1.07		.94	.94*	1.00		
OTTA	1.06	.93	[1.09]			.97			
SENE				[1.09]				.98	
KAW	1.03	1.06	1.03		[1.10]	.93*		1.03	.94
I_TR		1.06*			1.08	[1.10]	1.08		
STUR		1.00				.93*	[1.10]		
BUTL				1.02				[1.10]	
HUME									[1.11]
KNOX			1.11*	.97	.97			.94	
TR64		1.02	1.08		1.06	.98	1.08		
MONO		.99	1.16	1.02	1.02			.99	
CADD		1.04*			1.00	1.03	1.05		
EAGL		1.00				1.12			
MINT	1.11*								.94
WINA			1.05						1.03
GAGE	1.18	1.05	1.10		1.09	.99	.97		1.12
LANC	1.15	1.17*	1.08		1.17*				1.06
WINO									1.03
DANN		1.05				1.03			
PRON									
SCOU	1.16	1.10	1.13		1.12	1.01			1.07
SC66	1.15	1.01	1.18		1.18	1.05	1.06		1.10
KX62		1.05	1.18*	1.04	1.01	1.04			
BENH									
DUAL				1.09				1.13	
SAGE		1.08							
CENT		1.09							
REDC				1.11					
FULT				1.10				1.09	
AR71									
ARTH		1.19							

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*n $\geq$ 20 but S.E. > .05.

Table E.1 (continued) Winter wheat.

Code Name	KNOX	TR64	MONO	CADD	EAGL	MINT	WINA	GAGE	LANC
TASC		.84		.95				.92	
GUID		.91	.87	.96				.91	.93
OMAH						.90*		.85	.87
PARK		.98	1.01	.96*	1.00			.95	.85
OTTA	.90*	.93	.86				.95	.91	.93
SENE	1.03		.98						
KAW	.98	1.00						.92	.85*
I_TR		1.02		.97	.89			1.01	
STUR		.93		.95				1.03	
BUTL	1.06		1.01						
HUME						1.06	.97	.89	.94
KNOX	[1.12]†	.82	.93						
TR64	1.22	[1.13]	1.09	1.01	.97			1.02	1.19
MONO	1.08	.92	[1.14]					1.01	
CADD		.99		[1.14]				1.02	
EAGL		1.03			[1.14]	1.40		1.00	1.04
MINT					.71	[1.15]	.91	.86	1.02*
WINA						1.10	[1.15]	.94	1.01
GAGE		.98	.99	.98	1.00	1.16	1.06	[1.15]	1.01
LANC		.84			.96	.98*	.99	.99	[1.15]
WINO						1.07	.96	.86	
DANN		.97	1.01		1.06				
PRON									
SCOU		1.04	1.03	1.03	1.00		.91*	1.01	1.01
SC66		1.02	.97	.98	1.06			1.02	1.04
KX62	1.13	.99	1.04					1.07	
BENH			.99					1.17	
DUAL	1.10		1.05						
SAGE		1.07	1.32		1.10				1.13
CENT		1.08	1.22	1.05	1.10			1.10	1.10
REDC			1.06						
RULT			1.10						
AR71			1.19						
ARTH		1.16	1.19					1.26*	

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*n $\geq$ 20 but S.E. > .05.

Table E.1 (continued) Winter wheat.

Code Name	WINO	DANN	PRON	SCOU	SC66	KX62	BENH	DUAL	SAGE
TASC				.93	.93	.91			
GUID	.93			.94	.91	.83	.85		
OMAH				.86	.87				
PARK		.95		.91	.99	.95			.93
OTTA				.88	.85	.85*			
SENE						.96		.92	
KAW				.89	.85	.99			
I_TR		.97		.99	.95	.96			
STUR					.94				
BUTL								.88	
HUME	.97			.93	.91				
KNOX						.88		.91	
TR64		1.03		.96	.98	1.01			.93
MONO		.99		.97	1.03	.96	1.01	.95	.76
CADD				.97	1.02				
EAGL		.94		1.00	.94				.91
MINT	.93								
WINA	1.04			1.10*					
GAGE	1.16			.99	.98	.93	.85		
LANC				.99	.96				.88
WINO	[1.15]†			.95	.89				
DANN		[1.15]	1.00*		.98	.92			.85
PRON		1.00*	[1.15]	.90					.85
SCOU	1.05		1.11	[1.16]	.98	.97			.93
SC66	1.12	1.02		1.02	[1.17]	.90			.93
KX62		1.09		1.03	1.11	[1.19]	.91	.98	
BENH						1.10	[1.21]		
DUAL						1.02		[1.23]	
SAGE		1.18	1.18	1.08	1.07				[1.23]
CENT	1.14	.95*		1.06	1.05				1.00
REDC						1.10	1.13	1.00	
RULT						1.06		.99	
AR71						1.18	1.14		
ARTH		1.25*			1.28*	1.21	1.18		

