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CROP WATER USE AND YIELD MODELS WITH LIMITED SOIL WATER

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Colorado State University
Fort Collins, Colorado
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DISSERTATION

CROP WATER USE AND YIELD MODELS WITH LIMITED SOIL WATER

Submitted by

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In partial fulfillment of the requirements

for the Degree of Doctor of Philosophy

Colorado State University

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ABSTRACT OF DISSERTATION
CROP WATER USE AND YIELD MODELS WITH LIMITED SOIL WATER

The objectives of the study were to estimate crop water use, formulate and test crop yield models, and compare various phenological indices using a secondary analyses of seven years hard red winter wheat (Triticum aestivum L.) data grown at North Platte, Nebraska. The crop was grown on a Holdrege silt loam soil which is uniform and representative of much of the land used for wheat production in the Northern and Central Great Plains. Dry matter yields and soil water contents were measured at booting, heading, soft dough, and maturity stages. Dry matter samples were also taken late fall of the preceding year. Grain yield was measured at harvest. Under the conditions of limited soil water studied, neither the application of mulch nor nitrogen had significant effects on grain yield. Year to year variation was highly significant.

Wheat phenology was correlated to four climatic indices: number of days, growing degree days, solar thermal units, and potential evapotranspiration, each accumulated from spring growth initiation. The number of days was the least variable index.

The combination method with proper calibration of parameters for region and crop was used to estimate evapotranspiration (ET). Cumulative ET denoted by W_{et} was compared with measured water use (W_m). A linear regression indicates a one-to-one correspondence between W_{et} and W_m, with a very small intercept and high correlation.

A transpiration model was developed and cumulative transpiration (W_t) was estimated.

Four dry matter yield models were formulated and tested. The variables include W_{et}, W_t, W_r, and $\frac{W_t}{E_o}$. W_r is cumulative relative daily crop ET, and E_o is mean daily free water evaporation. Total

dry matter was highly correlated to W_{et}, W_t, W_r, and $\frac{W_t}{E_o}$. The linear models with marginal products of 195 kg ha^{-1} cm^{-1}, 228 kg ha^{-1} cm^{-1}, 100 kg ha^{-1}, and 140 kg ha^{-1} day^{-1}, respectively, have determination coefficients greater than 0.80 and may be sufficient for predicting dry matter yields when soil water is limiting. Use of W_r is believed to reconcile production models over varied climatic regions.

Linear and nonlinear grain yield models were developed and tested. Grain yield was related to dry matter production during the preceding fall (DM_p), tillers (N), final dry matter (DM_f), the interaction of climatic extremes $T_{max} \geq 27^oC$ and $U_a \geq 10$ kph (M), with a coefficient of determination $R^2 = 0.75$. The model may be used to predict grain yield. DM_p is a proxy for the factors affecting the vigor of growth during the fall. DM_f can be replaced by any one of the dry matter-water use relationships. Climatic extremes affect grain yield seriously. Therefore, the year to year variation in climate necessitates that crop response studies be conducted over several years.

Relating wheat grain yield to interstage dry matter involved negative coefficients implying a decrease in grain yield with an increase in interstage dry matter which is physically unacceptable. The multiplicative nonlinear model relates relative grain yields of wheat and grain sorghum to their respective interstate relative ET. The model was inapplicable for wheat production and insensitive for grain sorghum.

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Finally, while noting the ever increasing demand for the short supply of food and other agricultural products in Ethiopia whose economic backbone is agriculture, I wish to dedicate this work to the reform and progress in agriculture and the betterment of rural life in Ethiopia.

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LIST OF SYMBOLS

Symbol	Description
A	Sensible heat flux density (cal cm^{-2} day^{-1})
A_o	Sensible heat flux density when soil water is not limiting (cal cm^{-2} day^{-1})
AM	Percent available soil water
a	Empirical constant
a_i	Regression coefficients
$a_i(w_i)$	Multiplicative yield model coefficient functionally related to available soil water at end of ith period w_i
b	Empirical constant
b_i	Regression coefficients
C	Heat capacity of the soil (cal cm^{-3} $^oC^{-1}$)
c	Conversion factor (cm^3 cal^{-1})
c_i	Regression coefficients
C_p	Specific heat of air at constant pressure (cal g^{-1} $^oC^{-1}$)
D	Number of days after heading divided by 100
$\overline{D}$	Monthly normal degree days
DH	Degree hours
D_h	Transfer coefficient for heat (cm^2 day^{-1})
D_w	Transfer coefficient for water vapor (cm^2 day^{-1})
DM	Dry matter production (kg ha^{-1})
DM_f	Final dry matter production (kg ha^{-1})
DM_p	Dry matter production the preceding fall (kg ha^{-1})
d	Wind displacement parameter (cm)
E	Evaporation (cal cm^{-2} day^{-1})
E_o	Free water evaporation (cm day^{-1})
E_p	Potential evaporation (cal cm^{-2} day^{-1})
ET	Evapotranspiration (cm day^{-1})
ET_c	Crop evapotranspiration excluding evaporation due to surface wetness (cm day^{-1})
ET_o	Crop potential evapotranspiration (cm day^{-1})

Symbol	Description
ET_p	Potential evapotranspiration from a reference alfalfa crop (cm day^{-1})
ET_r	Relative daily evapotranspiration (ET_c/ET_o)
e	Water vapor pressure (mb)
e_o	Water vapor pressure at the surface (mb)
e'_o	Saturated water vapor pressure at T_o (mb)
e_z	Water vapor pressure in the air at height z (mb)
e'_z	Saturated water vapor pressure at T_z (mb)
G	Soil heat flux density (cal cm^{-2} day^{-1})
G	Grain yield (kg ha^{-1})
G_o	Soil heat flux density from a reference crop (cal cm^{-2} day^{-1})
G_o	Optimum grain yield (kg ha^{-1})
GDD	Growing degree days
G_r	Relative growth (dimensionless)
g	Ratio of grain yield to final dry matter (dimensionless)
$g(\theta)$	Functional relationship between relative growth and available soil water θ
K	Degree of homogeneity in multiplicative yield model
K_a	Crop coefficient adjustment factor for limited soil water (dimensionless)
K_c	Crop coefficient (dimensionless)
K_{co}	Basic crop coefficient (dimensionless)
K_s	Increase in crop coefficient due to surface wetness (dimensionless)
K_{tc}	Transpiration coefficient (dimensionless)
K_{tco}	Basic transpiration coefficient (dimensionless)
k	von Karman constant (dimensionless)
k_i	Regression coefficients
k_f	Crop constant (kg ha^{-1} day^{-1})
L	Proportionality constant (dimensionless)
L_s	Length of season (days)
M	Number of days $T_{max} \geq 27^oC$ and $U_u \geq 10$ kph

Symbol	Description
m	Crop constant in high radiation regions (kg ha^{-1} day^{-1})
m'	Crop constant in low radiation regions (kg ha^{-1} day^{-1})
m_i	Regression coefficients
N	Number of days in a month
N_t	Number of tillers per square meter
P	Fraction or percent of days from planting to time of heading (dimensionless)
P_o	Transpiration coefficient adjustment factor (dimensionless)
p	Atmospheric pressure (mb)
R_b	Net outgoing long wave radiation (cal cm^{-2} day^{-1})
R_{bo}	Net outgoing long wave radiation on a clear day (cal cm^{-2} day^{-1})
R_n	Net radiation flux density (cal cm^{-2} day^{-1})
R_{no}	Net radiation flux density from a reference crop (cal cm^{-2} day^{-1})
R_s	Short wave radiation flux density received by the surface (cal cm^{-2} day^{-1})
R_{so}	Short wave radiation flux density received by the surface on a clear day (cal cm^{-2} day^{-1})
r_i	Regression coefficients
S	Fraction of possible sunshine (dimensionless)
SD	Stress day (dimensionless)
T	Transpiration (cm)
T_a	Average temperature (^oC or ^oK)
T_e	Effective growing temperature (^oC)
T_l	Lower threshold temperature (^oC)
T_{max}	Maximum air temperature (^oC or ^oK)
T_{min}	Minimum air temperature (^oC or ^oK)
T_o	Potential crop transpiration (cm)
T_r	Relative daily transpiration (dimensionless)
T_u	Upper threshold temperature (^oC)
T_z	Temperature at elevation z (^oC)
t	Time (days)

Symbol	Description
t_i	Regression coefficients
U_z	Wind speed (km day^{-1})
W	Measured depletion of soil water during a sampling interval (cm)
W_{et}	Cumulative evapotranspiration (cm)
W_m	Measured water use (cm)
W_{oc}	Cumulative evapotranspiration when soil water is nonlimiting (cm)
W_r	Cumulative relative crop evapotranspiration or transpiration (dimensionless)
W_t	Cumulative transpiration (cm)
x_s	Volume fraction of solid matter in the soil (dimensionless)
x_w	Volume fraction of water in the soil (dimensionless)
z	Elevation above the surface (cm)
z_o	Roughness height (cm)
α	Short wave reflectance coefficient or albedo (dimensionless)
β	Constant (maximum response to an input) (kg ha^{-1})
γ	Psychometric constant (mb $^oC^{-1}$)
θ	Root zone water content (cm)
λ	Latent heat of vaporization (cal g^{-1})
λ_i	Stress exponent or elasticity (dimensionless)
π	Symbol meaning product of
ρ	Density of air (g cm^{-3}) or parameter (dimensionless)
σ	Standard deviation
σ	Stephan-Boltzman constant (cal cm^{-2} day^{-1} $^oK^{-4}$)

CHAPTER I
INTRODUCTION

The primary purpose of irrigation is to provide plants with adequate water for physical production of crops of desired quality at a level where economic returns can be maximized. There is a shortage of good quality water, which is becoming more critical with the sharp increase in demand by all economic sectors on the available water supply. Any approach to improve crop production and maximize returns from the variable inputs such as irrigation water requires the simultaneous consideration of soil-water-plant relationships, climatic factors, and economic and social constraints which reflect alternative uses.

Water is one of the most essential factors for crop production. It is, without exaggeration, the lifeblood of agriculture. About 60% of the land on the surface of the earth is classed as extremely arid, arid, or semi-arid, and is very responsive to irrigation. Growing populations and improvements in their standards of living continuously increase the demand for agricultural products, including food and natural fibers which require water for their production. Research and technological advances have resulted in great improvements in crop production. Yet, in most of the world today, particularly the less developed nations, the rate of food production increase is below the 2.3% per year needed to barely feed the world's population, whose growth rate is 1.8% per year.

Agriculture is the major consumptive user of water. The Water Resources Council (1968) reported that this sector of the U.S. economy uses 85% of the water consumptively used, with crop irrigation accounting for the largest share. In developing countries, which have a proportionately smaller industrial sector, an even larger percentage of consumptive use is by irrigation.

Average crop yields are now below the economic optimum because the best water and fertilizer use and other cultural practices, singly and in combination, are either not yet developed by agricultural research or are only used by a minority of growers possessing the knowledge and skill and apply them. The world record yields of wheat are 8800 kg ha^{-1} produced in England in 1952 and 9600 kg ha^{-1} in the Soviet Union in 1944 (New York Times, Dec. 8, 1952). If we compare these record yields with the average yields (1962-64) of North America, Europe, Asia, Africa, and the world which are 1650, 2040, 910, 820, and 1150 kg ha^{-1} (Reitz, 1967), it may become obvious that agriculture has a long way yet to go in using its land and water resources most efficiently.

More research efforts to determine crop responses to varying levels and amounts of water application during the growth period are essential for improvements in water use planning and operation. A functional relationship between crop yields and water use during the various phenological stages of the crop must be established for optimum allocation and use of the water resources.

Production functions are basic to natural resources economic analysis. They are important in determining the extent to which national products can be increased from a given stock of resources. Production functions serve as the basis of comparative analysis for interregional or international trade. The theory of functional distribution of income is based on the imputation of total output among factors of production based on the production function. The production function provides one of the two general categories of data for maximizing profits. The form of the supply and cost functions is dependent upon the nature of the production function.

Objectives

The objectives of this study are to:

1. Simulate crop water use with climatic, crop, and soils data,

2. Formulate operational response functions of crops to limited soil water, and

3. Compare various schemes of measuring phenological development.

Crop, soils, and climatic data

A seven year study was conducted by Dr. Darryl E. Smika, Research Soil Scientist, Northern Great Plains Soil and Water Conservation Branch, Agricultural Research Service, USDA, North Platte, Nebraska. The period of study was 1963 through 1970. The 1968 data were unavailable because the crop was destroyed by green bugs in the fall of 1967. The data included crop, soils, and climatic measurements.

Hard red winter wheat, *Triticum aestivum* L., was grown under four field conditions: bare soil with and without the addition of nitrogen fertilizer and mulched soil with and without the addition of nitrogen fertilizer. Stubble mulch tillage was used on the mulched plots during the 14-1/2 month fallow period. The mulch was wheat straw residue with an average 5160 kg ha^{-1} remaining at seeding time. The fertilized plots received 168 kg ha^{-1} of nitrogen applied as ammonium nitrate (NH_4NO_3) broadcasted prior to the last tillage before seeding. No supplemental irrigation water was applied.

The soil is Holdrege silt loam and is very uniform and representative of much of the land used for wheat production in the Northern Plains. The size of the plots was 0.01 ha. Each treatment was replicated three times. Wheat was seeded with shoe drill in 30.5 cm rows between September 17 and 20 each year. Plant population was kept constant at 96.8 plants per square meter each year of the study.

The time of growth initiation in the spring was recorded. Four stages of phenological development were observed. The four stages represented boot, heading, soft dough, and maturity. Plant samples were taken from a 0.84 m^2 area of each plot at each stage of development and late fall of the preceding year. The samples included entire above ground portions at all samplings and grain yield at maturity.

Soil water measurements were made at the start of spring growth initiation and at each of the four succeeding stages at which plant samples were taken. Soil water was measured by the neutron scatter method to a depth of 180 cm at increments of 30 cm.

Daily climatic records were kept at the weather station of the North Platte Experiment Station. The records included maximum and minimum air temperatures, precipitation, percent sunshine and wind speed.

Grain sorghum grain yield and water use data collected at Bushland, Texas, 1956 through 1959, were obtained from Dr. M. E. Jensen, director of the Snake River Conservation Research Center, USDA-ARS, Kimberly, Idaho. The data were received in final form as used by Jensen (1968) to develop stress exponents for the multiplicative model suggested by Jensen.

CHAPTER II

EVAPOTRANSPIRATION AND PLANT PHENOLOGY

A. Evapotranspiration

This section discusses the basic principles of the process of evapotranspiration and outlines the common estimating procedures. The combination method for estimating evapotranspiration from climatic, crop, and soil data is developed. The water balance equation is also given.

There are five general methods of estimating evaporation:

1. The hydrological or water balance method. It includes such diverse methods as lysimeters and soil sampling.

2. The eddy correlation approach. Several types of equipment have been developed to use this method, however, equipment complexity and sensor limitations have restricted widespread use.

3. The energy balance method. An enormous amount of energy is required to convert liquid water to vapor at the same temperature. The energy balance measures the energy flow in the various pathways to the vapor source, and from this derives the energy used in vaporization. From knowledge of the latent heat of vaporization, the volume and mass flux density can be evaluated. The energy balance is a favored micrometeorological method with the present level of technology.

4. The aerodynamic or profile method. This method describes the vapor mass flux. It requires an estimate of the turbulent diffusivity or transport coefficient and the vapor gradient. The transport coefficient and diffusivity are expressed in terms of the air speed past the surface. Compared to the energy balance, the aerodynamic method is less satisfactory.

5. The combination method. This method combines parts of each of the energy balance and aerodynamic methods.

The combination method of estimating potential evapotranspiration, ETp, will be developed by considering the appropriate parts of the energy balance and aerodynamic methods.

A.1. Energy balance method

The major components of the vertical energy balance at the soil surface or at the effective surface of the crop can be given by

$$R_n = E + G + A \tag{2.1}$$

where R_n is the net radiation flux received by the surface, positive upward; E is the latent heat flux density, positive for flow toward canopy; A is the sensible heat flux density to the air, positive for flow toward canopy; and G is sensible heat flux density to the soil, positive downward. All components of equation (2.1) have units of cal cm^{-2} day^{-1}.

The following assumptions have been made in the derivation of equation (2.1):

1. There is no horizontal divergence, that is, the surface is large and uniform. The fetch distance required to provide horizontal divergence may be 30 m or less for most short, closely spaced field crops. Rider et al. (1963) evaluated temperature, moisture, and wind profile variations over the first 16 m of grassed surface. Their measurements show that the greatest variation occurs in the first 10 to 15 m after a discontinuity is encountered. Bartholic et al. (1970) recommend that for instruments above the crop an allowance of roughly 200 m of fetch be made for each meter above the crop surface for 90 percent profile adjustment.

2. Energy of photosynthesis is negligible. It is reported not to exceed 1 or 2 percent of net radiation (Bartholic et al., 1970).

3. Energy stored in crops is negligible. This is generally valid except possibly during a short period during sunrise or sunset (Tanner, 1960).

A.1.1. Net radiation

The net radiation flux density in cal cm^{-2} day^{-1} can be estimated by considering the net short and long wave components of sky radiation.

$$R_n = (1 - \alpha)R_s - R_b \tag{2.2}$$

where α is the short wave reflectance or albedo; R_s is the total short wave radiation flux density received by the surface from the sun and sky; and R_b is the net outgoing long wave or nocturnal radiation flux density emitted by the surface, i.e., the difference between the emitted and absorbed.

Mean daily reflectance coefficients α for most green field crops with full cover range from about 0.22 to 0.25. A value of 0.23 is commonly used (Jensen and Haise, 1963).

Solar (short wave) radiation can be measured directly with instruments ranging in complexity from bimetallic sensors with spring wound chart recorders to thermopile sensors with electronic integrators and chart recorders. When measurements are not available, solar radiation can be estimated from clear sky solar radiation and fraction of possible sunshine. Values of clear day solar radiation, R_{so}, can be obtained by plotting daily solar radiation and establishing an envelope curve through the high points (Jensen et al., 1971). R_s can be estimated from R_{so} and either degree of cloud cover or percent sunshine (Jensen and Haise, 1963).

$$R_s = (0.35 + 0.61S)R_{so} \tag{2.3}$$

where S is the fraction of possible sunshine.

The net long wave radiation flux, R_b, can be estimated with sufficient accuracy using empirical relations between solar radiation, air temperature, and saturation vapor pressure by equations (2.4) and (2.5):

$$R_{bo} = (a_1 + b_1 \sqrt{e_z'})\sigma T_a^4 \tag{2.4}$$

and

$$R_b = (a \frac{R_s}{R_{so}} + b)R_{bo} \tag{2.5}$$

in which R_{bo} is the net outgoing long wave radiation flux on a clear day; $\sigma = 11.71 \times 10^{-8}$ cal cm^{-2} day^{-1} $^{o}K^{-4}$ is the Stefan-Boltzman constant; e'_z is the saturation vapor pressure in mb at height z meters; a, b, a_1, b_1 are empirical constants; and $T_a^4 = \frac{T_{max}^4 + T_{min}^4}{2}$ in which T_{max} and T_{min} are the daily maximum and minimum, respectively, absolute (^{o}K) air temperatures.

The form of equation (2.4) is that suggested by Brunt (1940). Many researchers have since evaluated local constants for various parts of the world. Appropriate for this study are constants calibrated by Heermann et al. (1974) for the Northern and Central Great Plains using observations gathered at Scotts Bluff, Nebraska. Heermann obtained values of 0.90, 0.10, 0.375, and -0.044 for a, b, a_1, and b_1, respectively.

A.1.2. Soil heat flux

The flux of sensible heat into the soil, G, is a function of the surface temperature and the composition of the soil; the flux increases with the temperature range and soil water content. Over periods of hours its magnitude can be significant, but is quite small from day to day because heat stored early in the day is released late at night. The maximum values, which occur in the spring, rarely exceed 10 percent of the net radiation (Sellers, 1965).

Sellers (1965) suggested the following relationship as the most accurate and most practical method for determining the flux of heat into the soil:

$$G = C \frac{\Delta T_a(z)}{\Delta t} \tag{2.6}$$

where $\frac{\Delta T_a}{\Delta t}$ is the time rate of temperature change averaged for the soil layer from the surface to a depth z of 5 to 10 cm, and C is the heat capacity of the soil.

The heat capacity C can be approximated from an expression given by de Vries (1963):

$$C = 0.50x_s + 1.0\,x_w \tag{2.7}$$

where x_s and x_w are, respectively, the volume fractions of solid matter and water in the soil, and the constants 0.50 and 1.0 are the corresponding heat capacities in cal $cm^{-3}\ {}^{o}C^{-1}$.

Considering the top 6 cm of the soil profile under crop culture to have an $x_s = 0.50$ and an $x_w = 0.25$ (50% available soil water level), equation (2.7) gives an approximate value of 0.50 cal $cm^{-3}\ {}^{o}C^{-1}$ for C; and equation (2.6) becomes

$$G = 3.0\,\frac{\Delta T_a}{\Delta t} \tag{2.8}$$

In the USDA irrigation scheduling computer program (Jensen and Heermann, 1970) Δt is one day and ΔT_a is the average air temperature for the day in question minus the mean of the average air temperatures for the three previous days in ${}^{o}C$, and the coefficient determined by calibration is 2.8 cal $cm^{-3}\ {}^{o}C^{-1}$.

A.2. Aerodynamic transfer method

The latent heat flux density E and the sensible heat flux density A, which are components of the vertical energy balance expressed by equation (2.1), are elements in the aerodynamic method of estimating vertical turbulent transport of heat and matter (water vapor).

Atmospheric motions near the earth's surface are always turbulent, even when the air is very stable. This turbulent motion is separated from the surface by a laminar boundary layer, within which heat and matter (water vapor) are transferred vertically only by molecular processes. The rates of transfer are proportional to the vertical gradients of temperature T and vapor pressure e. The basic equations in the aerodynamic method of determining the vertical fluxes of heat and water vapor are given below:

$$A = \rho C_p D_h (T_z - T_o) \tag{2.9}$$

$$E = 0.622 \frac{\rho \lambda D_w}{p} (e_z - e_o) \tag{2.10}$$

where

$$D_h = D_w = \frac{k^2 u_z}{(\ln \frac{z-d}{z_o})^2} \tag{2.11}$$

In the above equations the subscript "o" refers to surface values; z is height above the surface and is generally 1 or 2 m; C_p is the specific heat of air at constant pressure, cal g^{-1} $^oC^{-1}$; λ is the latent heat of vaporization, cal g^{-1}; ρ is the density of air, g cm^{-3}; p is the atmospheric pressure, mb; k is the von Karman constant, which is near 0.41; u_z is the wind speed at height z; d is the displacement parameter, cm; and z_o is the roughness height when an adiabatic wind profile exists and the wind follows the log profile. The transfer coefficients for turbulent heat and vapor D_h and D_w, respectively, vary very little with height above 1 m. This observation lead to their equality in equation (2.11).

A detailed derivation and more complete reviews of turbulent transfer processes are provided by Sellers (1965, pp. 141-155) and Tanner (1967).

A.3. Combination method for evaporation

Penman (1948) and Budyko (1956) have treated evaporation as a dynamic process by combining the energy balance and the aerodynamic methods. The resulting relationship is referred to as the combination equation. In this section the important relationships of the modified Penman (1963) method will be summarized. The derivation is based on equations (2.1), (2.9) and (2.10). By combining these equations, Penman obtained an expression for potential evaporation that eliminated the surface temperature dependence of the sensible heat in equation (2.9). The details of the steps involved can be found in the papers by Tanner (1968) and Bartholic et al. (1970).

The general form of the combination equation involving vapor pressure deficits is

$$E = \frac{\Delta}{\Delta+\gamma} \left[(R_n - G) + \frac{\rho C_p D}{\Delta} \{(e_z' - e_z) - (e_o' - e_o)\} \right] \quad (2.12)$$

where $\Delta = \frac{e_z' - e_o'}{T_z - T_o}$ is the slope of the saturation vapor pressure of water, $\gamma = \frac{\rho C_p}{0.622\lambda}$ is the psychometric constant, mb $^oC^{-1}$, and the other variables are as previously defined.

Modifications of equation (2.12) are possible with different surface conditions. If water is not limiting and there is no vapor pressure deficit at the evaporation surface, then $e_o' - e_o = 0$ and equation (2.12) reduces to

$$E_p = \frac{\Delta}{\Delta+\gamma} \left[(R_n - G) + \frac{\rho C_p D}{\Delta} (e_o' - e_z) \right] \quad (2.13)$$

which is the original Penman (1948) formula for potential evaporation, E_p.

Since the temperature at the surface is seldom known, the temperature at height z, T_z, is used in its place. Then Δ is given by the point slope of the saturation vapor pressure - temperature curve, $\frac{de}{dT}$, for water at T_z. T_z is also used in the calculation of the psychometric constant γ. Van Bavel (1966) confirmed that the use of T_z for T_o caused little error in the calculation of evaporation.

A.3.1. Potential evapotranspiration

Although many writers treat potential evaporation and potential evapotranspiration as synonymous, there are practical reasons for defining a potential evapotranspiration term ET_p which refers to a specific crop. First, irrigated projects do not have uniform, well-watered actively growing crop all season. Secondly, an infinite fetch does not exist throughout the growing season.

Evapotranspiration is the sum of water lost by evaporation and transpiration. Transpiration is the loss of water in vapor form from plants. All aerial parts of leaves may lose some water by transpiration, but most of the water is lost through the stomata which are concentrated mostly in the leaves. Evaporation is the loss of water vapor from the soil or from exterior portions of plants where water may have accumulated from irrigation, dew, or exudation from the interior parts of plants.

Potential evapotranspiration is defined as the upper limit of evapotranspiration that would occur with a given atmospheric demand from a well-watered reference crop that has an aerodynamically rough surface. Penman (1956) suggested the use of a short green grass, completely shading the ground, of uniform height and never short of water for a reference crop. On the other hand, Jensen and Haise (1963) and Jensen (1968) prefer alfalfa that is well-watered and has 30 to 50 cm of top growth for the following reasons: a) a 30 to 50 cm of top growth provides an aerodynamically rough surface representative of agricultural crops, which accounts for the common and important occurrence of advection; b) since plant leaves are relatively transparent to solar radiation, sufficient layer of leaves are desired to absorb most of the solar radiation before reaching the soil surface which is more subject to drying; c) alfalfa has a low leaf resistance to water vapor diffusion; and d) generally alfalfa has a root system that is in contact with soil volume several times larger than grass which minimizes the effect of decreasing soil water content. Van Bavel (1966) indicated that alfalfa may transpire at a potential rate for about 20 days after irrigation in arid regions in mid summer.

The general equation for potential evapotranspiration ET_p can be obtained from equation (2.13) by replacing the vertical transfer coefficient D by its value given by (2.11):

$$ET_p = cE_p = c\frac{\Delta}{\Delta+\gamma}\left[(R_n - G) + \frac{\rho C_p}{\Delta}\frac{k^2 u_z}{(\ln\frac{z-d}{z_o})^2}(e_z' - e_z)\right] \quad (2.14)$$

where c is the conversion factor to depth equivalents. Using 585 cal g^{-1} as the latent heat of vaporization for water at 20^oC, the value of c necessary to change ET_p to cm day^{-1} becomes 0.00171 cm^3 cal^{-1}.

Penman (1963) calibrated the constants in equation (2.14) for reflectance coefficient or albedo $\alpha = 0.25$. He obtained

$$ET_p = c\left[\frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{\gamma}{\Delta+\gamma}15.36\,(1.0 + 0.0062u_2)(e_2' - e_2)\right] \quad (2.15)$$

where u_2 is the wind speed at 2 m in km day^{-1} (for wind in miles day^{-1} $0.01u_2$ is used). If wind speed is measured at elevations other than 2 m, it can be approximated from the empirical expression (Sellers, 1965),

$$u_2 = u_z\left(\frac{2.0}{z}\right)^{0.2} .$$

Heermann et al. (1974) calibrated the wind function for the Northern and Central Great Plains using data gathered at Scotts Bluff, Nebraska, and obtained 0.0093 as a coefficient for u_2. Under high advective conditions the combination equation tends to underestimate ET_p (Jensen, 1969). Under these conditions the aerodynamic term proposed by van Bavel (1966), $7.149u_z/\ln(z/z_o)$, may be preferred in place of $15.36(1.0 + 0.0062u_z)$ provided z_o is in the range of 0.6 to 1.0 cm.

When climatic input is incomplete to evaluate ET_p by the combination method, ET_p can be estimated by other empirical methods, preferably developed for the particular geographic area, that make use of the measured climatic input. One such is the Jensen-Haise method (Jensen and Haise, 1963) which requires average daily temperature and solar radiation as input data. The equation is given by (2.16):

$$ET_p = (0.025\,T_a + 0.080)\,R_s \quad (2.16)$$

where T_a is the average daily temperature in ^oC. If direct measurements of the solar radiation R_s are not available, it can be evaluated from equation (2.3). Equation (2.16) was developed from observations in the Western United States. Therefore, it applies for the Northern Great Plains.

A.3.2. Actual evapotranspiration

Daily evapotranspiration for a given agricultural crop under actual conditions of soils and climate, ET, is related to daily potential evapotranspiration, ET_p, as follows:

$$ET = K_c ET_p \tag{2.17}$$

where K_c is a dimensionless coefficient similar to that proposed by van Wjik and de Vries (1954). It represents the combined relative effects of the resistance of water movement from the soil to the various evaporating surfaces and the resistance to the diffusion of water from the surface to the atmosphere, as well as the relative amount of radiant energy available as compared to the reference crop (Jensen, 1968). Jensen defined K_c as

$$K_c = \frac{R_n - G - A}{R_{no} - G_o - A_o} \tag{2.18}$$

The subscript "o" designates concurrent values for the reference crop in the immediate vicinity of the crop in question.

Typical examples of the effects of stage of growth on the crop coefficient where soil water is not limiting have been presented for grain sorghum by Jensen and Haise (1963) and Jensen (1968), and for corn by Denmead and Shaw (1959). The crop coefficient derived from conditions of water nonlimiting is designated by K_{co}.

In the USDA irrigation scheduling computer program (Jensen and Heermann, 1970, and Jensen et al., 1971), the crop coefficient is adjusted for soil water availability and soil surface wetness as follows:

$$K_c = K_a K_{co} + K_s \tag{2.19}$$

where K_a is the relative coefficient related to percent available soil water, AM, as follows:

$$K_a = \ln(AM + 1)/\ln 101 \tag{2.20}$$

K_s is the increase in the coefficient when the soil surface is wetted by irrigation or rain. It is approximated by

$$K_s = (0.90 - K_c)m \tag{2.21}$$

in which m = 0.8, 0.5, or 0.3, respectively, for the first, second, or third day after irrigation or rain.

The mean crop coefficient where soil moisture was not limiting and normal irrigation stands are used, K_{co}, varies with type of crop. For small grains, K_{co}, is given by

$$K_{co} = 0.23 - 1.140P + 4.843P^2 - 2.893P^3 \tag{2.22}$$

where P is the fraction of days from planting to time of heading. After heading, K_{co} is given by

$$K_{co} = 1.02 + 8.532D - 7.260D^2 + 4.440D^3 \tag{2.23}$$

in which D is the number of days after heading divided by 100.

A.4. Water balance

A quantitative measure of soil water depletion between sampling intervals can be obtained from the water balance equation (2.24):

$$W = \theta_i - \theta_{i+1} + R_{ci} - W_{di} \tag{2.24}$$

in which W is the measured depletion of soil water during the sampling interval i to i+1, cm; θ_i and θ_{i+1} are the root zone water contents at the beginning and end of the given interval which may represent a

phenological stage of a crop, cm; R_{ei} is the rainfall excluding surface runoff, cm, during the interval; and W_{di} is the deep percolation loss, cm, from the root zone during the interval.

The depletions can be accumulated to succeeding stages of growth to determine the total use to that point in time. In this study, the cumulative depletion of soil water obtained by summing the measured depletion is defined as W_m.

B. Plant phenology

Phenology is the science that deals with the time of appearance of characteristic periodic phenomena in the life cycle of natural organisms including plants, especially in relation to climate and other environmental factors. Several methods are used to correlate plant development to climatic conditions. The most common is the thermal unit. Photo-thermal units, solar thermal units, modifications of the thermal unit, and number of days are frequently used. This section presents discussions of the thermal unit, solar thermal unit, number of days, and potential evapotranspiration as measures to which plant development can be correlated. First, basic definitions of terms related to plant phenology and descriptions of developmental stages are given.

B.1. Developmental stages

Whyte (1946) gives the following distinction between growth and development phenomena: "Growth is an increase in size without any profound qualitative changes in the growing parts," and "By development is generally understood the progress of internal qualitative changes (with or without external change) governed by the factors of the environment and which lead ultimately to the production of fruit, and in annual plants, to death."

Following the suggestion of Salter and Goode (1967), the word "stage" is used to delimit any period of growth or development which is based on changes in the external appearance of the plant. The term "phase" refers to developmental periods with qualitative internal changes.

The terms used to describe the growth and developmental stages of the majority of grain crops are similar and have been standardized to some extent. Table 2.1 has been adapted from an outline by Salter and Goode (1967) which describes the sequence of stages of growth and development of the grain crops as determined by external

Table 2.1. Stages of growth and development of grain crops based on external appearance.

Stage	Description
Germination	The appearance of the radicle.
Tillering	The formation of tillers, i.e., branches produced from the base of the stem.
Jointing	The stage when two nodes can be seen, i.e., the beginning of shooting.
Shooting	The stage of elongation of internodes.
Booting	The end of the shooting stage and just prior to the emergence of the ears.
Heading) Earing)	The emergence of the ear from the tube formed by the leaf sheath.
Flowering	The opening of the flowers. In corn this stage is often divided into tasseling and silking being the time of appearance of the male and female flowers, respectively.
Grain formation	The period of grain development from fertilization until maturity. This period can be further subdivided into the following stages:
milk-ripe	grain contents have a milky consistency.
soft-dough	grain contents have a dough consistency.
waxy-ripe	grain contents have waxy appearance.
full-ripe	grain contents hard.
dead-ripe	grain ripe for cutting.

appearance. Alternative terms are included when there is a doubt whether two terms are synonymous.

Some Russian workers have criticized the use of stages based on external appearance as it may not be associated with developmental changes in the productive organs. Zabluda (1940), for example, has defined six stages of development of the wheat plant (which can be applied to other grain crops) based on the formation of (1) the leaves, (2) the spikelets, (3) the florets, (4) the reproductive cells, (5) the grain, and (6) the ripening of the grain; and he suggests that the variable and often conflicting results obtained in drought resistance studies may be due to varietal difference in the time of formation of the reproductive organs relative to the external appearance of the plant.

Some workers (Salter and Goode, 1967) have determined the limits of various phases in relation to morphological changes and have also studied the effect of soil moisture conditions imposed during different developmental phases. Skazkin (Salter and Goode, 1967) has summarized much of the work on this subject and related, in diagram form, the development phases of wheat, barley, and oats to the more commonly used stages of growth and development of these crops (Figure 2.1). This information is regarded as a great help in comparing and interpreting experimental results.

B.2. Thermal unit

The thermal unit has been in use for over two centuries. It is a scheme for measuring plant-temperature relationships by the accumulation of differences between daily mean temperature, T_a, and a lower threshold temperature, T_1 during the growing season. Algebraically, the thermal unit is expressed as

$$GDD = \sum_{i=t_p}^{t_m} [T_{ai} - T_1] \qquad (2.25)$$

in which GDD is the growing degree-days which is equivalent to thermal units, and t_p and t_m are dates of planting and maturity, respectively.

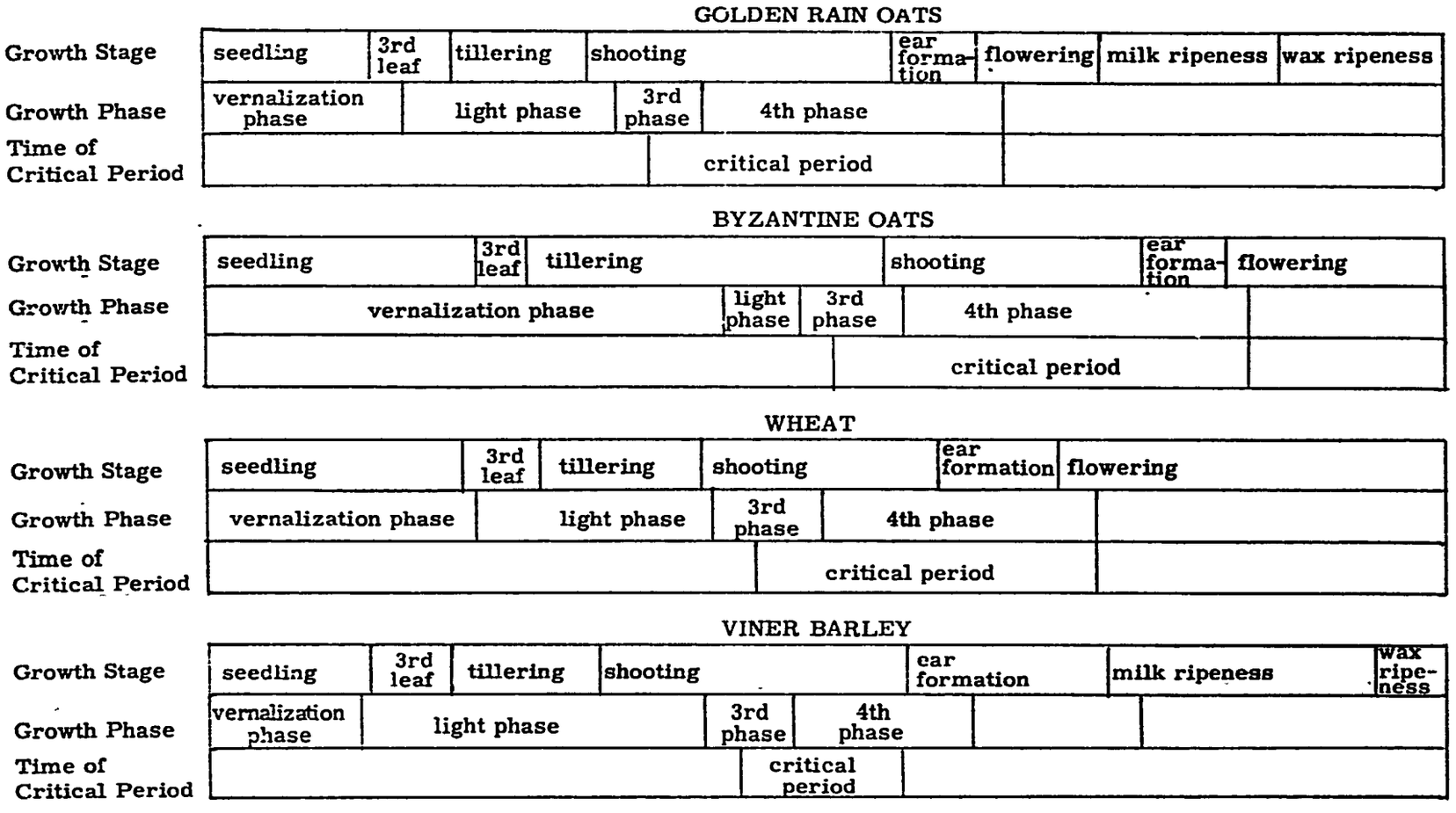

Figure 2.1. The critical periods of spring cereals in relation to their growth stages and phases (after Skazkin, 1961).

Certain sums of thermal units or growing degree-days have been defined as crop varietal constants. A linear relationship was assumed to exist between crop development and temperature. This assumption led to the "remainder index method" of calculating the relationship, which in turn gave rise to a number of expressions such as "degree-days" "growing degree-days", "heat units", "growth units", and "thermal units".

The remainder index method has been applied to numerous native and cultivated plants. In addition to the lower threshold temperature, and upper threshold is sometimes specified. Both are considered to vary with crop variety. Nuttonson (1955) compared various lower and upper threshold temperatures for cultivated crops in several parts of the United States. For winter wheat grown near Lincoln, Nebraska, he recommended 2-5°C as a range for the lower threshold temperature and 27°C as the upper. Nutlon (1948) attempted to improve the remainder index method by considering the length of photo-period. The resultant photo-thermal unit was defined by introducing a term P as a multiplying factor within the summation of equation (2.25). P refers to the length of daily photo-period.

Lindsey and Newman (1956), in a study of the flowering of native plants, considered diurnal temperature spread as a refinement in the remainder index method. The relationship, expressed in degree-hours (DH), reflected the approximate duration of the different temperature levels:

$$DH = \frac{12(T_{max}-T_1)}{T_{max}-T_{min}} \tag{2.26}$$

where T_{max} and T_{min} are the maximum and minimum daily temperatures, respectively.

Podolskii (1958) in his study of the phenology of cotton in the USSR found that neither the heat sum nor the threshold temperature is

constant. He constructed a pheno-temperature nomograph to eliminate the nonlinearity and achieved greater accuracy in phenological prognosis.

Holmes and Robertson (1959) introduced a generalized formula for the computation of weekly degree-days above 5°C for nine stations in Canada using the expression given by (2.27).

$$\bar{D} = N[(T_a - T_1) + L\sigma\sqrt{N}] \tag{2.27}$$

where $\bar{D}$ is the normal degree-days accumulated for a given month, N is the number of days in a month, L is a proportionality constant, and σ is the standard deviation of the mean temperature. The value of the constant L can be obtained from a specially prepared table.

The remainder index system continues to be most widely used in studies attempting to correlate growth and development of crops to temperature. It is widely used for its simplicity and its value in satisfying practical needs and definitely not for its accuracy nor its theoretical soundness.

This system has been used in field works, planning, and research. For example, the canning industry uses the thermal unit system in scheduling planting dates to insure orderly flow of optimally mature crops. Disease, weed, and insect control are generally correlated to the thermal unit system. It is widely used in the selection of suitable areas for specific crop varieties. Many branches of the applied sciences such as agronomy, engineering, entomology, zoology, make use of thermal units.

Some of the major limitations of the thermal unit system are as follows (Wang, 1960):

1. Varietal constants obtained from the thermal unit system fail to take into account the phenological development of the plant.

2. The threshold temperatures change with advancing stage of plant development, contrary to the assumption that they are constant.

3. The thermal unit system does not consider many factors vital to plant growth and development, such as solar radiation, soil moisture, relative atmospheric radiation, wind, crop cover, etc.

In addition to the modifications mentioned earlier in this section, the solar thermal unit and evapotranspiration are two alternatives that have relatively stronger theoretical and physical bases.

B.3. Solar thermal unit

Recently Caprio (1971) suggested a further improvement to the remainder index method by incorporating solar radiation. The resulting expression defining the solar thermal unit, STU, is given by

$$STU = \sum_{i=t_p}^{t_s} R_{si}(T_{ai} - T_l) \tag{2.28}$$

where R_s is the daily net radiation in the range of 0.3 to 4.0 micron wave length, which is equivalent to the shortwave radiation estimated by equation (2.3); and t_s is the date to a specified stage of growth. Lilac was taken as the reference plant. The STU requirements for several other plants, including alfalfa, to achieve prescribed stages of growth were compared. Equation (2.28) is analogous with (2.16), the Jensen-Haise method for estimating ETp in that the two expressions depend on daily temperature and solar radiation. Thus, ETp can be estimated from STU by a simple conversion as was done by Caprio.

B.4. Potential evapotranspiration

Correlating plant growth and development to ETp would eliminate most of the weaknesses of the thermal unit. More relevant variables that affect plant growth are included in estimating potential evapotranspiration by the combination method (equation 2.15). For this reason potential evapotranspiration would also be theoretically superior to the solar thermal unit method.

The idea of using evapotranspiration to measure plant development is not new. Thornthwaite (1952) defines a growth unit as the amount of

development that will occur in a plant transpiring a unit of water. One centimeter of evapotranspiration was equivalent to 100 growth units. Thornthwaite (1953) used peas as a reference crop and reported growth unit requirements for pea varieties of 16.80, 17.20, 17.90, and 21.00 cm for Alaska, Glacier, Thomas Laxton, and Shasta peas, respectively.

Alfalfa has been adopted as a reference crop in recent researches as indicated earlier. Use of potential evapotranspiration from alfalfa as a reference crop to measure growth and development of agricultural crops would benefit from progressive improvements derived from the ever-increasing research findings on evapotranspiration studies.

CHAPTER III

CROP RESPONSE TO LIMITED SOIL WATER: A BACKGROUND

Water use by growing crops has been the subject of many research studies. The total above ground production is generally measured in units of total dry matter. The grain component is studied more intensely since it represents the fraction of economic interest. Very little attention has been given to the root component since it generally has less economic value and is very difficult to sample. A background of the appropriate work on water-input / crop-output will be presented. Dry matter and grain responses will specifically be covered.

The classical work of Briggs and Shantz (1913a) followed by the works of Miller (1916), Kieselback (1916), Shantz and Piemeisel (1927), and Dillman (1931) dealt with the generalized relationship between plant growth and transpiration. The relationship was defined as a water requirement or transpiration ratio. Both terms indicate the ratio of water transpired by the plant during its growth to the weight of dry matter produced. Many other researchers have since contributed to the understanding of water use by plants. Water use efficiency, WUE, a term more commonly in use today, is the reciprocal of the transpiration ratio.

The term water use efficiency, WUE, does not reveal relative ratios to have the commonly accepted dimensionless meaning of efficiency. The units of WUE may be kg ha^{-1} cm^{-1} which express average rate rather than efficiency. Under its present definition it is equivalent to an average crop yield (average product) for seasonal water use, which is total yield divided by total water use. Since the term WUE may be misleading to users with specialties other than agronomy, attempts should be made to replace it with terminology compatible with its definition. Until then it must be explicitly defined whenever it is used.

Many comprehensive reviews of the general subject of plant-water relationships have been made. Briggs and Shantz (1913b) reviewed the work that had been published to that date. Veihmeyer and Hendrickson (1950) and Richards and Wadleigh (1952) reviewed the studies since 1913. Reviews were added by Veihmeyer and Hendrickson (1950) and de Wit (1958). There are many comprehensive reviews after 1960 (Heady and Dillon, 1961; Hagan, Haise and Edminster, eds., 1967; Change, 1968; Koslowski, ed., 1968; Salter and Goode, 1969; and Hillel, 1971).