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*n $\geq$ 20 but S.E. > .05.

Table E.1 (continued) Winter wheat.

Code Name	CENT	REDC	FULT	AR71	ARTH
TASC					
GUID	.88				
OMAH					
PARK	.92				.84
OTTA		.90	.91		
SENE					
KAW					
I_TR					
STUR					
BUTL			.92		
HUME					
KNOX					
TR64	.93				.86
MONO	.82	.94	.91	.84	.84
CADD	.95				
EAGL	.91				
MINT					
WINA					
GAGE	.91				.79
LANC	.91				
WINO	.88				
DANN	1.05				.80
PRON				.71	
SCOU	.94				
SC66	.95				.78
KX62		.91	.94	.85	.83
BENH		.88		.88	.85
DUAL		1.00	1.01		
SAGE	1.00				
CENT	[1.23]†				.87
REDC		[1.24]	1.00	1.04	.95
RULT		1.00	[1.28]		
AR71		.96		[1.34]	.97
ARTH	1.15	1.05		1.03	[1.36]

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*n ≥ 20 but S.E. > .05.

Table E.2 Comparative yielding ability of spring wheat and durum varieties.

Code Name	MARQ	REWD	PNTD	RSCU	CERS	CNLY	TCHR	PILT	RGNT
MARQ	[.89]†	1.00		1.01	.90	1.10	.89	.88	
REWD	1.00	[.92]		.96	.92		.92		
PNTD			[.93]				.93		
RSCU	.99	1.04		[.94]	.96	.98	.94	.92	
CERS	1.11	1.09		1.04	[.97]		.97	.97	
CNLY	.91	.91		1.02		[.97]	.97	.86	
TCHR	1.12	1.09	1.07	1.06	1.03	1.03	[1.00]	1.00	1.00
PILT	1.13			1.09	1.03	1.16	1.00	[1.00]	
RGNT							1.00		[1.00]
CHNK	.99			1.01		.99	.96	.95	
CRLT							.97		
MNDM	1.22*		1.02	1.08	1.14*	1.07	1.06	1.11	
JSTN				1.14	1.09		1.03		
MIDA	1.32*	1.05		1.07	1.02	1.03	1.05	1.03	
RENN									
HERC							1.17*		
RIVL				1.06	1.12		1.08	1.07	1.06
CDET				1.12	1.11		1.08	1.06	1.10
PEMB				1.11*	.89	1.09	1.09		
RMSY	1.03			1.13		1.12	1.09		
PREM									
LEDS				1.07			1.10		
POLK							1.12		
KUBK	1.21*						1.12*	1.07	
STEW							1.13*		
RDMN				1.08			1.13*	1.07	
CRIS					1.06		1.13		
FORT			.92		1.18		1.13		
SELK				1.11	.91	1.12	1.18	.96	
RUSH				1.10	1.00	.97	1.14	1.00	
LEE	1.35*	1.13		1.08	1.00	1.06	1.15	1.03	
LANG	1.05			1.13		1.17	1.14		
CANT				1.16		1.10	1.06		
CRIM				1.18	1.15		1.14		
ROLT							1.08		
BNTY							1.17		
WALD							1.01		
WARD									
WELL				1.15*		1.26	1.18		
SNTY				1.03		1.05	1.19*		
MANT							1.13		
LARK									
LKTA				1.19		1.29*	1.24		
ERA-							1.26*		

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*n ≥ 20 but S.E. > .05.

Table E.2 (continued) Spring wheat and durums.