A. Dry matter production

Briggs and Shantz (1913a) initiated their experiments at Akron, Colorado. They grew about 55 species and varieties in pots under various soil water levels. Their results and those of later researchers, Shantz and Piemeisel (1927), showed close relationship between dry matter and transpiration. Since these studies were not conducted under field conditions, Briggs and Shantz (1914) stated "the water requirement measurements must be considered relative rather than absolute." This basic qualification of the data was often overlooked or disregarded for the next half-century.

De Wit (1958) analyzed data, including that of Briggs and Shantz (1913a), from many parts of the world in an attempt to describe the influence of transpiration on crop production. He, and later Arkley (1963), found that dry matter yield is linearly related to transpiration. For areas of high radiation, the semi-arid Great Plains of the United States, de Wit proposed the following relationship:

$$DM = m\frac{W_t}{E_o} \tag{3.1}$$

where DM is the total dry matter produced, W_t is the total transpiration, E_o is the free water evaporation, and m is a constant which depends only on the plant. The dimensions of m may be kg dry matter ha^{-1} day^{-1}, depending on the dimensions of DM, W_t and E_o.

For areas of low radiation, the Netherlands, de Wit's equation using free water evaporation as a correction factor did not apply. For such areas he suggested a simple linear relationship:

$$DM = m' W_t \tag{3.2}$$

Arkley (1963) reconciled the discrepancy in the results of the two climatic regions using mean monthly atmospheric relative humidity deficit as a correction factor. The resulting equation was of the form:

$$DM = k_f \frac{W_t}{100-H} \tag{3.3}$$

where H is the mean daily relative humidity of the atmosphere during the period of most active growth and k_f is a constant for a given crop.

Some points regarding the analysis by de Wit (1958) and Arkley (1963) deserve special elaboration:

1. The analysts did not consider the amount of transpiration or water use attributable to the root biomass and other conventionally unharvestable parts of the plant. Of course, measurements of these parts are rarely available, unless such parts are of economic significance like sugar beets and potatoes. However, if more accurate explanatory and/or predictive relationships between plant growth and water and nutrient use are desired, the relationships must be based on the total plant production which result from the input resources.

2. The main concern of de Wit and Arkley was to scale transpiration such that yield response models become applicable under any climatic condition. This is an important consideration. The way the two authors present their models is a little misleading in that they imply zero intercept, contrary to some of their statistical results. The models should include a term for the intercept.

3. Most of the data analyzed were not from field studies. Hence, the results should be considered relative rather than absolute.

4. The yield models proposed by the two authors require the separation of transpiration through the plant population and evaporation from the surface. Until techniques for estimating transpiration and also suppressing or controlling soil surface evaporation in the field become reliable, relating plant production to evapotranspiration may have greater planning and operational facility.

Legget (1959), Powers et al. (1961), Arkley (1963), Whittlesly and Calyar (1968), and Hanks et al. (1969) have shown that dry matter is linearly related to evapotranspiration. The studies of Hanks et al. included grain sorghum, wheat, oats, and millet grown in field and lysimeter plots. Dry matter and evapotranspiration were highly correlated for all cases. The linear relationships had positive abscissa intercepts for all cases. The range of the intercept for wheat from the above citations was 5 to 10 cm. The general explanation is that the positive abscissa intercept reflects water use during the early part of the growing season, which does not significantly contribute to the above ground dry matter accumulation.

B. Grain yield

Mitscherlich in 1909 and Spillman in 1923 (Heady and Dillon, 1961) independently defined nonlinear production functions relating nutrient input and crop output. Their equation can be written in general form as

$$G = G_o - \beta\rho^x \qquad (3.4)$$

$$0 < \rho < 1.0$$

where G is the total yield, x is the input nutrient, G_o is the maximum yield attainable by increasing the magnitude of x, β is a constant defining the maximum response (integral of dG/dx) attainable from the use of x, and ρ is the factor by which marginal productivity of x declines. G_o, β and ρ are parameters. (The above equation is actually that of Spillman, but Mitscherlich's $G = G_o(1-10^{-cx})$ can

easily be transformed to that of Spillman.) The function allows diminishing marginal productivity of x but does not allow negative marginal products, i.e. $\frac{dG}{dx} \geq 0$, and G_o is the asymptotic value of G.

Denmead and Shaw (1962) identified three stages of corn development. The first stage starts 30 days after planting and extends to tasselling. The second stage covered silking and was 17 days long. The third stage included ear growth and was 30 days long. Interactions between stresses at different stages were also considered. Stresses were imposed by allowing the plant to suffer until near wilting point. Their results indicated that yields were reduced by 25, 50 and 21% by stresses during the respective stages. Interactions were not significant at a 10% level. The effects of stresses were reported additive. Similar studies were made by many investigators on corn and other crops. Robins and Domingo (1956), Schreiber and Stanbery (1965), and Jensen and Sleten (1965) investigated the effects of stress on dry beans, barley and grain sorghum, respectively.

Moore (1961) attempted to develop an analytical framework for estimating the production function for irrigated crops from which the value of irrigation water can be imputed. He made several critically gross assumptions:

1. the farmer has complete knowledge of the soil moisture status (in actuality this is seldom the case),

2. potential growth is linear over time, and

3. different plants are affected similarly by soil water stress.

He divided the growing season into n periods of irrigation. The periods were not necessarily equal. During each period, the relative growth, Gr_i, defined as the ratio of actual growth to potential growth for the ith period is given by (3.5):

$$Gr_i = \frac{\int_{\theta_i}^{\theta_i} g(\theta)\, d\theta}{100\, \theta_i} \qquad (3.5)$$

where θ_i is the water depletion percent at which the irrigation cycle is terminated during period i and $g(\theta)$ is a functional relationship between relative growth and available soil water θ.

The total relative growth for the entire season is given by equation (3.6):

$$Gr = \frac{1}{L_s} \sum_{i=1}^{n} Gr_i \cdot t_i \tag{3.6}$$

where L_s is the length of season and t_i is the length of the ith irrigation period.

By assigning costs to irrigation water and prices to crop yield, Moore used his production function to optimize irrigation water use. As equations (3.5) and (3.6) indicate, Moore's model is additive.

Flinn and Musgrave (1967) and Dudley, Howel, and Musgrave (1971) also used an additive model similar to Moore's. They, however, recognized that relative growth is different for different stages of growth and assumed that growth occurs on days when the actual evapotranspiration is equal to the potential and growth ceases otherwise. This assumption was critical. Plants do grow when the actual evapotranspiration is less than the potential. In fact, actual evapotranspiration may be less than potential, except immediately after irrigation or rain. A dynamic solution was presented for the optimal allocation of irrigation water since the assumed production function was suitable for dynamic programming. DeLucia (1971) used Moore's model to determine water resources allocation.

Anderson and Maas (1971) simulated economic returns from irrigated crops assuming a multiplicative yield model in which missing two successive irrigations in a two week cycle results in a total crop loss. Otherwise, a percentage reduction was applied to the expected final yield. The reduction factors were not derived from theoretical or experimental analysis. They were estimates based on pure judgment.

Jensen (1968) suggested that the relative yield of a determinate crop that flowers could be determined by the multiplicative model:

$$\frac{G}{G_o} = \prod_{i=1}^{n} \left(\frac{W_{et}}{W_{oc}} \right)_i^{\lambda_i} \tag{3.7}$$

where G is the actual yield, G_o is the yield when soil moisture is not limiting, n is the number of physiological stages, $\left(\frac{W_{et}}{W_{oc}}\right)_i$ is the ratio of the actual to maximum evapotranspiration for the ith stage of growth, and λ_i represents the relative sensitivity of the crop to water stress during the ith period. For indeterminate crops, such as grass, Jensen suggested the following additive model:

$$\frac{G}{G_o} = \frac{\sum_{i=1}^{n} a_i \left(W_{et} \right)_i}{\sum_{i=1}^{n} a_i \left(W_{oc} \right)_i} \tag{3.8}$$

Jensen (1968) evaluated equation (3.7) for grain sorghum considering three stages of growth. The crop sensitivity factors, λ_i, were assigned values of 0.5, 1.5, and 0.5 for the three stages, and were not statistically determined.

Hall and Butcher (1968) proposed that the yield of crops under limited moisture conditions could be defined by the multiplicative model given by (3.9):

$$G = \prod_{i=1}^{n} a_i G_o \tag{3.9}$$

where G is the actual crop yield, G_o is the yield when soil water is not limited.

$$a_i = a_i \left(w_i \right) \tag{3.10}$$

w_i is gravimetric or volumetric soil moisture content at the end of the ith period.

Hall and Butcher transformed the production function (3.9) logarithmically so that it was suitable for dynamic programming, but no data were presented to support the function.

The relationships given by equations (3.7) and (3.9) are similar. The major differences are that the exponents λ_i in equation (3.7) are functions of evapotranspiration and have fixed values for a given period i, while the coefficients $a_i(w_i)$ in equation (3.0) are functions of gravimetric soil moisture and have variable values for a given period i. Thus statistical or experimental verification is difficult. Utilization of weighting factors that are functions of evapotranspiration seem to be more sound provided the model has physical significance. Identical soil water contents can have different crop stresses with differences in soil, climate, soil water salinity, and the relative development of the crop. Actual evapotranspiration is a more representative and a better measure of the ability of the crop to use water. Thus, (3.7) may be preferred over (3.9).

Stewart and Hagan (1972) are conducting irrigation studies at Davis, California, and developing functional relationships between grain yield and evapotranspiration. The study was initiated in 1969 with corn and grain sorghum. Reports from their 1970 and 1971 observations indicate strong linear relationships between grain yield and seasonal evapotranspiration.

Powers et al. (1961) studied spring wheat in field plots at four water levels and reported that grain yield was almost a constant fraction (0.42) of the final dry matter. They also found a linear relationship between dry matter and evapotranspiration.

Jensen and Sletten (1965) found that relative grain yield decreased more rapidly than relative seasonal evapotranspiration when irrigation of fertilized grain sorghum was delayed. Upon further observation,

their results reveal that the ratio of the change in relative yield to relative evapotranspiration is nearly constant with a value of about 1.6. Stewart and Hagan (1972) contend that the constancy of the ratio shows reductions or deficits in evapotranspiration and reductions in grain yield are linearly related, provided the origin of the function is (ET_{max}, G_{max}), where the terms refer to maximum of water use and grain yield.

Despite the above citations, some researchers, Musick, et al. (1963), Musick and Dusek (1971), and Stewart and Hagan (1969) indicated that grain yield and seasonal evapotranspiration relations may be convex curvilinear implying diminishing returns. The reported curvilinear relations resulted from general over irrigation. Hiler and Clark (1971) indicated that such results can be linearized by relating reductions in grain yield to deficits in evapotranspiration below the respective optimums.

CHAPTER IV

WHEAT PHENOLOGY AND WATER USE: RESULTS AND DISCUSSION

This chapter presents the results and discussion of wheat phenology and water use. The analyses are based on the procedure outlined in Chapter II. Four methods of correlating wheat developmental stages to climatic indices are compared. Also, comparison of measured (water balance method) and estimated evapotranspiration (combination method) is made. For clarity, the measured ET is referred to as "water use." A transpiration model is developed to separate daily ET into transpiration and soil evaporation.

A. Phenological stages of wheat

Phenological development of wheat is correlated to: (1) the number of days (2) the accumulation of degree-days (3) the accumulation of solar thermal units; and (4) the accumulation of potential evapotranspiration. Each of these is accumulated from spring growth initiation to the successive developmental stages of boot, heading, soft dough, and maturity. Growing degree-days are calculated with equation (2.25) with 3°C and 27°C as the lower and upper threshold temperatures. Solar thermal units are obtained by equation (2.28). Potential evapotranspiration is computed by the combination method (equation (2.15)).

In wheat, boot stage is characterized by the appearance of sheath-like structure on the upper end of the grain which encloses the inflorescence prior to its emergence. Heading is represented by the appearance of the tightly formed fruit cluster. Soft dough is the stage in which the kernel when broken open shows a soft starchy or cheesy condition. Maturity is the state of full or complete development.

Tables 4.1 through 4.4 present the number of days, growing-degree days, solar thermal units, and potential evapotranspiration, respectively, accumulated at each stage of growth. The means,

Table 4.1. Average number of days accumulated from spring growth initiation for the four treatments of hard red winter wheat, North Platte, Nebraska, 1963-70, 1968 excluded.

Year	Boot	Heading	Soft dough	Maturity
1963	62	75	97	114
1964	59	67	87	107
1965	57	74	100	115
1966	65	78	99	113
1967	46	60	95	113
1969	63	71	99	113
1970	72	81	107	121
Mean	60	73	98	113
Standard deviation	6	7	6	4
Coefficient of variation, %	12	10	6	4

Table 4.2. Average growing degree days accumulated from spring growth initiation for the four treatments of hard red winter wheat, North Platte, Nebraska, 1963-70, 1968 excluded. (Units: day - ^{o}C)

Year	Boot	Heading	Soft dough	Maturity
1963	492	628	995	1345
1964	425	563	839	1248
1965	381	608	1024	1305
1966	423	616	1063	1197
1967	323	483	1004	1277
1969	493	608	1032	1276
1970	565	591	953	1255
Mean	420	585	973	1272
Standard deviation	63	50	64	47
Coefficient of variation, %	15	9	7	4

Table 4.3. Average solar thermal units accumulated from spring growth initiation for four treatments of hard red winter wheat, North Platte, Nebraska, 1963-70, 1968 excluded. (Units: 10^{-3} cal cm^{-2} day^{-1} day - ^{o}C)

Year	Boot	Heading	Soft dough	Maturity
1963	203	273	482	703
1964	206	289	434	683
1965	188	304	517	672
1966	221	342	538	677
1967	154	247	511	653
1969	252	298	532	566
1970	209	323	540	736
Mean	205	296	508	684
Standard deviation	28	31	37	28
Coefficient of variation, %	14	10	7	4

Table 4.4. Average potential evapotranspiration accumulated from spring growth initiation for four treatments of hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded. (Units: cm)

Year	Boot	Heading	Soft dough	Maturity
1963	22.88	28.43	40.78	55.20
1964	19.88	24.68	32.86	46.36
1965	19.30	27.12	39.04	48.55
1966	26.25	34.08	45.74	53.25
1967	19.02	25.18	39.57	47.90
1969	26.98	29.80	44.70	52.08
1970	26.91	33.77	46.40	57.11
Mean	23.03	29.01	41.31	51.50
Standard deviation	3.47	3.61	4.59	3.83
Coefficient of variation, %	15	12	11	7

standard deviations and coefficients of variation of these climatic indices are also given.

The entries in Tables 4.1 through 4.4 are based on observed data. The coefficient of variation was least for the number of days decreasing from 12% at boot stage to 4% at maturity. Similarly, the variabilities for the other methods decreased from boot to maturity: growing degree days 15% to 4%, solar thermal units 14% to 4%, and potential evapotranspiration 15% to 7%.

Each of the phenological stages is not achieved by all plants at the same time; rather, there is a range of time during which all plants display the external properties characterizing a stage. Thus the recorded phenological dates are subjective observations. The degree of the subjectiveness creates some year to year variation in the magnitude of the index to which the developmental stage is correlated. For example, compare the 1967 data in Table 4.1 with the mean of all years. Boot stage occurred 46 days after spring growth initiation, and heading at 60. The corresponding means for all years to boot and heading stages are 60 and 73 days. The length of time to boot stage was relatively short in 1967. An attempt to reduce the variation caused by the subjective classification of the developmental stage was made by selecting the mean number of days for all years of 60, 73, 98, and 113 days as representing boot, heading, soft dough, and maturity.

Although the number of days varied least, the variations for the other methods are comparable and differ little from the number of days. It appears that wheat phenology could be correlated with growing degree-days, solar thermal units, and potential evapotranspiration. However, potential evapotranspiration and solar thermal units have stronger theoretical basis since they include more climatic elements which directly affect growth. Solar thermal units include temperature and short wave solar radiation, both in the range suited for plant growth and development. Potential evapotranspiration includes temperature, short and long wave radiation, atmospheric saturation, and

wind. The interaction of these climatic elements is known to affect the growth and development of the plant. Therefore, an index which incorporates more climatic factors should be preferable.

B. Measured water use (water balance method)

As indicated in Chapter I, the neutron scatter method was used to measure soil water content. Readings were taken at 30 cm increments over the 180 cm root zone. The water holding capacity of the Holdrege silt loam is 0.175 cm cm^{-1} which gives a total water holding capacity of 31.5 cm in the 180 cm root zone.

Table 4.5 presents the available soil water measured at spring growth initiation, boot, heading, soft dough, and maturity. Also included in the table are rainfall amounts accumulated from spring growth initiation.

C. Estimated ET (combination method)

The USDA-ARS-SWC irrigation scheduling computer program reviewed in Chapter II which is based on the combination method was calibrated and used to calculate ET_p and ET. ET is obtained by considering a crop factor K_c. As indicated in Chapter II, Heermann et al. (1974) calibrated the constants in equation (2.15) for the Central Great Plains using data from Scotts Bluff, Nebraska. The computer program as modified for this particular study is listed in the Appendix.

Precipitation and wind speed were observed 20, 10, and 16 days after spring growth initiation in 1963, 1964, and 1965, respectively. The Jensen-Haise method given by equation (2.16) was used to estimate ET_p from solar radiation and average temperature inputs for these periods of incomplete data.

C.1. Modification of crop coefficient

The basic crop coefficient for small grains, K_{co}, given by equations (2.22) and (2.23) was modified for winter wheat. Before heading, equation (2.22) was subjected to $K_{co} = 0.09$ for $p \leq 0.20$ and the first term was reduced to 0.160 from 0.230 for $p \leq 0.20$. After heading

Table 4.5. Available soil water in 180 cm root zone at each stage by treatment and cumulative rainfall (cm), hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded.

Year	Treatment	Spring growth initiation	Boot	Heading	Soft dough	Maturity
1963	BON	15.44	11.33	12.67	8.56	7.47
	BN	16.84	15.24	13.54	8.79	7.14
	MON	18.59	12.14	11.53	8.81	5.21
	MN	17.12	12.62	11.05	8.41	4.22
	rainfall, cm	--	5.79	8.86	15.57	20.22
1964	BON	17.22	15.67	16.00	16.43	12.90
	BN	19.20	16.43	16.31	13.64	12.57
	MON	27.69	23.95	19.45	19.43	16.83
	MN	24.66	20.60	18.44	19.58	15.04
	rainfall, cm	--	12.52	14.20	19.20	26.42
1965	BON	24.21	18.87	20.32	23.87	22.48
	BN	24.38	18.44	20.60	23.98	22.58
	MON	24.41	18.41	20.70	23.88	22.88
	MN	24.66	18.69	20.32	23.62	21.36
	rainfall, cm	--	3.96	15.72	31.17	37.77*
1966	BON	23.29	20.28	16.36	11.58	10.54
	BN	23.24	17.65	13.08	11.76	10.44
	MON	31.27	23.85	19.79	17.14	16.31
	MN	27.71	23.42	16.97	15.87	13.64
	rainfall, cm	--	8.00	8.00	14.25	21.79
1967	BON	16.26	16.94	13.18	19.69	15.82
	BN	17.20	17.40	13.74	20.69	16.13
	MON	17.31	18.16	13.89	19.68	17.40
	MN	16.94	17.65	12.75	18.06	14.55
	rainfall, cm	--	6.07	8.69	30.63	34.95
1969	BON	20.63	15.21	11.43	8.97	6.32
	BN	20.50	17.91	14.91	8.97	5.26
	MON	23.04	17.04	13.94	6.48	7.62
	MN	23.16	19.18	14.27	4.95	6.32
	rainfall, cm	--	6.12	6.98	15.01	20.29
1970	BON	22.50	16.20	11.43	9.22	5.15
	BN	22.50	15.57	11.25	8.76	5.92
	MON	23.63	17.25	12.07	8.51	6.02
	MN	24.49	17.60	13.43	10.69	8.15
	rainfall, cm	--	8.59	9.40	18.67	19.10

* Includes 12.5 cm supplemental irrigation.

the highest value of equation (2.23) was increased to 1.250 with K_{co} constrained to be less than or equal to 1.00. Jensen used 1.04 as an upper limit for small grains. These adjustments were made to correct the tendencies of the original expression to overestimate during the early part of the growing season and underestimate during the later. The original and adjusted basic crop coefficients are compared in Figure 4.1.

D. Comparison of measured water use and estimated ET

Estimated ET accumulated from spring growth initiation to observed dates of boot, heading, soft dough, and maturity (W_{et}) were compared with corresponding cumulative water use calculated from the soil water measurements (W_m). The results are plotted in Figure 4.2. A linear regression given by equation (4.1) indicates a one-to-one correspondence between W_{et} and W_m, with a small intercept value and a high correlation.

$$W_m = 0.15 + \underset{(0.02)}{1.00}\, W_{et} \qquad (4.1)$$

$$n = 112$$

$$R^2 = 0.94.$$

The intercept value of 0.15 cm does not differ from 0.0 at 1-percent probability level. The regression coefficient of 1.00 cm cm^{-1} with a standard error of regression of 0.02 cm and coefficient of determination (R^2) of 0.94 indicates good relationship between W_{et} and W_m. Since the agreement was good, W_{et}, which can be accumulated to any desired time from computations of daily ET, was used for the subsequent analysis.

E. Model for estimating transpiration

Development of two methods for estimating transpiration is the subject of this section. The two alternative models depend on the basic crop coefficient extensively reviewed in Chapter II. Both models obtain transpiration by defining a basic "transpiration coefficient" K_{tco} which is related to the basic crop coefficient K_{co}.

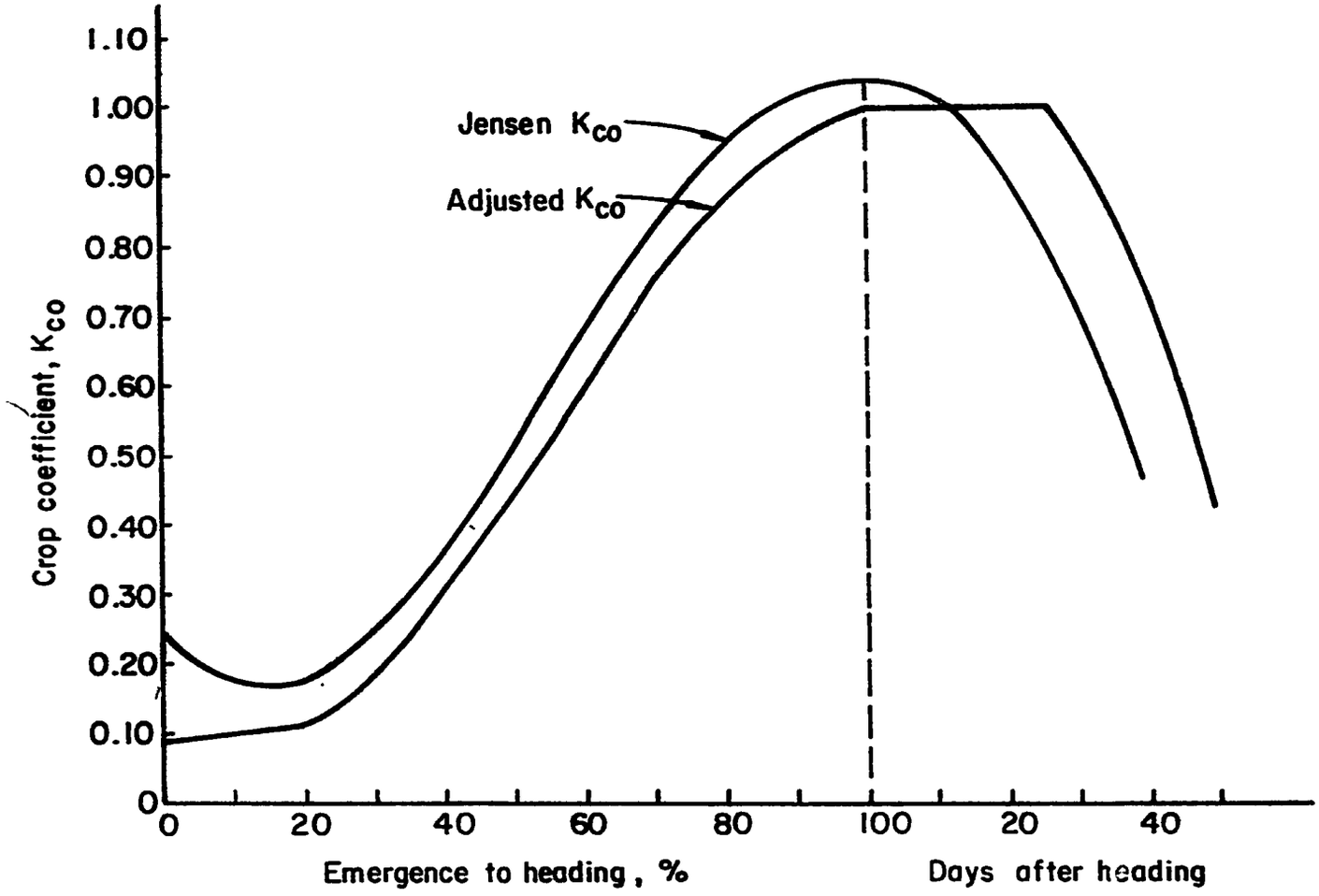

Figure 4.1. Crop coefficient adjusted for winter wheat (small grain).

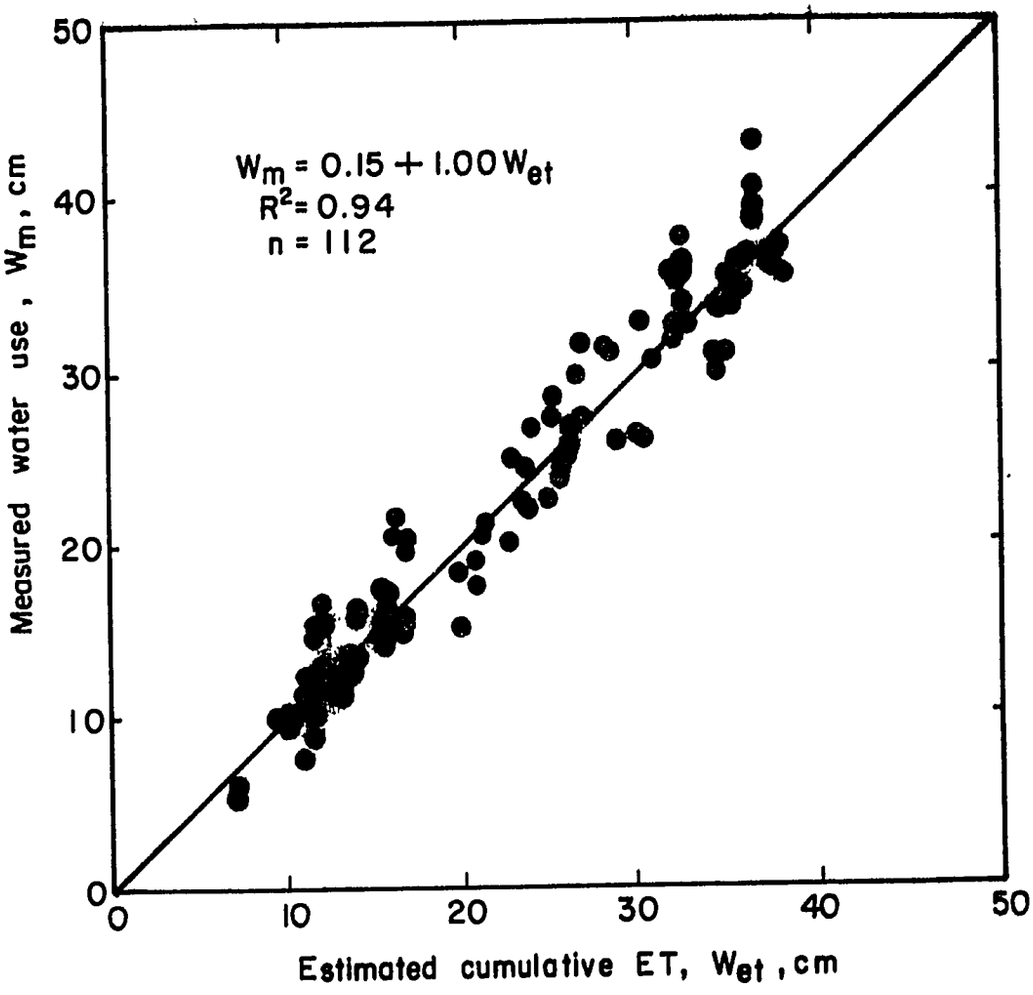

Figure 4.2. Comparison of estimated cumulative evapotranspiration and measured water use for hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded.

Model 1

Transpiration coefficient K_{tco} is defined by equation (4.2):

$$K_{tco} = (P - P_o) K_{co} \tag{4.2}$$

where P is the fraction of days from plant emergence to heading, and P_o is a constant.

During the early stages of plant development the constant P_o indicates the period at which crop transpiration becomes a significant component of evapotranspiration. After full cover or heading K_{tco} is restrained to be $(1.00 - P_o) K_{co}$. Substitution of the adjusted expressions for before and after heading into equation (4.2) results in the following expression for K_{tco}:

Emergence to heading

$$K_{tco} = (P - P_o)[0.160 - 1.140P + 4.843 P^2 - 2.893 P^3] \tag{4.3}$$

for

$$P_o \leq P \leq 1.00$$

with a constraint that $K_{tco} \geq 0.04$ early in the season.

After heading

$$K_{tco} = (1.00 - P_o)[1.250 + 8.532D - 7.260 D^2 + 4.440 D^3] \tag{4.4}$$

where D is the number of days after heading divided by 100.

Daily transpiration (T) is then estimated from the relationship

$$T = K_{tc} ET_p \tag{4.5}$$

with the transpiration coefficient defined by

$$K_{tc} = K_a K_{tco} \tag{4.6}$$

where K_a is the adjustment factor for limiting soil water.

Model 2

Ritchie and Burnett (1971) have shown that, when water movement to the plant roots is not limited, the transpiration rate for developing cotton and grain sorghum canopies T_o is related to potential evapotranspiration above the plant canopy ET_o and leaf area index L_{ai} by

$$T_o = (-0.21 + 0.70\, L_{ai}^{\frac{1}{2}})\, ET_o \tag{4.7}$$

$$0.1 \leq L_{ai} \leq 2.7$$

A transpiration coefficient K_{tco} can be developed from equation (4.7) by replacing ET_o by

$$ET_o = K_{co}\, ET_p \tag{4.8}$$

Thus

$$K_{tco} = (-0.21 + 0.70\, L_{ai}^{\frac{1}{2}})\, K_{co} \tag{4.9}$$

Daily data reported by Ritchie (1972) show that grain sorghum L_{ai} increases linearly to a maximum of 2.5 in about 40 days (Figure 4.3). A similar relationship between time (t) and L_{ai} is obtained by using the mean $L_{ai} = 2.4$ for wheat which was observed at heading. This L_{ai} is plotted against the mean date to heading (73 days from spring growth initiation for wheat). L_{ai} is very small for the first 20% of this time or about 15 days. As shown in Figure 4.6,

$$L_{ai} = 0.041t - 0.52 \tag{4.10}$$

Substituting this into equation (4.9), K_{tco} becomes

$$K_{tco} = [-0.21 + 0.14\ (t - 13)^{\frac{1}{2}}]\, K_{co} \tag{4.11}$$

P, which by definition is related to t by $P = \frac{t}{73}$, can be substituted for t in equation (4.10) so that K_{co} and K_{tco} become functions of the same variable P.

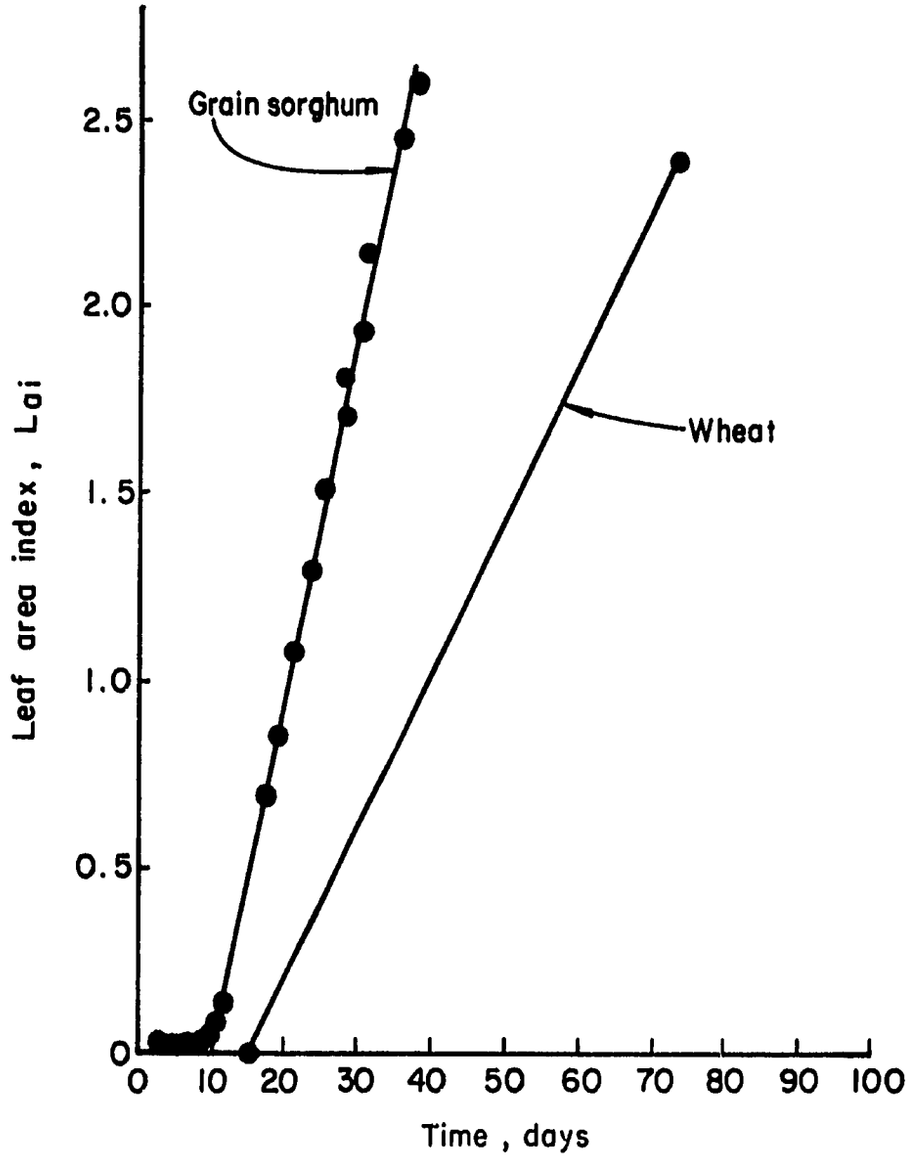

Figure 4.3. Leaf area index as a function of time for grain sorghum and winter wheat (grain sorghum data, after Ritchie and Burnett, 1971).

Then before heading

$$K_{tco} = [-0.21 + 1.20\,(P - 0.18)^{1/2}]\,K_{co} \qquad (4.12)$$

$$\text{for } 0.20 \leq P \leq 1.00$$

The constraint that $K_{tco} \geq 0.04$ still holds here for $P \leq 0.20$.

Letting $P = 1.00$ after heading,

$$K_{tco} = 0.88\,K_{co} \qquad (4.13)$$

Daily transpiration under conditions of limiting soil water can then be estimated by equation (4.5) with the current expression for K_{tco}. Potential transpiration can be expressed in terms of K_{tco} as:

$$T_o = K_{tco}\,ET_p \qquad (4.14)$$

The transpiration coefficient K_{tco} for wheat (small grain) obtained from K_{co} by the two methods are presented in Figure 4.4. The upper curve is the adjusted K_{co} which was given in Figure 4.1. The parameter P_o in equation (4.2) was set equal to 0.10. Since the two methods give nearly identical K_{tco} when $P_o = 0.10$, either equations (4.3) and (4.4) or (4.12) and (4.13) can be used to derive the transpiration coefficient. At this point, it must be emphasized that experimental tests must be made to validate the models.

Cumulative transpiration (W_t) relative to cumulative evapotranspiration (W_{et}) increases as the crop season progresses (Figure 4.5). The mean seasonal ratio $\frac{W_t}{W_{et}} = 0.67$ may be compared with 0.59 and 0.56 for grain sorghum deducible from the works of Ritchie (1972) and Hanks et al. (1969).

W_t and W_{et} will be employed as independent variables for crop response models developed in the next chapter. At this point it can be observed that relating yields to transpiration has greater conservation implications. Evaporation from the soil surface, which is the other component of ET, may not be necessary for plant growth. Nevertheless, it can not be totally controlled with present field conservation

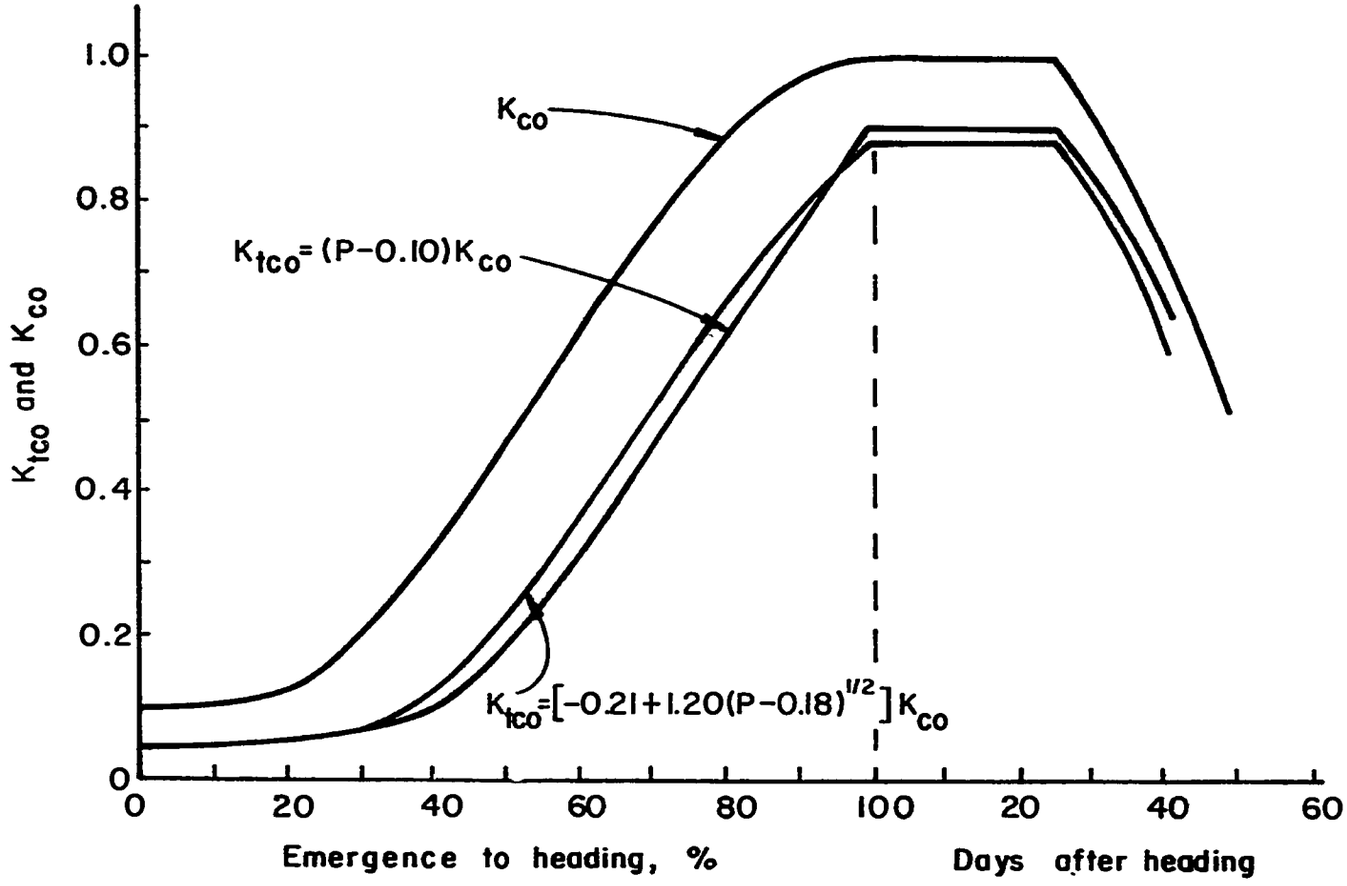

Figure 4.4. Transpiration coefficient for small grain (winter wheat) K_{tco} obtained from K_{co} by two methods are almost identical when P_o = 0.10.

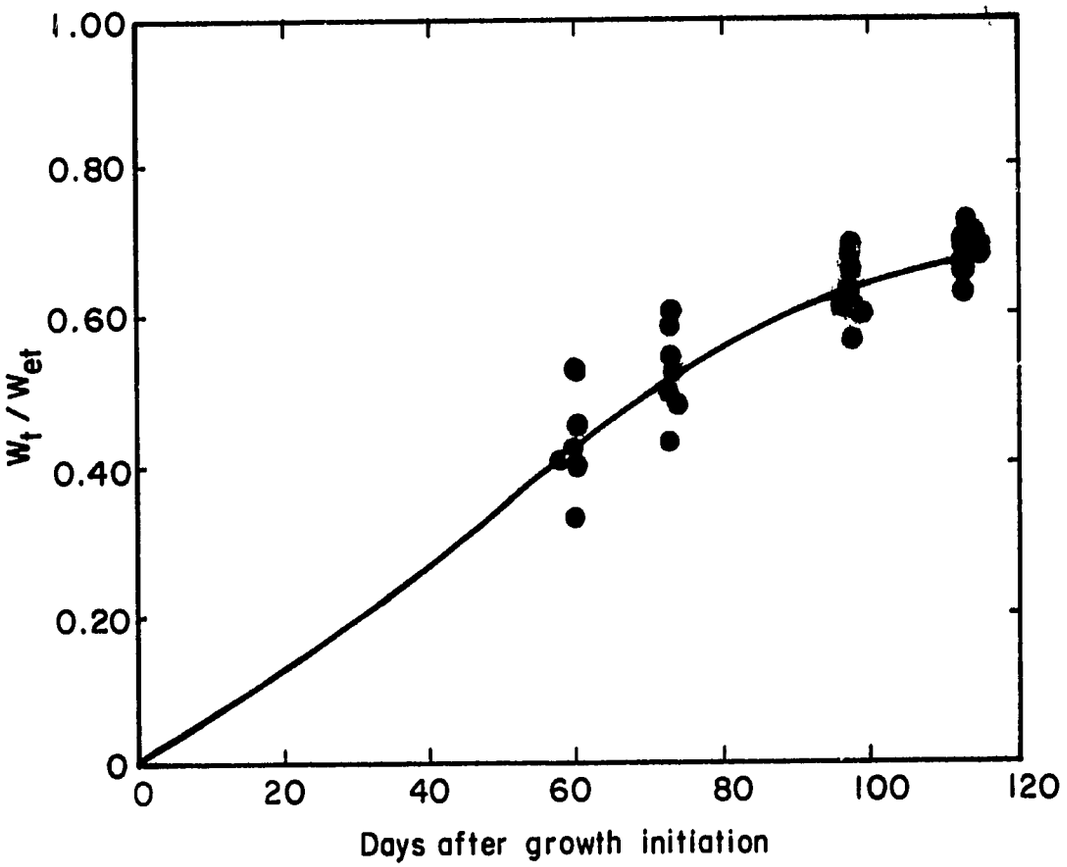

Figure 4.5. Cumulative transpiration relative to cumulative evapotranspiration as related to time after growth initiation.

methods. But as the demand for agricultural products increases, as is the current worldwide experience, it would be economically feasible to introduce more and better water conservation measures. Also the demand on the available supplies is increasing and competing users will be willing to pay higher prices for the use of water. Inefficient use will be more costly. Since agriculture is the largest user of water, improvements in irrigation methods and practices will be the most significant in saving water. The amount of water saved would be available for additional, intensive and extensive, uses in agriculture and for transfers to nonagricultural industries. For example, if soil surface evaporation can be reduced by 50 percent, a saving of 15 to 20 percent of the seasonal crop consumptive use may be possible. In the U.S. alone, where the estimated daily use of water for irrigation is 246 million m^3 (U.S. Water Resources Council, 1968), a saving of 4.4 to 5.9 billion m^3 over a three month crop season may be possible.

F. Relative ET or relative T

Daily relative ET (ET_r) is the ratio of the actual crop evapotranspiration ET_c to the potential crop evapotranspiration ET_o. Similarly, daily relative T (T_r) is the ratio of actual crop transpiration T to potential crop transpiration T_o. The variables T, ET_o, and T_o have been presented by equations (4.5), (4.8), and (4.14). ET_c is defined by

$$ET_c = K_a ET_o = K_a K_{co} ET_p \tag{4.15}$$

K_a is the crop coefficient adjustment factor for limited soil water given by equation (2.20).

ET_r and T_r, mathematically defined by (4.16) and (4.17), are equivalent.

$$ET_r = \frac{ET_c}{ET_o} = K_a \tag{4.16}$$

$$T_r = \frac{T}{T_o} = K_a \tag{4.17}$$

A term W_r is used to represent cumulative ET_r or T_r. W_r is computed by (4.18).

$$W_r = \int_{t_o}^{t_i} K_a \, dt \tag{4.18}$$

where t is the time in days, t_o is the date of growth initiation, and t_i is the date of the ith stage of growth.

CHAPTER V
DRY MATTER YIELD MODELS: RESULTS AND DISCUSSION

This chapter presents the wheat yield data and results and discussion of dry matter yield models. The models include linear and quadratic formulations. A model relating interstage dry matter with interstage stress day is investigated.