Code Name	CHNK	CRLT	MNDM	JSTN	MIDA	RENN	HERC	RIVL	CDET
MARQ	1.01		.82*		.76*				
REWD					.95				
PNTD			.98						
RSCU	1.01		.93	.88	.93			.94	.89
CERS			.88*	.92	.98			.89	.90
CNLY	1.01		.93		.97				
TCHR	1.04	1.03*	.94	.97	.95		.85*	.93	.93
PILT	1.05		.90		.97			.93	.94
RGNT								.94*	.91
CHNK	[1.01]†		1.01	.95	.96				
CRLT		[1.01]	.83		.85			.93	1.03*
MNDM	.99	1.20	[1.03]	.93	.99			.92	1.00
JSTN	1.05		1.08	[1.03]				.98	
MIDA	1.04	1.18*	1.01		[1.05]			1.01	1.00
RENN						[1.06]			
HERC			1.09	1.02			[1.07]		
RIVL		1.08	1.00		.99			[1.08]	.98
CDET		.97*			1.00			1.02	[1.08]
PEMB	1.00		1.02	1.00	.95				
RMSY	1.07		1.03	1.04	1.01				
PREM									
LEDS	.93		1.06	1.07			.98	1.03*	
POLK			1.14	1.08			1.00		
KUBK		.98	.95					.99	
STEW		1.16	.99		1.03*			1.05	1.19
RDMN			.93*		.98			1.00	
CRIS	1.06		1.14	1.10			1.01		
FORT			.97	1.03			1.05		
SELK	1.20*		1.09	.98	1.32*		1.22		
RUSH	1.06		1.06	1.06	1.06			1.10	
LEE	1.04		1.05	.94	1.17			1.20*	1.04*
LANG	1.06		1.09	1.03	1.04				
CANT	1.07		1.00	1.00	.98				
CRIM	1.08		1.18	1.11					
ROLT			1.10	1.01			1.10		
BNTY									
WALD				1.07					
WARD									
WELL	1.04		1.15	1.17			1.02		
SNTY	1.04		1.28*		1.11				
MANT	1.10		1.12	.92			1.03		
LARK									
LKTA	1.09		1.22	1.20					
ERA-			1.54	1.41			1.20		

† [ ] means numbers on diagonal are values for VYA for the specified varieties.

* $n \geq 20$ but S.E. > .05.

Table E.2 (continued) Spring wheat and durums.

Code Name	PEMB	RMSY	PREM	LEDS	POLK	KUBK	STEW	RDMN	CRIS
MARQ		.97				.83*			
REWD									
PNTD									
RSCU	.90*	.88		.93				.93	
CERS	1.12								.94
CNLY									
TCHR	.92	.92		.91	.89	.89*	.88*	.88*	.88
PILT						.93		.93	
RGNT									
CHNK	1.00	.93		1.08					.94
CRLT						1.02	.86		
MNDM	.98	.97		.94	.88	1.05	1.01	1.08*	.88
JSTN	1.00	.96		.93	.93				.91
MIDA	1.05	.99					.97*	1.02	
RENN									
HERC				1.02	1.00				.99
RIVL				.97		1.01	.95	1.00	
CDET							.84		
PEMB	[1.09]†	.96							.92
RMSY	1.04	[1.09]							
PREM			[1.10]						
LEDS				[1.10]	.98			.89	1.01
POLK				1.02	[1.12]				1.00
KUBK						[1.12]	.91		
STEW						1.10	[1.13]		
RDMN				1.12				[1.13]	
CRIS	1.09			.99	1.00				[1.13]
FORT	1.10			1.04	1.04				1.04
SELK	1.01	.99		.91	.99				.89
RUSH	1.02	.93		.98*			1.12*	1.00	.90
LEE-	.93	.95					1.19*	1.12	
LANG	1.10	1.04							
CANT	.98	.98			1.03				
CRIM	1.08			.96					.98
ROLT					1.00				
BNTY					1.12				
WALD					1.05				1.06
WARD									
WELL	1.17	1.09		1.03	1.03				1.05
SNTY		.93							
MANT	1.12			1.02	1.00	.83			1.01
LARK									
LKTA	1.19	1.11		1.04					1.05
ERA-				1.19	1.19				1.22

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*$n \geq 20$ but S.E. > .05.