A. Wheat yield data

Hard red winter wheat yield of dry matter and grain yield are presented in Table 5.1 for each of the four treatments during the seven years of the experiment. Number of tillers per square meter and the ratio of grain to final dry matter are also included in Table 5.1. The four annual treatments abbreviated by BON, BN, MON, and MN represent bare no nitrogen added, bare nitrogen added, mulched no nitrogen added, and mulched nitrogen added, respectively. The dry matter yields were interpolated to correspond to the mean phenological dates of 60, 73, 98, 113 days from spring growth initiation in an attempt to remove variation caused by the subjectivity of establishing stages of growth.

The seven year averages and overall averages are given for each column in Table 5.1. The dry matter yields had a variability that decreased with season. The coefficients of variation decreased from 27% at boot stage to 8% at maturity. The overall standard deviation, however, remained essentially constant (about 625 kg ha^{-1}) during the respective samplings. The increase in total sample weight during the progressive stages of development probably contributed to the decrease in variation.

An analysis of variance (AOV) for the final dry matter and grain yields is presented in Table 5.2. The sources of variation include year-to-year and treatment variation. The treatment variation was divided into nitrogen fertilizer, mulch, and interaction between

Table 5.1. Dry matter and grain yields and number of tillers, hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded.

Year	Treatment	Dry matter kg ha^{-1} late preceeding fall	Tillers per m^2	Dry matter, kg ha^{-1} at boot	heading	soft dough	maturity	Grain yield kg ha^{-1}	Ratio grain to final dry matter
1963	BON	246	960	2188	3416	5660	6608	1630	0.25
	BN	314	1100	3136	4368	6608	7448	1755	0.24
	MON	224	880	2688	3920	5600	6216	1632	0.26
	MN	246	1100	3360	4872	6720	7392	1760	0.24
1964	BON	1019	1000	2912	4331	6309	7056	3412	0.48
	BN	1053	1070	3733	5488	7728	8475	3544	0.42
	MON	918	860	2352	3360	5115	5899	2660	0.45
	MN	1030	1050	2800	4069	6197	6981	2975	0.43
1965	BON	403	1070	1182	3140	5227	6384	3273	0.51
	BN	504	980	1145	2949	5451	6673	3188	0.48
	MON	347	700	1444	3065	5563	6496	2353	0.36
	MN	436	1060	1369	3177	5712	6795	2824	0.42
1966	BON	549	1320	2837	4480	7019	7691	3665	0.48
	BN	549	1360	3099	4928	7328	8139	3800	0.47
	MON	538	1100	2464	3845	6533	7317	3309	0.45
	MN	538	1160	2837	4667	7280	8027	3500	0.44
1967	BON	258	820	3323	4592	6459	7243	2365	0.34
	BN	291	870	3061	4480	6421	7108	2477	0.35
	MON	168	870	2949	4256	6212	7170	2423	0.34
	MN	190	840	2613	4002	6197	7019	2633	0.38

Table 5.1. Dry matter and grain yields and number of tillers, hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded. (Cont'd.)

Year	Treatment	Dry matter kg ha^{-1} late preceeding fall	Tillers per m^2	Dry matter, kg ha^{-1} at boot	heading	soft dough	maturity	Grain yield kg ha^{-1}	Ratio grain to final dry matter
1969	BON	493	1630	1941	3883	7019	8139	3640	0.45
	BN	504	1350	1941	3659	6421	7541	3611	0.48
	MON	358	1460	1605	3360	5973	7800	3618	0.53
	MN	358	1240	1605	3211	5675	8022	4069	0.51
1970	BON	179	980	2464	3584	6175	7168	2652	0.37
	BN	246	810	2539	3957	6757	7855	2984	0.38
	MON	235	1310	2464	3584	6175	7168	2795	0.39
	MN	325	1250	2464	3584	5949	6944	2821	0.41
7-year averages	BON	450	1111	2406	3918	6258	7183	2947	0.41
	BN	494	1077	2664	4261	6673	7563	3065	0.39
	MON	398	1025	2281	3626	5881	6863	2732	0.40
	MN	446	1100	2435	3940	6246	7311	2939	0.40
Overall average		447	1078	2446	3936	6264	7230	2906	0.40

Table 5.2. Analysis of variance for final dry matter and grain yield presented in Table 5.1.

Source of variation	Degrees of freedom	Sums of squares	Mean squares	F
Final dry matter				
Treatments	3	1,979,981	659,993	3.15
Nitrogen	1	1,317,625	1,317,625	6.34*
Mulch	1	657,903	657,903	3.17
Mulch x nitrogen	1	4,453	4,453	0.02
Years	6	5,075,949	845,991	4.17*
Error	18	3,743,429	207,968	
Total	27	10,799,357		
Grain yield				
Treatments	3	311,485	103,828	2.57
Nitrogen	1	94,540	94,540	2.34
Mulch	1	107,756	107,756	2.66
Mulch x nitrogen	1	109,189	109,189	2.70
Years	6	11,444,883	1,907,480	47.13***
Error	18	728,597	40,476	
Total	27	12,484,947		

* = Significant at the 5 percent level.

*** = Significant at the 0.1 percent level.

nitrogen and mulch, each with 1 degree of freedom. The application of nitrogen significantly affected final dry matter yields at $\alpha = 0.05$ but not grain yields. Neither the application of mulch nor its interaction with nitrogen was significant. The year-to-year variation was significant at $\alpha = 0.05$ for final dry matter and highly significant at $\alpha = 0.001$ for grain yield.

Grain yields by treatments and replications are presented in Table 5.3 with an AOV in Table 5.4 for each of the seven years. The annual analysis shows that the effect of nitrogen was significant only during 1967 at $\alpha = 0.05$ and the effect of mulch only during 1964 and 1965. Mulch decreased the yield during five out of the seven years. The positive but nonsignificant effect of mulch during 1969 is due to the unusually high grain yield of the MN treatment. The interaction between mulch and nitrogen and effect of replications were significant ($\alpha = 0.05$) only during 1969. Their significance is due to the unusually high yield of the MN treatment.

Therefore, the year-to-year variation was the major component of grain yield variation and not the treatments. In general, neither the application of nitrogen nor mulch had significant effects.

Mulch is considered to improve the soil water storage efficiency. Although small, mulching generally had an adverse effect on winter wheat grain yields. It must be noted that there was no surface runoff from the bare or mulched treatments during the seven years of the study. Even though mulch may reduce soil surface evaporation, the adverse effect is probably due to the cooler soils under the mulch during the spring (Smika and Ellis, 1971).

The nitrogen fertility of the soil was about 90 kg ha^{-1} in nitrate (NO_3^{-1}) form, which is nonlimiting for wheat production under the conditions of limiting soil water.

The overall average grain yield was 2906 kg ha^{-1}. This is significantly higher than the average of 1770 kg ha^{-1} for the United States

Table 5.3. Grain yield by treatments and replications, hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded.

Year	Treatments	Grain yield, kg ha^{-1}, for replications I	II	III	Average
1963	BON	1661	1560	1668	1630
	BN	1748	1714	1802	1755
	MON	1869	1478	1648	1632
	MN	1850	1527	1896	1750
	Average	1784	1569	1759	1694
1964	BON	3328	3201	3705	3412
	BN	3732	3550	3349	3543
	MON	2985	2387	2609	2660
	MN	2891	2945	3087	2974
	Average	3234	3021	3187	3147
1965	BON	3497	2891	3430	3272
	BN	3026	3228	3160	3188
	MON	2085	2252	2824	2854
	MN	3096	2421	2959	2825
	Average	3126	2699	3093	2909
1966	BON	3853	3577	3564	3665
	BN	3638	3712	4048	3799
	MON	3517	3214	3194	3309
	MN	3207	4856	3443	3500
	Average	3593	3587	3562	3567
1967	BON	2293	2367	2434	2365
	BN	2488	2414	2528	2477
	MON	2454	2414	2400	2423
	MN	2764	2656	2474	2631
	Average	2499	2462	2459	2473
1969	BON	3927	3322	3671	3640
	BN	3960	3302	3570	3611
	MON	3812	3375	3665	3618
	MN	4028	4095	4081	4068
	Average	3931	3523	3746	3733
1970	BON	2176	3076	2704	2652
	BN	2849	3200	2901	2984
	MON	2424	3050	2908	2795
	MN	2862	2662	2937	2821
	Average	2577	2997	2862	2812
7-year averages	BON	2962	2852	3024	2947
	BN	3063	3086	3051	3065
	MON	2735	2712	2749	2732
	MN	2952	2879	2982	2939
Overall average		2929	2865	2951	2906

Table 5.4. Analysis of variance by year for grain yield presented in Table 5.3.

Source of variation	Degrees of freedom	Sums of squares	Mean squares	F	Sums of squares	Mean squares	F
		1963			1964		
Treatments	3	38,100	12,700	1.22	1,481,622	493,874	9.45
N[a]	1	36,190	36,190	3.47	149,410	149,410	2.86
M	1	1,220	1,220	0.12	1,307,460	1,307,460	25.02**
MXN	1	689	689	0.07	24,751	24,751	0.48
Replications	2	107,137	53,658	5.13	100,591	50,296	0.96
Error	6	62,647	10,441		313,492	52,248	
Total	11	207,885			1,895,705		
		1965			1966		
Treatments	3	1,392,408	464,136	5.78	405,279	135,093	1.93
N	1	69,160	69,160	0.86	79,218	79,218	1.13
M	1	910,252	910,252	11.33*	333,737	323,737	4.62
MXN	1	412,981	412,981	5.12	2,324	2,324	0.03
Replications	2	314,905	157,452	1.96	2,426	1,213	0.02
Error	6	481,982	80,330		420,675	70,112	
Total	11	2,189,296			828,278		
		1967			1969		
Treatments	3	118,049	39,350	4.16	447,643	149,214	5.07
N	1	77,120	77,120	8.10*	133,141	133,141	4.53
M	1	33,920	33,920	3.56	141,708	141,708	4.82
MXN	1	7,009	7,009	0.74	172,794	172,794	5.87*
Replications	2	4,058	2,029	0.21	334,311	167,155	5.68*
Error	6	57,114	9,519		170,495	28,416	
Total	11	179,222			952,450		
		1970					
Treatments	3	166,076	55,359	0.90			
N	1	96,302	96,302	1.57			
M	1	310	310	0.01			
MXN	1	69,464	69,464	1.13			
Replications	2	367,330	183,665	2.99			
Error	6	368,712	61,452				
Total	11	902,118					

* = Significant at the 5 percent level
** = Significant at the 1 percent level
[a]N = nitrogen fertilizer, M = mulch, MXN = mulch and nitrogen interaction

and comparable with the average of 2840 kg ha^{-1} for Mexico (Framji and Mahajan, 1972).

Extreme temperatures (above upper threshold) and high winds were more prevalent in 1963, mostly during the last part of June, and damaged the grain yields before normal maturity was reached. Maximum temperatures were 37 to 41°C and wind runs were 10 to 20 km per hour June 23 to 30. As a result, the grain yields for this year were very low. The amount of dry matter production late fall of the preceeding years was very low for 1963 and 1967. This may also explain the low grain yields for these two years. However, the final dry matter was not similarly affected. The final dry matter for 1963 and 1967 was comparable with the other years. The normal dry matter and low grain yields for the two years may partly account for the lowest grain yield to final dry matter ratios.

Exclusion of the 1963 grain yields increases the mean to 3107 kg ha^{-1} for the remaining six years. The low yield in 1963 accounts for about one third of the annual variation. Therefore, climatic extremes late in the season exhibited serious adverse effects on grain yield.

B. Dry matter yield models

Dry matter yield (DM) of hard red winter wheat was related to cumulative ET (W_{et}), cumulative T (W_t), cumulative relative ET or relative T (W_r), and W_t scaled by mean daily free water evaporation E_o, $\frac{Wt}{E_o}$, respectively. The general expressions are given by models (5.1), (5.2), (5.3) and (5.4).

$$DM = k_o + k_1 W_{et} + k_2 W_{et}^2 \tag{5.1}$$

$$DM = t_o + t_1 W_t + t_2 W_t^2 \tag{5.2}$$

$$DM = r_o + r_1 W_r + r_2 W_r^2 \tag{5.3}$$

$$DM = m_o + m_1 \frac{W_t}{E_o} + m_2 \left(\frac{W_t}{E_o}\right)^2 \tag{5.4}$$

The units of the variables and parameters in the above expressions are given below:

DM, k_o, t_o, m_o, r_o, r_1, r_2	--- kg ha^{-1}
W_{et}, W_t	--- cm
k_1, t_1	--- kg ha^{-1} cm^{-1}
k_2, t_2	--- kg ha^{-1} cm^{-2}
E_o	--- cm day^{-1}
m_1	--- kg ha^{-1} day^{-1}
m_2	--- kg ha^{-1} day^{-2}

Since the variable W_r is dimensionless, its coefficients in model (5.3), r_1 and r_2, have the same units as DM.

Use of W_r is an attempt to reconcile yield models over varied climatic regions. The terms ET_o and T_o incorporate many climatic variables including the atmospheric saturation deficit which Arkley (1963) selected as a scaling factor. Scaling on a daily basis renders the variable W_r in model (5.3) dimensionless and forces the coefficients r to retain units of DM. This may be compared with the dimensions of m in model (3.1) or (5.5) and k_f in (3.3) where m is in kg ha^{-1} day^{-1} and k_f is in kg ha^{-1} cm^{-1}. If the scaling in (3.1) and (3.3) were done on a daily basis with a scaling factor having the same units as the variable being scaled, cm day^{-1} in this case, the coefficients would consistently have units of a dependent variable.

Linear and quadratic cases of the four models (5.1), (5.2), (5.3) and (5.4) were tested. Least squares estimate of the coefficients are summarized in Table 5.5. The regression coefficients are significant (α = 0.001) for each model and have high determination coefficients. Comparison of the respective linear and quadratic models show that the addition of the quadratic terms does little in reducing the variation.

Table 5.5. Least squares estimate of coefficient in the dry matter yield models (5.1), (5.2), (5.3), and (5.4) for linear and quadratic cases, hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded. (n = 112).

Model	Case	Independent variable	Coefficients			
			Intercept	Linear	Quadratic	Determination R^2
(5.1)	Linear	W_{et}	600	195 (7)*		0.87[1]
	Quadratic	W_{et}	-1500	415 (50)	- 5 (1.1)	0.89[1]
(5.2)	Linear	W_t	1866	228 (9)		0.84[1]
	Quadratic	W_t	912	423 (49)	- 7 (1.7)	0.86[1]
(5.3)	Linear	W_r	-2712	100 (4)		0.81[1]
	Quadratic	W_r	-9330	282 (52)	-12 (0.3)	0.86[1]
(5.4)	Linear	$\frac{W_t}{E_o}$	1926	140 (6)		0.83[1]
	Quadratic	$\frac{W_t}{E_o}$	913	267 (29)	-28 (6.1)	0.86[1]

* Numbers in parentheses are standard error of regression coefficients.
[1] Coefficient of determination significant at 1% probability level.

For example, in model (5.1), the coefficient of determination R^2 is increased from 0.87 to 0.89 by inclusion of the quadratic term. The same holds for the other models. The linear models are presented in Figures 5.1, 5.2, 5.3, and 5.4. Since the quadratic terms do not significantly improve the correlation the linear models are used for predicting dry matter.

Scaling does not seem to affect the regression (Table 5.5). The determination coefficients are not significantly different from each other at the 1% probability level. Therefore, other than the possibility of reconciling different climatic regions that may be realized by scaling and the greater conservation implications in using W_t instead of W_{et}, the models are equally applicable for predicting dry matter yield.

Model (5.4) was formulated to test the applicability of de Wit's (1958) model (3.1) to field data. The free water evaporation E_o was 0.92 times the mean daily pan evaporation for the period 15 days after spring growth initiation to soft dough, during which transpiration was considered to be a significant component of crop ET. W_t was scaled by E_o at each stage of growth. The factor 0.92 was used to correspond with de Wit's definition.

The value of $m_1 = 140$ kg ha^{-1} day^{-1} is higher than the value of $m = 115$ kg ha^{-1} day^{-1} for wheat obtained by de Wit. However, m_1 falls within the range $90 \leq m \leq 160$ kg ha^{-1} day^{-1} for winter wheat obtained by Hanks et al. (1969). They estimated W_t as varying fractions of fallow evapotranspiration, thus the range in the values of m.

The following specific points must be emphasized in comparing the different estimates of m: (1) In the analysis of de Wit and Hanks et al., DM and W_t were seasonal, whereas in this analysis the two variables were estimated at four stages of development, (2) In this analysis W_t was estimated by the procedure developed in Chapter IV compared to the controlled container measurements in the data analyzed by de Wit

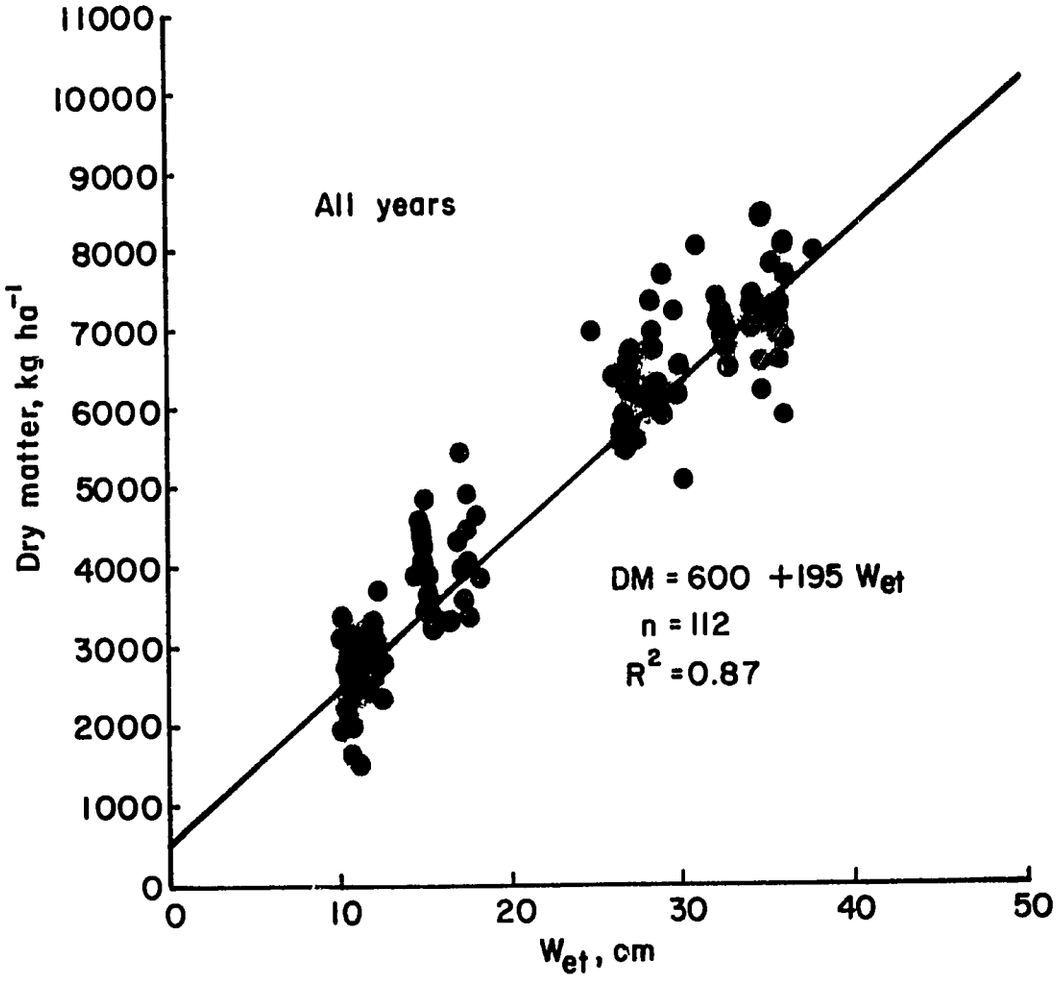

Figure 5.1. Dry matter as a function of cumulative evapotranspiration, W_{et}, for hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded.

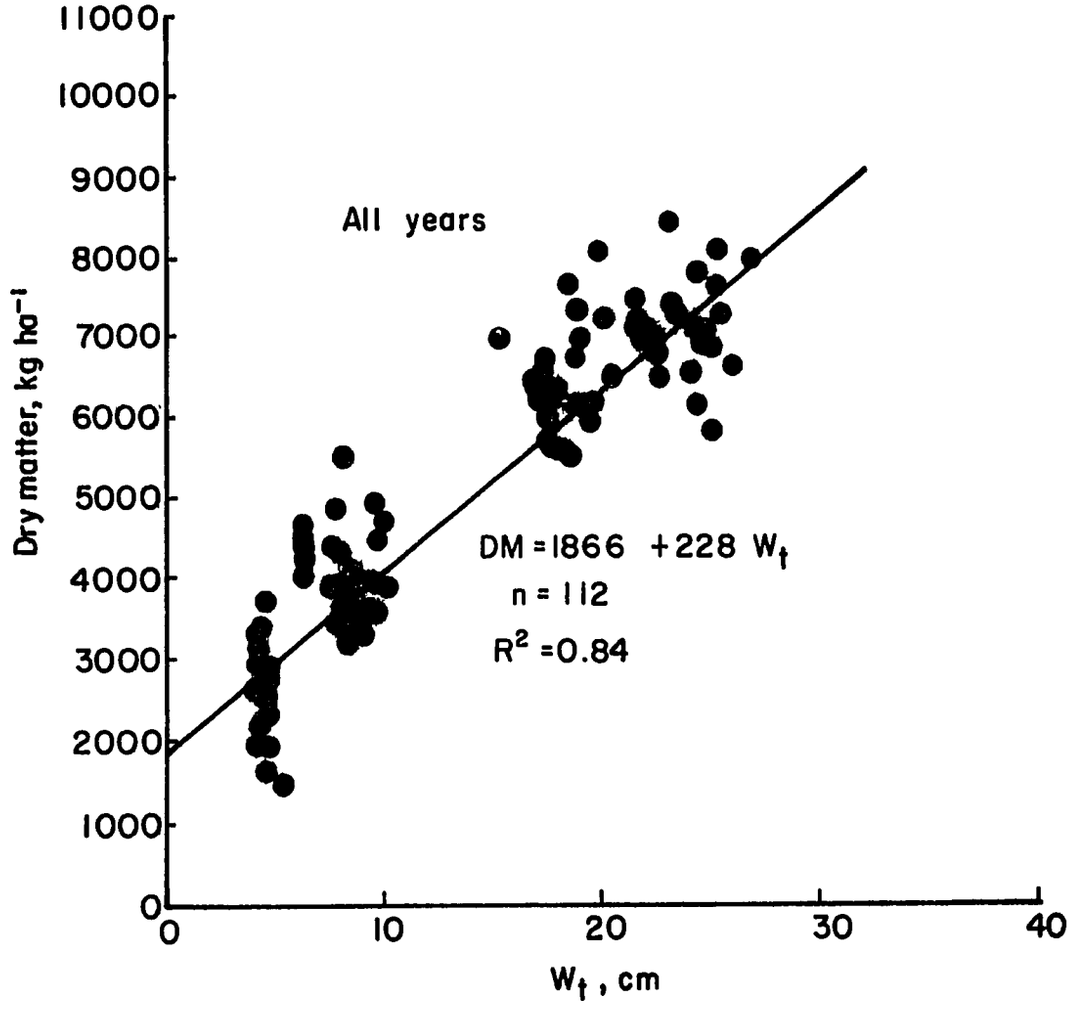

Figure 5.2. Dry matter as a function of cumulative transpiration, W_t, for hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded.

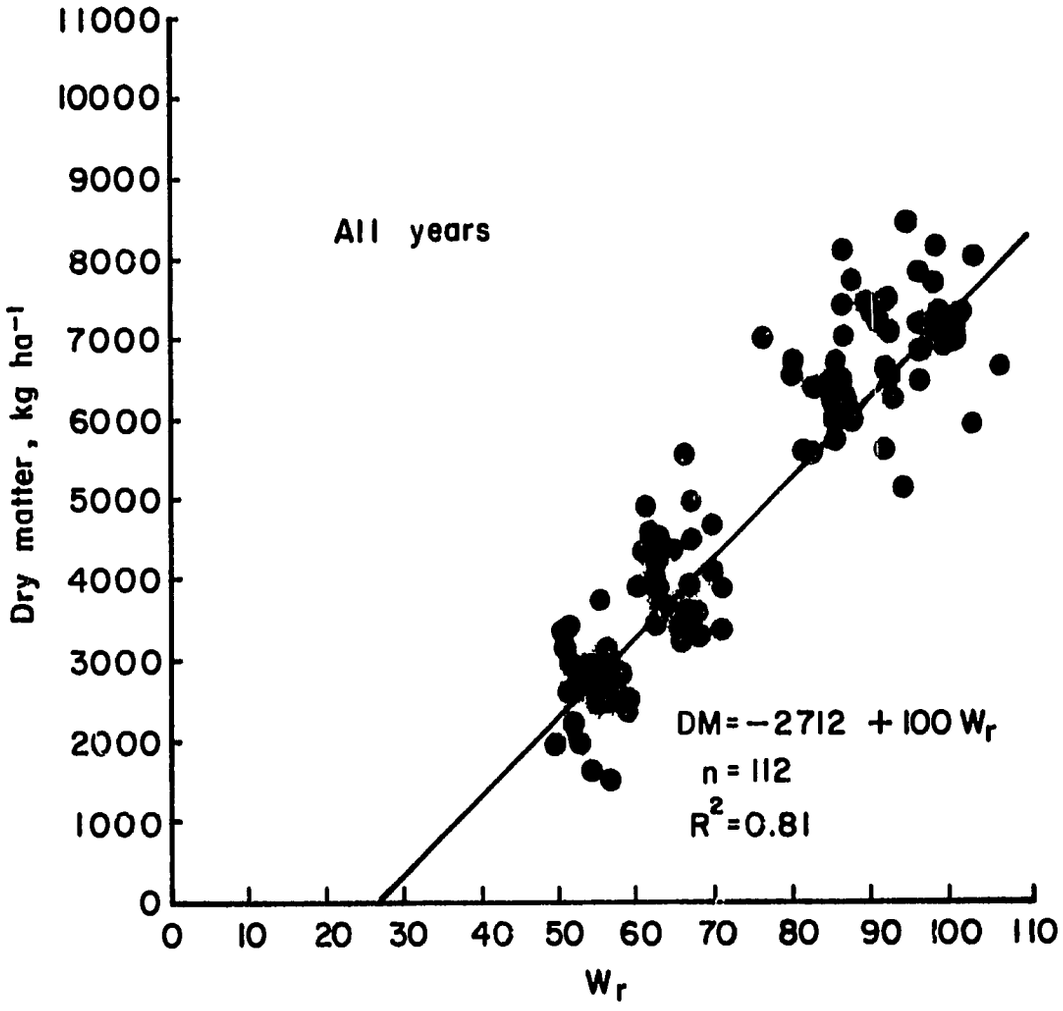

Figure 5.3. Dry matter as a function of relative evapotranspiration or relative transpiration, W_r, for hard red winter wheat North Platte, Nebraska, 1963-1970, 1968 excluded.

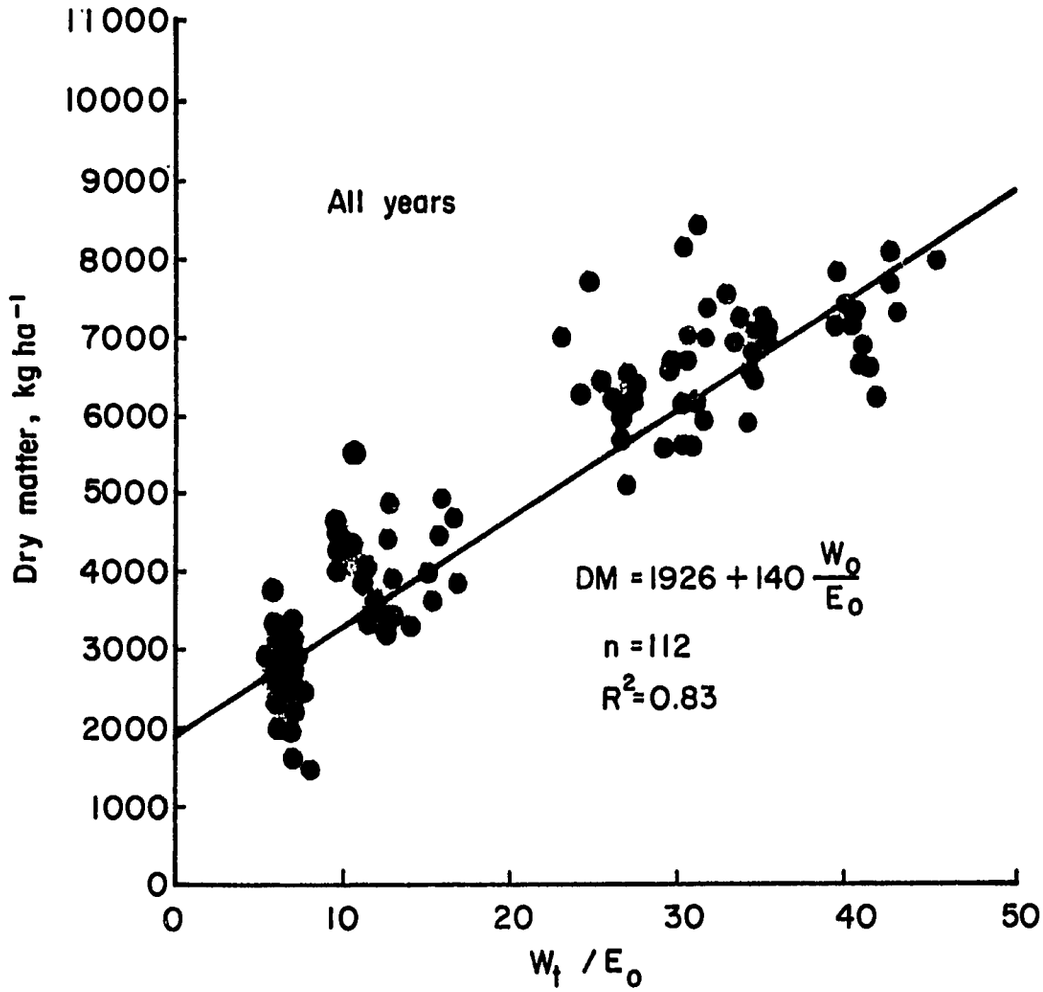

Figure 5.4. Dry matter as a function of cumulative transpiration, W_t, scaled by mean daily free water evaporation, E_o, for hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded.

and the estimation of W_t as a varying fraction of fallow evapotranspiration by Hanks et al., (3) A zero intercept is implied by model (3.1). Model (3.5) incorporates an intercept value. The estimate of m in (3.1) is analogous to water use efficiency or average yield, while in the linear case of model (5.4) m_1 is strictly the marginal product of DM with respect to $\frac{W_t}{E_o}$. The intercept m_o = 1926 kg ha^{-1} (Figure 5.4) is significantly greater than zero at $\alpha = 0.001$. A reason for the positive intercept in (5.5) may be that W_t was accumulated from spring growth initiation and not from date of planting.

For winter wheat the marginal products are equal to the regression coefficients of the linear models in Table 5.5: 195 kg ha^{-1} cm^{-1} for W_{et}, 100 kg ha^{-1} cm^{-1} for W_r, 228 kg ha^{-1} cm^{-1} for W_t, and 140 kg ha^{-1} day^{-1} for $\frac{W_t}{E_o}$. Inputs of water during the various stages of growth produced the same increment of dry matter yield under the conditions of the limited soil water experiments. The data did not include treatments of soil water maintained near optimum throughout the season.

Marginal products, $\frac{d\,DM}{d\,W_{et}}$, estimated from wheat water use data gathered by various researchers, are comparable with the 195 kg ha^{-1} cm^{-1}. Some examples are 186 kg ha^{-1} cm^{-1} for spring wheat, and 197 for wheat varieties analyzed by Arkley (1963), and 210 estimated from the winter wheat water use data reported by Hanks et al. (1969).

C. Relationships between dry matter and stress day in an interstage

Hiler and Clark (1971) developed a concept of a stress day index to characterize effects of water stress on crop yields. The definition of a stress day (SD) given by equation (5.5) is based on this concept. For a given day

$$SD = 1 - \frac{T}{T_o} \qquad (5.5)$$

SD indicates the relative stress the plant experiences on a given day during its growth cycle. It is the difference between the crop potential transpiration T_o and actual transpiration T relative to the potential.

The form of equation (5.5) implies that no crop water deficit occurs until T decreases below T_o ($T < T_o$).

SD was accumulated for each of the four interstages for winter wheat. An attempt was then made to determine effects of water stress during a given interstage on corresponding dry matter yields. The interstage dry matter was plotted versus the interstage stress days (Figures 5.5 - 5.8) for the stage of growth.

Definite trends between stress and production are not obvious. Ideally the trend should show high interstage dry matter for low interstage stress days, that is, a linear or curvilinear relationship with a negative slope. Such relationship is intuitively reasonable. A zero stress day should indicate an optimum soil water condition for plant growth. Greater stresses should indicate greater reductions in yield.

Water stress in plants is believed to be exerted in the following three ways as water stress increases: (1) reduction in cell turgor as this affects cell elongation and possibly carbohydrate and nitrogen metabolism, (2) reduction in CO_2 intake rate, and (3) increase in leaf temperature as this affects metabolism (Kramer, 1969). Thus, it may be possible that the form of SD given by equation (5.5) may not be sensitive to early signals of crop water stress. The apparent insensitivities in Figures 5.6 - 5.8 may be due to the procedure of computing SD and also the great variation in the dry matter measurements.

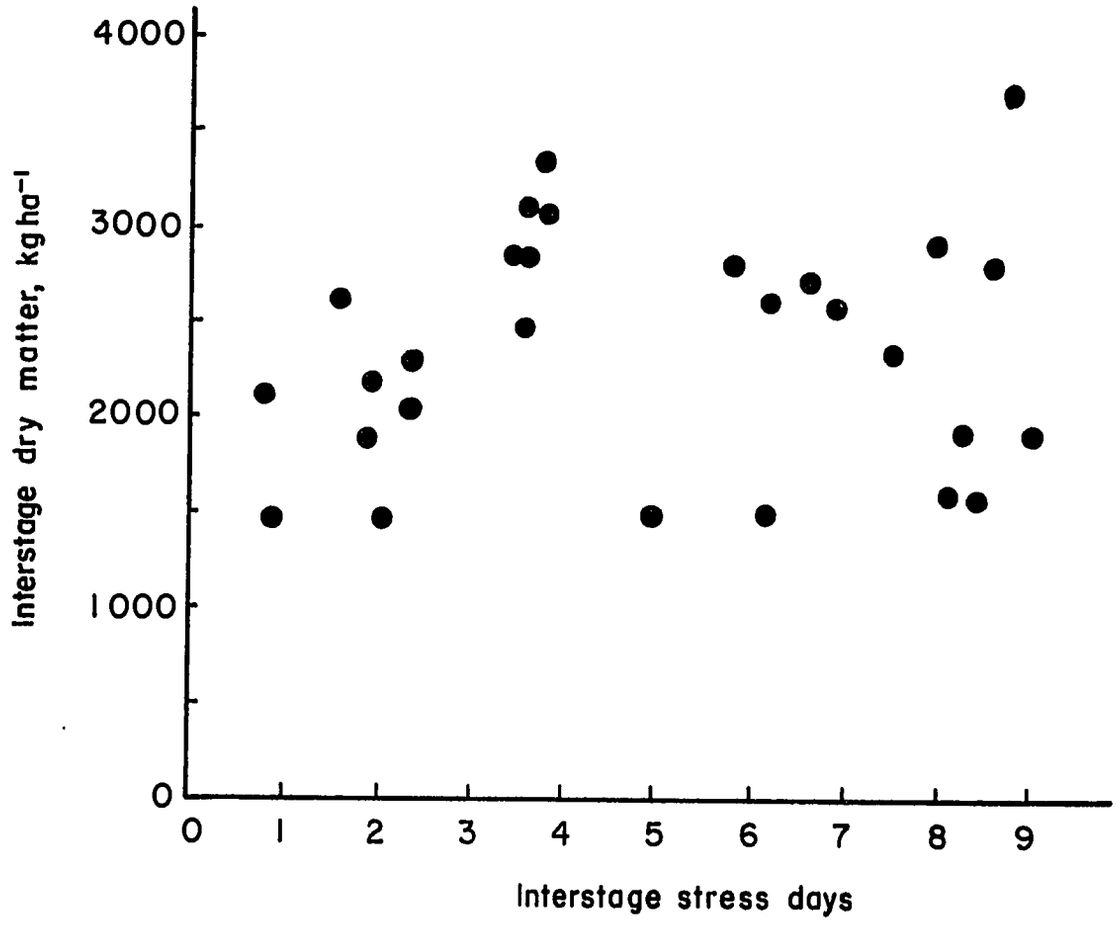

Figure 5.5. Interstage I - spring growth to boot (60 days) - dry matter versus stress days, hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded.

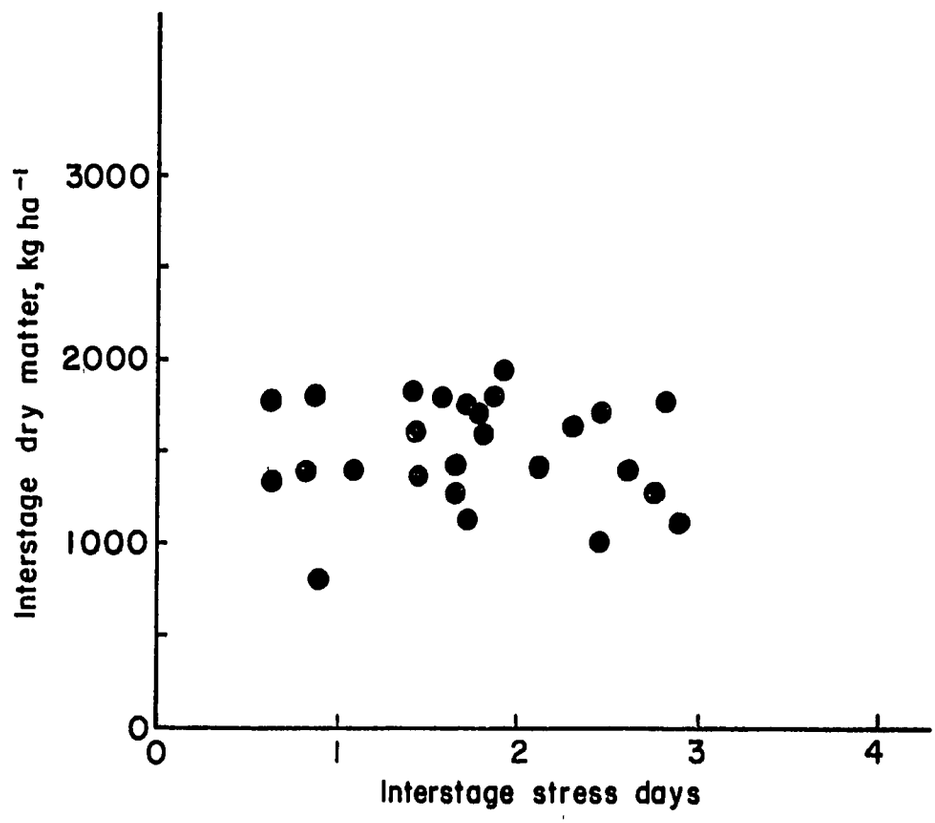

Figure 5.6. Interstage II - boot to heading (13 days) - dry matter versu stress days, hard red winter wheat, North Platte, Nebraska, 1963-197(1968 excluded.

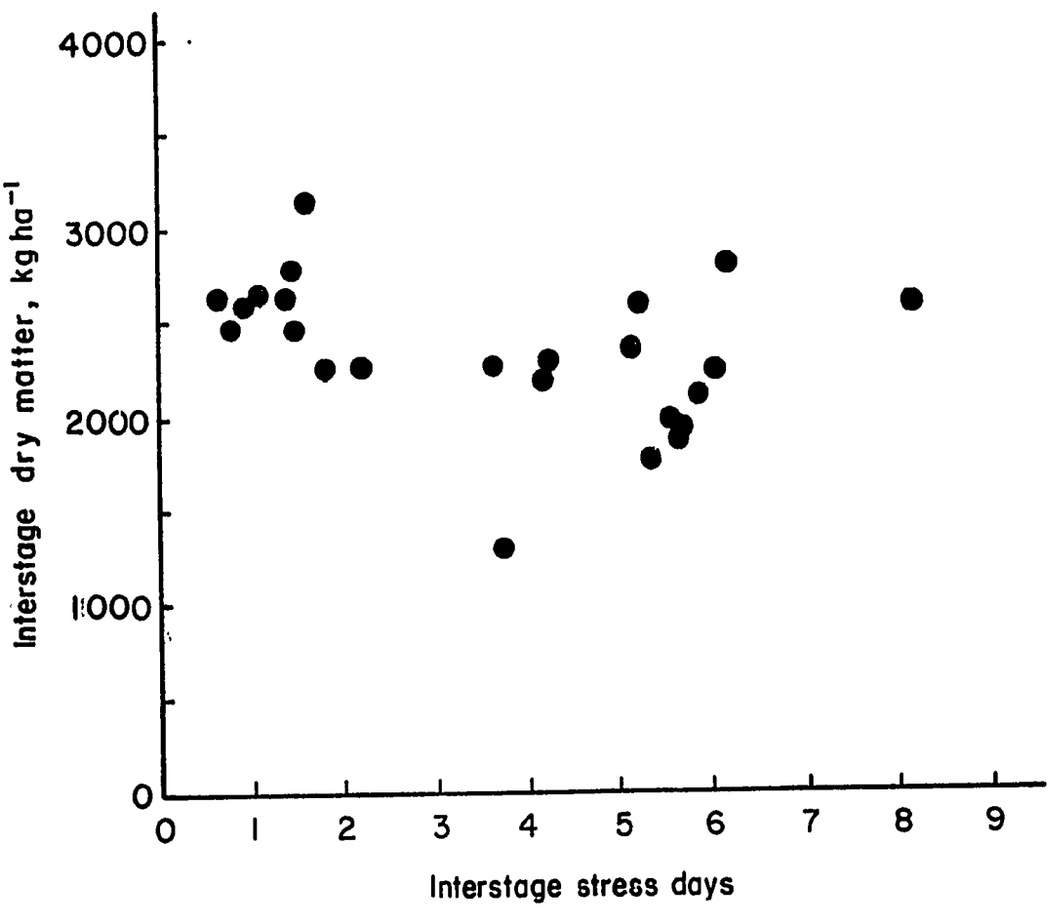

Figure 5.7. Interstage III - heading to soft dough (25 days) - dry matter versus stress days, hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded.

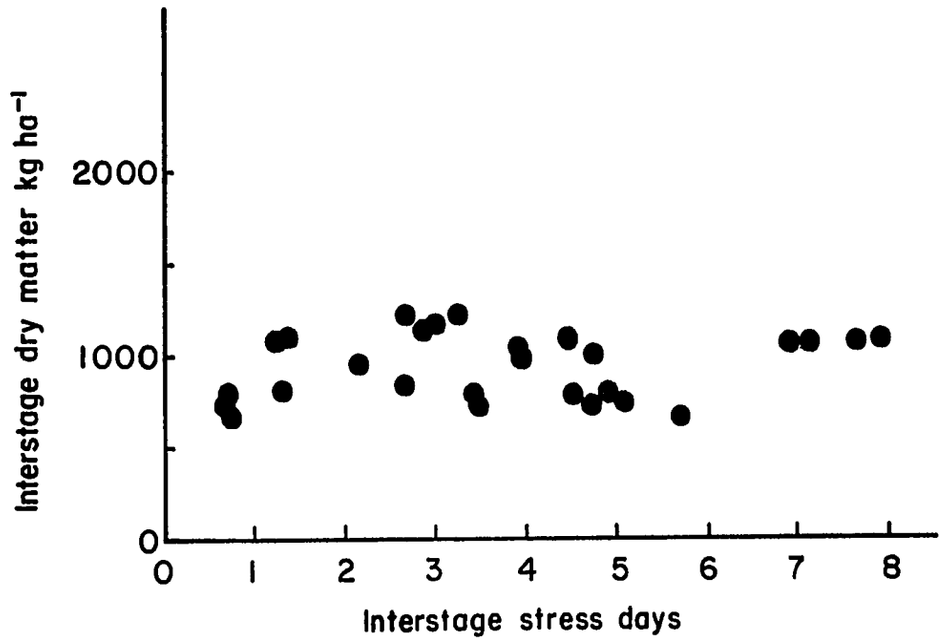

Figure 5.8. Interstage IV - soft dough to maturity (15 days) - dry matter versus stress days, hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded.

CHAPTER VI

GRAIN YIELD MODELS: RESULTS AND DISCUSSION

This chapter presents test results and discussion of grain yield models. Linear and nonlinear models are formulated and tested.

A. Linear grain yield models

Grain yield can be measured only after crop maturity. This poses a major problem in studies attempting to trace the effect of water stress during the various stages of growth, and also in formulating appropriate models. The diversity of grain yield models is, in part, due to this problem. One way of approximating the effect of stress on grain yield may be by tracing the effects of stress on dry matter yield, as was done in Chapter IV, and then relating grain yield to dry matter. Other possibilities include interstage relative ET and yield indicators such as tillers, vigor of growth during the preceeding fall, and climatic extremes. These variables may be considered separately or in combinations in linear or nonlinear models.

The linear models (6.1), (6.2), (6.3), and (6.4) are formulated on the basis of the hypothesis presented above:

$$G = g\, DM_f \qquad 0 < g < 1 \tag{6.1}$$

$$G = a_o + \sum_{i=1}^{n} a_i \, \Delta DM_i \tag{6.2}$$

$$G = b_o + b_1\, DM_p + b_2 N_t + b_3\, DM_f \tag{6.3}$$

$$G = c_o + c_1\, DM_p + c_2 N_t + c_3\, DM_f + c_4\, M \tag{6.4}$$

where DM_p is the dry matter produced during the preceeding fall, kg ha^{-1} ; DM_f is the final dry matter, kg ha^{-1}; ΔDM_i is the amount of dry matter, kg ha^{-1}, during the interstage i (i = 1, 2, . . . , n); N_t is tillers per m^2, M denotes the number of days $T_{max} \geq 27^oC$ and

$U_a \geq 10$ kph; and the a's, b's, c's, and g are parameters. $\Delta DM_1 = DM_p$ in model (6.2).