Table E.2 (continued) Spring wheat and durums.

Code Name	FORT	SELK	RUSH	LEE-	LANG	CANT	CRIM	ROLT	BNTY
MARQ				.74*	.95				
REWD				.88					
PNTD	1.09								
RSCU		.90	.91	.93	.88	.86	.85		
CERS	.85	1.10	1.00	1.00			.87		
CNLY		.89	1.03	.94	.85	.91			
TCHR	.88	.85	.88	.87	.88	.94	.88	.93	.85
PILT		1.04	1.00	.97					
RGNT									
CHNK		.83*	.94	.96	.94	.93	.93		
CRLT									
MNDM	1.03	.92	.94	.95	.92	1.00	.85	.91	
JSTN	.97	1.02	.94	1.06	.97	1.00	.90	.99	
MIDA		.76*	.94	.85	.96	1.02			
RENN									
HERC	.95	.82						.91	
RIVL			.91	.83*					
CDET				.96*					
PEMB	.91	.99	.98	1.07	.91	1.02	.93		
RMSY		1.01	1.08	1.05	.96	1.02			
PREM									
LEDS	.96	1.10	1.02*				1.04		
POLK	.96	1.01				.97		1.00	.89
KUBK									
STEW			.89*	.84*					
RDMN			1.00	.89					
CRIS	.96	1.12	1.11				1.02		
FORT	[1.13]†	1.06					1.01	1.06	
SELK	.94	[1.13]	1.15	1.08	.95	1.00	.89		
RUSH		.87	[1.14]	.94	.91	1.03	.94		
LEE-		.93	1.06	[1.14]	.92	.95			
LANG		1.05	1.10	1.09	[1.14]	1.08	.96		
CANT		1.00	.97	1.05	.93*	[1.15]	.89		
CRIM	.99	1.12	1.06		1.04	1.12	[1.15]		
ROLT	.94							[1.15]	.91
BNTY								1.10	[1.17]
WALD	.98							1.04	.89
WARD									
WELL	.99	1.15	1.20	1.24	1.00	1.20	1.09		
SNTY		.93	1.07	1.00	.92				
MANT	.98	1.14	1.11			1.11	1.04	.99	
LARK								1.12	1.05
LKTA	1.00	1.17	1.20*	1.27*	1.03	1.23*	1.10		
ERA-	1.10*	1.25							

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*n ≥ 20 but S.E. > .05.

Table E.2 (continued) Spring wheat and durums.

Code Name	WALD	WARD	WELL	SNTY	MANT	LARK	LKTA	ERA-
MARQ								
REWD								
PNTD								
RSCU			.87*	.77				.84
CERS								
CNLY			.79	.95			.78*	
TCHR	.91		.85	.84*	.88		.81	.79*
PILT								.92
RGNT								
CHNK			.96	.96	.91			
CRLT								
MNDM			.87	.78*	.89		.82	.65
JSTN	.93		.85		.92		.83	.71
MIDA				.90				
RENN								
HERC			.98		.97			.83
RIVL								
CDET								
PEMB			.85		.89		.84	
RMSY			.92	1.08			.90	
PREM								
LEDS			.97		.98		.96	.84
POLK	.95		.97		1.00			.84
KUBK					1.20			
STEW								
RDMN								
CRIS	.94		.95		.99		.95	.82
FORT	1.02		1.01		1.02		1.00	.91*
SELK			.87	1.08	.88		.85	.80
RUSH			.83	.93	.90		.83*	
LEE-			.81	1.00			.79	
LANG			1.00	1.09			.97	
CANT					.90		.81*	
CRIM			.92		.96		.91	
ROLT	.96				1.01	.89		
BNTY	1.12					.95		.86
WALD	[1.17]				.99	.93		.86
WARD		[1.18]						
WELL			[1.18]	1.05	1.02		.97	.84
SNTY			.95	[1.19]			.90	
MANT	1.01		.98		[1.19]		.98	.80
LARK	1.07					[1.23]		
LKTA			1.03	1.11	1.02		[1.24]	
ERA-	1.16		1.19		1.25			[1.26]

†[ ] means numbers on diagonal are values for VYA for the specified varieties.

*n $\geq$ 20 but S.E. > .05.