The treatment averages presented in Table 5.1 were used to test the linear models. The least squares estimate of the coefficients are summarized in Table 6.1.

In model (6.1) g is the ratio of grain yield to final dry matter. The least squares estimate g = 0.44 presented in Table 6.1 is obtained by assuming a nonzero intercept. The intercept value -86 kg ha^{-1} is not significantly different from zero (α = 0.30). The mean ratio of grain to final dry matter for the seven years was 0.40 (Table 5.1) with a standard deviation of 0.08 and coefficient of variation of 20%. Excluding the 1963 data, g = 0.43 with a coefficient of variation of 12%, which also shows that most of the variation is due to very low yields in 1963. The estimates of g are comparable with the results of g = 0.42 obtained by Powers et al. (1961) for spring wheat studied under four water levels in Montana.

Although the coefficient of determination R^2 = 0.48 is significant at the 1% probability level, grain yield final dry matter ratio ranged from 0.35 to 0.51 for the six years excluding 1963, with the scatter observed in Figure 6.1.

An attempt was made to determine and compare g from other published data. Irrigated winter wheat data grown in Bushland, Texas (Jensen and Sletten, 1965) and western Kansas (Musick, et al., 1963) were analyzed. The one year data from Texas in which grain yield and straw grain ratios were reported involved six fertilizer levels and six water levels. There is an excellent linear relationship between grain yield and final dry matter, regardless of the water and fertilizer levels (Figure 6.2). The estimated value of g is 0.36 with a coefficient of determination R^2 = 0.96. It appears that irrigation and fertilization increased dry matter and grain yields by the same proportion.

The two year data from western Kansas reported by Musick et al. involved five fertilizer and three water levels. Unlike the linear

Table 6.1. Least squares estimate of coefficients in linear grain yield models (6.1), (6.2), (6.3) and (6.4).

Model	Coefficients								Sample size n
	Symbol	Subscripts						Determination R^2	
		0	1	2	3	4	5		
6.1	g	-86	0.44 (0.10)[2]					0.48[1]	24*
6.2	a	2196	1.09 (0.32)	-0.48 (0.16)	0.43 (0.32)	1.09 (0.28)	-1.98 (0.75)	0.71[1]	28
6.3	b	-1314	0.98 (0.36)	0.85 (0.51)	0.40 (0.18)			0.53[1]	28
6.4	c	232	1.27 (0.27)	0.91 (0.38)	0.31 (0.13)	-114.12 (24.64)		0.75[1]	28

* Excludes 1963.

[1] R^2 is significant at 1% probability level.

[2] Numbers in parentheses are standard errors of regression coefficients.

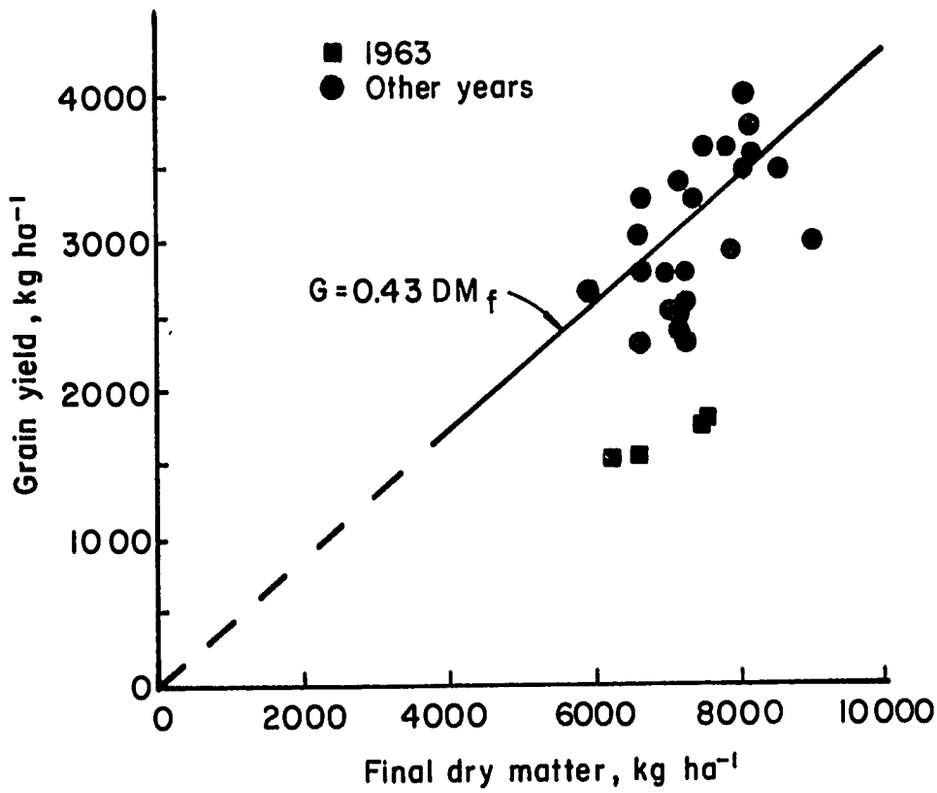

Figure 6.1. Grain yield versus final dry matter, hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded.

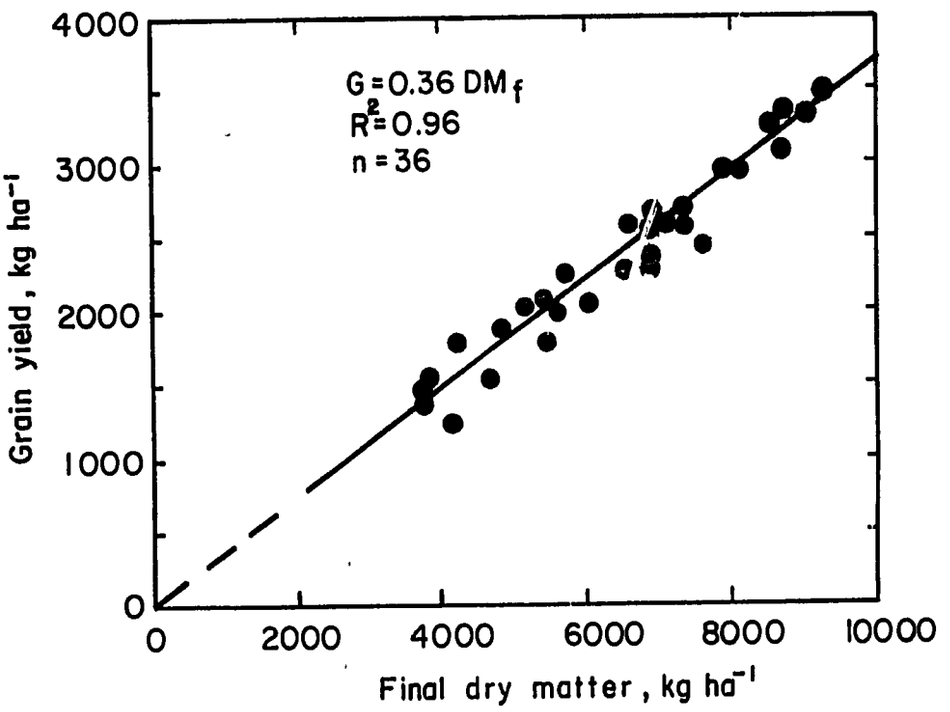

Figure 6.2. Grain yield versus final dry matter, irrigated winter wheat, Bushland, Texas (data after Jensen and Sletten, 1965).

relationship presented in Figure 6.2, there is curvilinear relationship between grain yield and final dry matter (Figure 6.3). When combining different years, the linearity does not appear to exist. The dry matter yields exceeded 7200 kg ha^{-1} and grain yields exceeded 3700 kg ha^{-1}, both relatively high. It may be that linear relationships hold for lower ranges and that the flattening curvilinear relationships results with the higher yields. Since a higher g implies a smaller straw to grain ratio, varieties and/or production factor combinations that give a high g would have greater beneficial implications.

Model (6.2) relates grain yield to interstage dry matter. The negative coefficients a_2 and a_5 (Table 6.1) imply that grain yield decreases with increase in interstage dry matter during the first and last interstages. a_1 is the coefficient for the dry matter produced during the preceding fall. If the models were applicable, supplemental irrigation of dry land winter wheat would be more beneficial between boot and soft dough stages. However, Figure 2.1, which is based on extensive literature reviews, indicates that the time from shooting to flowering is the "critical period" for wheat. Shooting, which is the stage of elongation of internodes, occurs in the first interstage or between spring growth initiation and booting (Table 2.1). Thus the negative coefficient a_2 is in apparent disagreement with previous investigations. The significance of the negative coefficient a_5 may be that after soft dough stage no supplemental irrigation is necessary. Further tests are necessary to determine the applicability of Model (6.2).

Model (6.3) relates grain yield to dry matter produced during the preceding fall (DM_p), tillers (N_t), and final dry matter (DM_f) and appears to have physical basis. DM_p may be considered as a proxy for the factors that affect growth and development of the root system and above ground parts after planting and before the plant goes into winter dormancy. The coefficient of determination $R^2 = 0.53$ is significant at the one percent probability level. The regression coefficients are significantly different from zero.

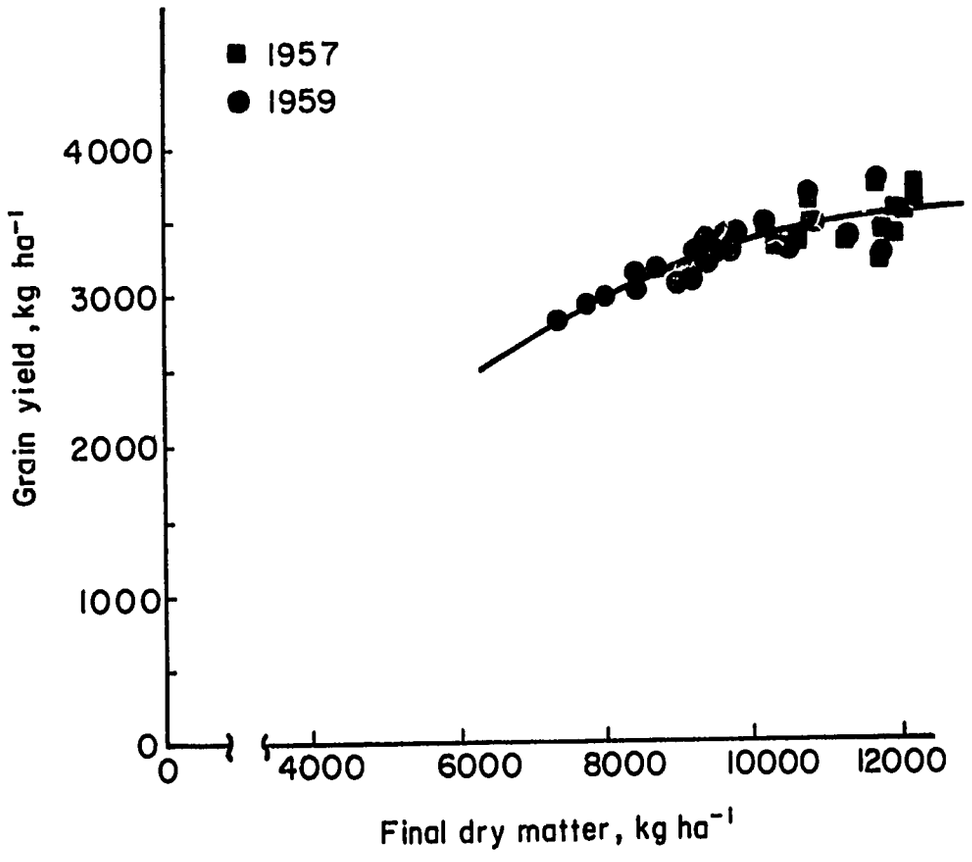

Figure 6.3. Grain yield versus final dry matter, irrigated winter wheat in Western Kansas (data after Musick, et al. 1963).

B. Effect of climatic extremes on grain yield

Model (6.4) adds the term M representing the interaction of $T_{max} \geq 27^{o}C$ and wind speed $U_a \geq 10$ kph. Other climatic extremes were also considered. Number of days in which maximum temperatures T_{max} were equal or greater than the upper threshold of $27^{o}C$, 3-day duration of the extremes, and interaction $T_{max} \geq 27^{o}C$ and wind speed $U_a \geq 10$ kilometers per hour are given in Table 6.2. Also included are number of days $T_{min} \leq 3^{o}C$, and 3-day durations of the lower extremes. The number of days in which $T_{max} \geq 27^{o}C$ did not vary much from year to year (range 27 to 34). However, the greatest number occurred during 1963. The low 1963 grain yield was also associated with 10 three-day periods of $T_{max} \geq 27^{o}C$ and 15 days of $T_{max} \geq 27^{o}C$ and $U_a \geq 10$ kph, which are the highest for the respective extremes. For the remaining six years no obvious relationship is apparent between grain yield and these climatic extremes. In fact, the second lowest yield for 1967 is associated with lowest upper and lower extremes: 27 days $T_{max} \geq 27^{o}C$, 2 three-day periods $T_{max} \geq 27^{o}C$, 6 days $T_{max} \geq 27^{o}C$ and $U_a \geq 10$ kph, 32 days $T_{min} \leq 3^{o}C$, and 7 three-day periods $T_{min} \leq 3^{o}C$.

The low temperature extremes do not show possible reductions in yield. The two years (1963 and 1967) in which yields were lowest experienced 32 and 33 days $T_{min} \leq 3^{o}C$ compared to 52 when the yield was highest (3734 kg ha^{-1}) in 1969. Therefore, it appears that temperatures above the upper threshold and their interaction with high winds affect winter wheat grain yields.

The low yields in 1963 and 1967 are partly due to the poor growth the preceding fall (Table 5.1). DM_p for both years was very low.

The negative coefficient of M (Table 6.2) indicates that yield decreases with increasing M, which is reasonable. The regression coefficients and the coefficients of determination $R^2 = 0.75$ are significant at the one percent probability level. The explained variation is the highest.

Table 6.2. Cumulative number of periods temperatures exceeded upper and lower thresholds and interaction of temperature and wind extremes, hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded.

Year	Stage of growth	Average annual grain yields kg ha^{-1}	No. days $T_{max} \geq 27^oC$	No. 3-day periods $T_{max} \geq 27^oC$	No. days $T_{max} \geq 27^oC$ and $U_a \geq 10$kph	No. days $T_{min} \leq 3^oC$	No. 3-day periods $T_{min} \leq 3^oC$
1963	boot		7	1	4	31	9
	heading		8	1	4	33	10
	soft dough		21	4	4	33	10
	maturity	1702	34	10	15	33	10
1964	boot		6	1	3	32	9
	heading		10	3	3	32	9
	soft dough		24	6	7	32	9
	maturity	3147	33	8	11	32	9
1965	boot		9	1	3	36	11
	heading		12	1	3	37	11
	soft dough		19	3	4	37	11
	maturity	2909	32	6	8	37	11
1966	boot		4	1	0	43	11
	heading		9	2	1	45	11
	soft dough		23	6	4	45	11
	maturity	3568	33	8	11	45	11
1967	boot		5	0	4	32	7
	heading		11	1	4	32	7
	soft dough		20	2	5	32	7
	maturity	2474	27	2	6	32	7
1969	boot		6	1	1	29	8
	heading		11	3	3	30	8
	soft dough		18	4	4	52	8
	maturity	3733	28	6	7	52	8
1970	boot		2	0	1	51	15
	heading		7	1	3	52	15
	soft dough		21	4	4	52	15
	maturity	2812	33	9	8	52	15

The amount of rainfall after spring growth initiation was identical (20 cm) during the 1963 and 1969 crop seasons (Table 4.5). The available soil water declined from 17 cm to 6 cm during 1963 and from 22 to 6 cm during 1969. Yet the yields during these two years represented the highest (1969) and lowest (1963)(Table 5.2). The distribution of available soil water was the highest during 1965, 24 cm at growth initiation and 22 cm at maturity; yet the yield was equivalent to the seven year average (2909 kg ha^{-1}). Thus differences in soil water distribution or cumulative rainfall after spring growth initiation do not explain annual differences in grain yield.

C. Derived linear grain yield models

The dry matter yield models presented in Chapter V can be substituted in the appropriate grain yield models presented in the preceding sections to derive grain yield models as a function of W_{et}. Substitution of the linear case of model (5.1) into model (6.1) is compared with the estimated water use efficiency in Figure 6.4.

For $g = 0.44$ and the intercept of -0.86 kg ha^{-1}, the derived relationship between grain yield and seasonal water use W_{et} is

$$G = 178.0 + 85.8\ W_{et} \qquad (6.5)$$

The estimated water use efficiency, which is the slope of the line through the origin, is 85.8 kg ha^{-1} cm^{-1}, which is identical with the derived marginal product. The equality of the water use efficiency and marginal product in this case is strictly coincidental. If the intercept value were large or the dry matter model were nonlinear, the derived relationship would definitely have a marginal product different from the water use efficiency. The derived relationship may have an advantage because the dry matter water use relationships can be traced through the season.

Even though the extremely low yield of 1963 was excluded in this derivation, the variability from estimated lines is still large

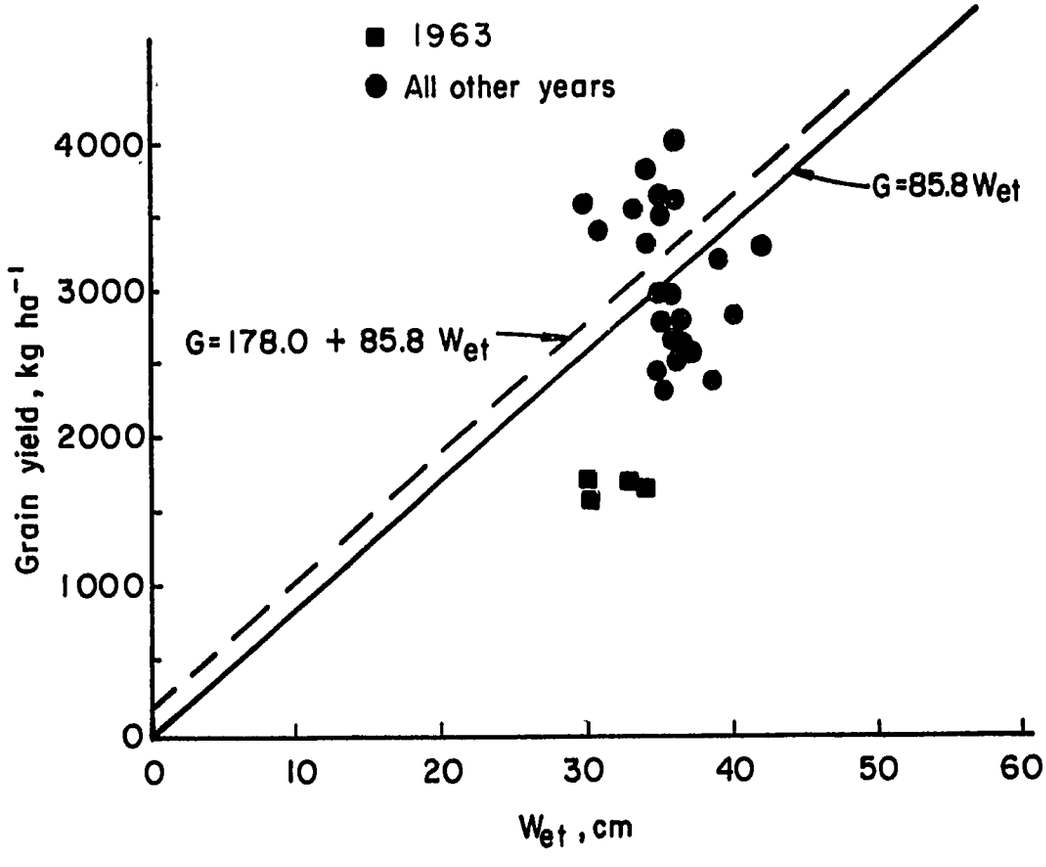

Figure 6.4. Comparison of derived grain yield model and estimated water use efficiency, hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded.

(Figure 6.4). Grain yield and seasonal water use are poorly and negatively correlated. That is, if derived grain yield water use relationships or water use efficiency are not used, direct use of seasonal water use in the multiple linear regressions (models 6.1, 6.3, and 6.4) would have negative coefficient for W_{ct}, which is not reasonable.

In addition to the linear yield models presented, sigmoid models were considered and found inapplicable. However, it must be noted that the main reason sigmoid and quadratic models are used in applied fields, mainly economics, is that they display certain characteristics basic to marginal economic analysis. Sigmoid functions, an example of which is shown in Figure 6.5, allow for increasing, decreasing, and negative marginal products or rates of change of yield per unit change in input. Thus the law of diminishing returns holds. These properties enable identification of the three classical stages of production. Stage II is the rational level over which input resources should be employed. Quadratic models allow for decreasing and negative marginal productivity. Linear models allow for none of these; they have a constant marginal productivity.

D. Nonlinear grain yield model

The nonlinear multiplicative model (3.7) suggested by Jensen (1968) as discussed in Chapter III.

$$G = G_o \prod_{i=1}^{n} \left(\frac{W_{et}}{W_{oc}}\right)_i^{\lambda_i} \qquad (3.7)$$

It is analogous to the Cobb-Douglas Model which is used mostly in aggregate industrial economic analysis. The model is nonlinear in the parameters λ_i. It may be classified as intrinsically linear or intrinsically nonlinear depending on whether the model can be transformed into linear form. If the error term is additive, model (3.7) would be intrinsically nonlinear; and if the error term is multiplicative, it would be intrinsically linear since it can be transformed logarithmically.

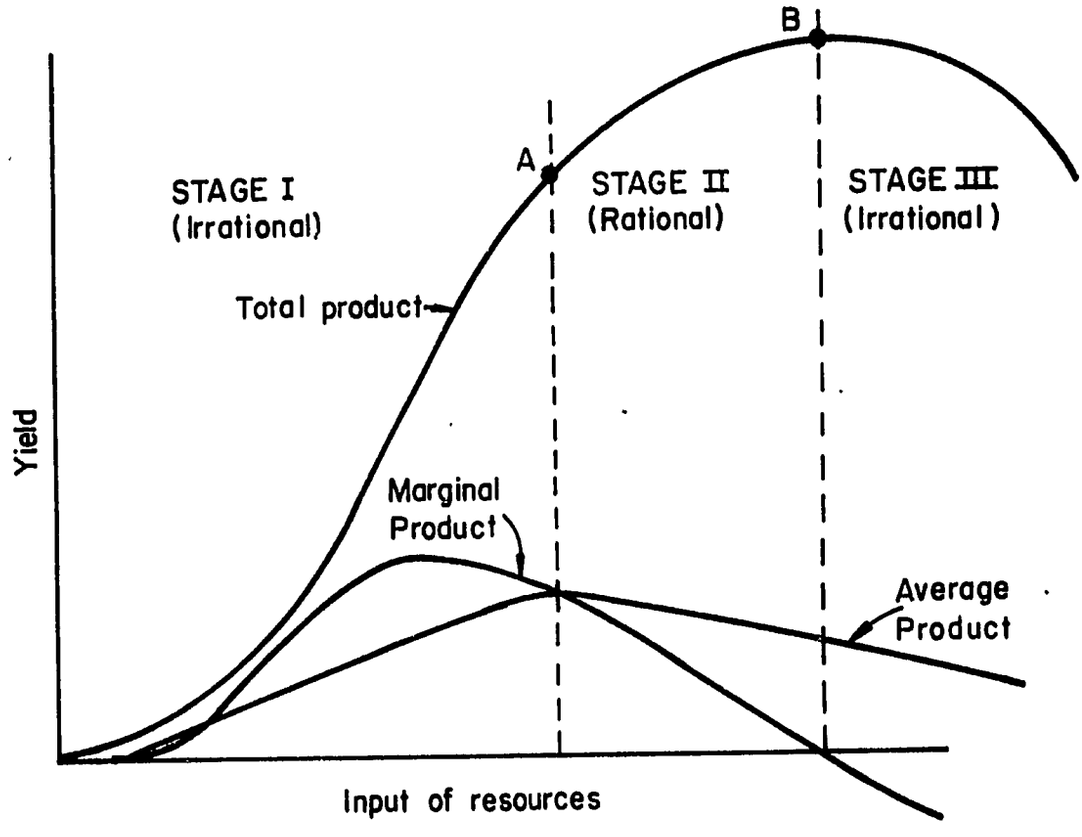

Figure 6.5. Stages of production in a classical production function and rational level of resource use.

Statistical computer algorithms for estimating parameters of nonlinear systems are available (Draper and Smith, 1966). The Marquardt's compromise (Marquardt, 1963), which represents a compromise between the linearization and the steepest descent methods (STAT 31R), was used in the present analysis.

Before presenting the parameter estimates for model (3.7), the concepts of elasticity and homogeneity will be introduced.

D.1. Elasticity and homogeneity

The concept of elasticity and homogeneity is helpful for assigning exacting physical significance of the parameters λ_i. The concept will be introduced in this section with reference to model (3.7). Generalized physical significance of $\lambda_i > 0$ and $\lambda_i < 0$ will then be presented.

For brevity of notation, x and y will be used in this section such that

$$x_i = \left(\frac{W_{et}}{W_{oc}}\right)_i \tag{6.6}$$

$$y = \frac{G}{G_o} \tag{6.7}$$

Model (3.7) can then be written as

$$y = \prod_{i=1}^{n} x_i^{\lambda_i} \tag{6.8}$$

Model (6.8) is homogeneous of degree K since the following relationship holds:

$$(tx_1)^{\lambda_1} (tx_2)^{\lambda_2} \ldots (tx_n)^{\lambda_n} = t^K y \tag{6.9}$$

where K is a constant and t is a positive real number. (6.9) states that if all inputs x_i are multiplied by a factor t, output y is multiplied by a factor t^K.

Application of Euler's theorem to equation (6.9) leads to the conditions expressed by (6.10) and (6.11).

$$\sum_{i=1}^{n} x_i \frac{\partial y}{\partial x_i} = Ky \tag{6.10}$$

Dividing both sides by y,

$$\sum_{i=1}^{n} \frac{x_i}{y} \frac{\partial y}{\partial x_i} = K \tag{6.11}$$

Each term on the left side of (6.11) is an elasticity of relative grain production y with respect to relative evapotranspiration x_i. In other words, elasticity is defined as the percentage change in quantity produced attributable to given percentage change in an independent variable. Each term under the summation sign equals the stress parameter λ_i. Therefore, λ_i is the elasticity of production model (3.7) with respect to the ith interstage relative ET. Equation (6.11) can thus be rewritten as

$$K = \sum_{i=1}^{n} \lambda_i \tag{6.12}$$

which states that the sum of the production elasticities λ_i in a homogenous production function equals the degree of homogeneity K. Returns to scale are increasing if $K > 1$, constant if $K = 1$, and decreasing if $K < 1$.

The grain sorghum parameters for the two stage case (Table 6.3) can be interpreted as follows: for one percent change in x_i ($i = 2$ and 3) yield changes by 1.091 and 0.545 percent; and returns to scale are increasing since $K = 1.636$. The same argument applies to the other entries in Table 6.3.

Another use of elasticity can be demonstrated with reference to Figure 6.5. Stage II is the rational stage of production for sigmoid models. Points A and B which define the upper and lower boundaries of Stage II are characterized by elasticities of 1 and 0, respectively. At point A the marginal product $\frac{\partial y}{\partial x}$ equals the

average product $\frac{y}{x}$ and elasticity equals 1. At point B the marginal product equals zero and elasticity is zero.

Therefore, the rational stage of production (Stage II) lies between the two values. Stages I and III are characterized by production elasticities of greater than one and less than zero, respectively.

D.2. Physical significance of $\lambda_i > 0$

The physical significance of $\lambda_i > 0$ is that for a given level of stress $\frac{W_{et}}{W_{oc}}$, the greater the stress exponent (elasticity) the greater the reduction in yield. Figure 6.6 displays the relationship between $\frac{W_{et}}{W_{oc}}$ and $(\frac{W_{et}}{W_{oc}})^{\lambda_i}$ with λ_i as a parameter. The term $(\frac{W_{et}}{W_{oc}})^{\lambda_i}$ is referred to as stress factor. Since $0 < (\frac{W_{et}}{W_{oc}})_i < 1$ for all i, the following general conditions hold for $\lambda_i > 0$:

$$
\begin{aligned}
(\frac{W_{et}}{W_{oc}})_i^{\lambda_i} &< \frac{W_{et}}{W_{oc}} \quad \text{if } \lambda_i > 1.0 \\
&= \frac{W_{et}}{W_{oc}} \quad \text{if } \lambda_i = 1.0 \\
&> \frac{W_{et}}{W_{oc}} \quad \text{if } 0 < \lambda < 1.0
\end{aligned}
\tag{6.13}
$$

The conditions stated in equation (6.13) can readily be seen in Figure 6.6.

D.3. Physical significance of $\lambda_i < 0$

If λ_i is less than zero ($\lambda_i < 0$), the yield increases with increasing stress. That is, as $\frac{W_{et}}{W_{oc}}$ get smaller, the stress factor $(\frac{W_{et}}{W_{oc}})^{\lambda_i}$ becomes larger. The effects are illustrated in Figure 6.7.

Under normal conditions it is impossible to increase crop yield by decreasing the water available to the crop plant. Decreasing the amount of water in the plant root zone following excessive water can increase crop production. Decreasing the amount of water in the root

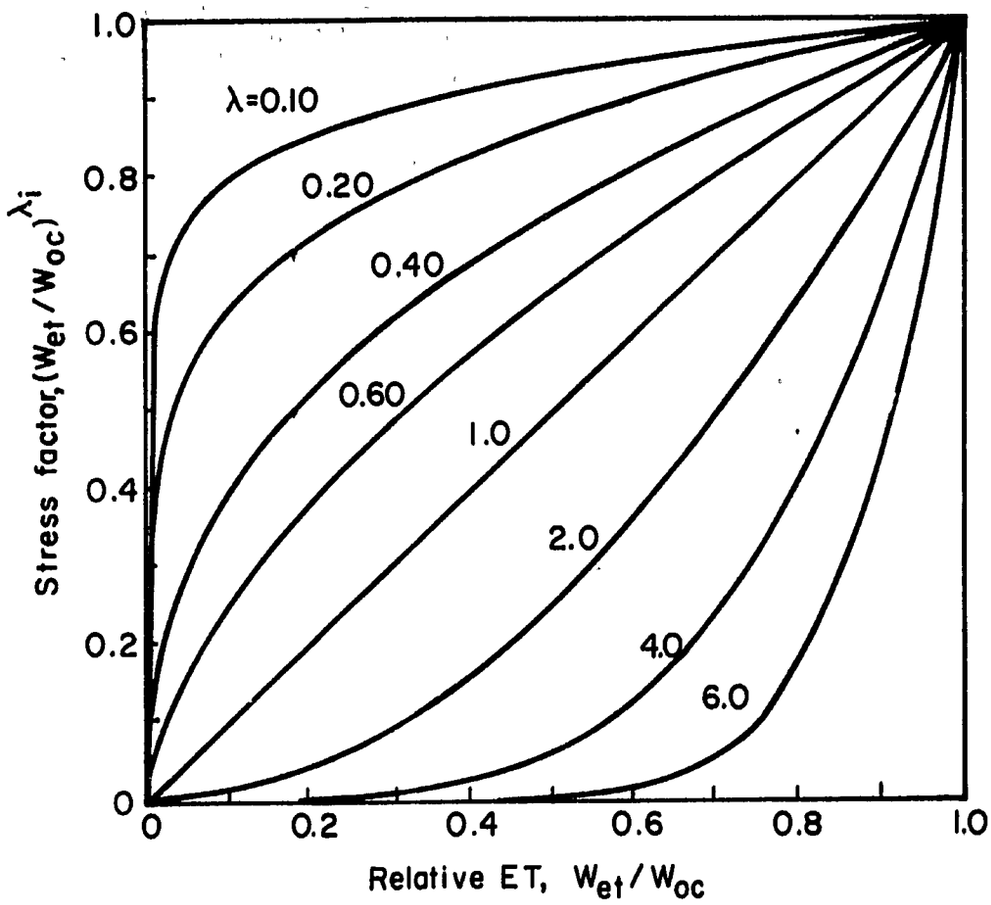

Figure 6.6. Effect of varying values of stress exponent (elasticity) λ_i on crop yield response, Jensen model, when $\lambda_i \geq 0$.

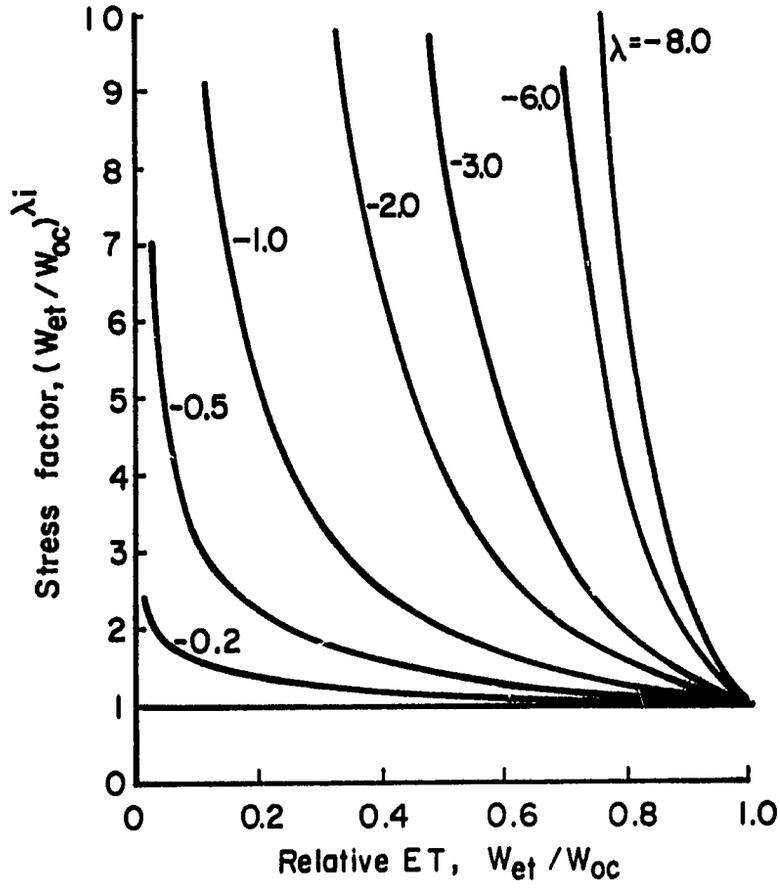

Figure 6.7. Effect of varying values of stress exponent (elasticity) λ_i on crop yield response, Jensen model, when $\lambda_i < 0$.

zone improves aeration and crop yield response. Normally the stress parameter λ_i must exclude $\lambda_i < 0$ in order to have physical relevance.

D.4. Estimates of λ_i for wheat and grain sorghum

The nonlinear least squares estimates of the stress parameters (elasticities) λ_i for hard red winter wheat and grain sorghum are summarized in Table 6.4. Four interstages of wheat and three of grain sorghum were considered. The interstage relative ET for winter wheat are presented in Table 6.5.

The λ_i for winter wheat involve both positive and negative values (Table 6.3). The negative values imply that yield increases with severity of stress. This is physically unrealistic. Negative λ_i can not have any physical relevance under any condition of limiting soil water. A reanalysis by imposing a requirement that $\lambda_i \geq 0$ resulted in all parameters but one to have boundary values of 0.0. This again has problems because boundary values $\lambda_i = 0$ imply stress has no effect on yield.

The interstage relative ET, like the variables discussed earlier, do not show values that are in the same direction as grain yield. Relative ET were consistently highest in 1963. They were comparable in 1963 and 1969 (Table 6.5). On the contrary, however, grain yields were the lowest in 1963, highest in 1969 and average in 1965. Ideally yields would be expected to be highest in 1965 and lowest in 1963 and 1969. Relative ET were about the same during the first and second interstages of 1967 and 1969. During the third and fourth interstages the 1969 wheat experienced greater water stresses and the 1967 was nearly optimum. On the basis of the above argument, yields should have been higher in 1967 than they were in 1969. However, the 1967 grain yield was the second lowest. The relative water stresses for the respective interstages during 1966 and 1970 were comparable. The yields differed greatly: average 3568 kg ha^{-1} in 1966 and 2813 kg ha^{-1} in 1970.

Table 6.3. Values of stress exponents (elasticities) λ_i in Jensen model for hard red winter wheat and grain sorghum.

Phenological stage* i	Stress exponent λ_i			
	Wheat	Grain sorghum		
		Jensen	Statistical STAT 31R	
			Three-stage	Two-stage
1	-0.490	0.50	0.677	
2	2.709	1.50	0.961	1.091
3	-5.451	0.50	0.547	0.545
4	4.580			

*The phenological stages for wheat represent intervals from spring growth initiation to boot, boot to heading, heading to soft dough, soft dough to maturity. For grain sorghum, they represent planting to boot, boot to milk, and milk to maturity. The maximum observed wheat grain yield of 4069 kg ha^{-1} was considered optimum for all years.

Table 6.4. Interstage relative ET $\frac{W_{et}}{W_{oc}}$ by treatment, hard red winter wheat, North Platte, Nebraska, 1963-1970, 1968 excluded.

Year	Treatment	$\frac{W_{et}}{W_{oc}}$ for interstage			
		1	2	3	4
1963	BON	0.85	0.80	0.77	0.68
	BN	0.84	0.79	0.75	0.65
	MON	0.86	0.81	0.78	0.69
	MN	0.84	0.79	0.75	0.66
1964	BON	0.90	0.86	0.83	0.79
	BN	0.92	0.88	0.85	0.82
	MON	0.99	0.95	0.93	0.90
	MN	0.97	0.93	0.91	0.88
1965	BON	0.91	0.89	0.96	0.95
	BN	0.93	0.90	0.97	0.94
	MON	0.92	0.89	0.97	0.95
	MN	0.93	0.90	0.96	0.96
1966	BON	0.93	0.87	0.78	0.77
	BN	0.93	0.87	0.78	0.77
	MON	0.98	0.93	0.85	0.84
	MN	0.97	0.92	0.84	0.82
1967	BON	0.84	0.86	0.94	0.91
	BN	0.86	0.87	0.94	0.92
	MON	0.86	0.87	0.94	0.92
	MN	0.85	0.87	0.94	0.91
1969	BON	0.81	0.78	0.67	0.69
	BN	0.86	0.83	0.75	0.76
	MON	0.89	0.87	0.79	0.80
	MN	0.89	0.87	0.79	0.80
1970	BON	0.93	0.86	0.75	0.74
	BN	0.93	0.86	0.75	0.74
	MON	0.94	0.88	0.77	0.75
	MN	0.94	0.88	0.79	0.77

The uncorrelated relationships between grain yield and water stresses noted above may be the cause for the physically unacceptable negative $\lambda_1 = -0.490$ and $\lambda_3 = -5.451$ (Table 6.3).

The value of the grain sorghum parameters in Table 6.4 includes three different estimates. The estimates by Jensen were obtained by trial and error. The other two entries were statistically obtained considering two and three stages of growth. The data included many entries in which the interstage relative evapotranspiration $\frac{W_{et}}{W_{oc}}$ were 1.0 or near 1.0. The first interstage had 1.0 for twelve out of sixteen data points. Since 1.0 to any power does not differ from 1.0, $(\frac{W_{et}}{W_{oc}})_1$ was excluded in the two stage analysis. Graphical comparison of observed and predicted relative grain sorghum yields using the three estimates does not show much sensitivity to the change in λ_i (Figure 6.8). No such figure is included for wheat because the negative λ_i are unrealistic.

The insensitivity in the grain sorghum is primarily due to the nature of the relative ET data, many of which were 1.0 or near 1.0. A further experiment in which the stress has a greater range is necessary to test whether the model is valid. Experiments may be set up such that the interstage relative ET may have ranges from 0.6 to 1.0.

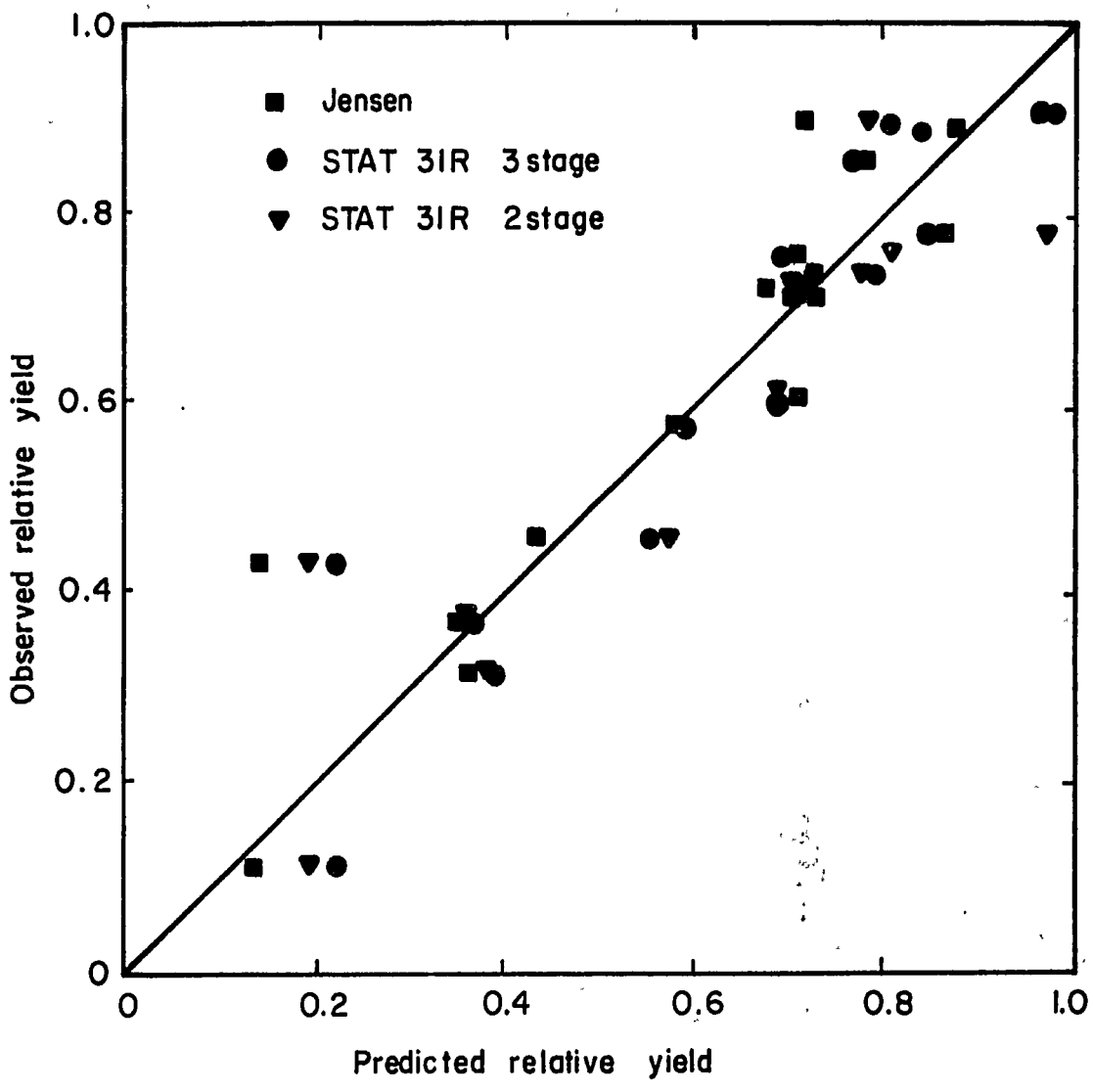

Figure 6.8. Comparison of predicted and observed relative yield of grain sorghum, Bushland, Texas, 1956-1959, 4 moisture levels.

CHAPTER VII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This chapter presents the summary and conclusions of crop water use estimation, phenological indices, and yield models. Recommendations for further study are outlined.

A. Summary

A.1. Wheat phenological stages

Phenological stages of wheat were correlated to four different estimates of climatic indices, namely, number of days, growing degree days, solar thermal units, and potential evapotranspiration. Each of the indices was accumulated from spring growth initiation to boot, heading, soft dough, and maturity stages of wheat. The number of days had the least variation when correlated with the different stages of growth (Tables 4.1 through 4.4). The coefficients of variation decreased from a high at boot stage to a low at maturity: number of days 12% to 4%, growing degree days 15% to 4%, solar thermal units 14% to 4%, and potential evapotranspiration 15% to 7%.

A.2. Wheat water use

Daily evapotranspiration was estimated by the combination method. The crop coefficient was adjusted to correct overestimating tendencies early in the season and underestimation late in the season (Figure 4.1). Water use was also computed by the water balance method at each of the four stages.

Estimated ET accumulated from spring growth initiation to boot, heading, soft dough, and maturity (W_{et}) were compared with corresponding cumulatives calculated by the water balance method (W_m). A linear regression indicates a one-to-one correspondence between W_{et} and W_m, with a small intercept value and high correlation (Figure 4.2). Since there was a good relationship, W_{et}, which can be accumulated to any desired time from daily ET, was used in the subsequent analysis.

A.3. Model for estimating transpiration

A model for estimating transpiration is obtained by developing a transpiration coefficient K_{tco} by two methods. K_{tco} is related to the basic crop coefficient K_{co}. K_{tco} is given by equations (4.3) and (4.4)--Model 1--and by equations (4.12) and (4.13)--Model 2. For $P_o = 0.10$ Model 1 is almost identical with Model 2 (Figure 4.4).

Daily transpiration T is then estimated by equation (4.5). The distribution of cumulative transpiration W_t relative to W_{et} (Figure 4.5) shows that W_t becomes a greater fraction of W_{et} as the season progresses. For the growing season W_t was about 67% of W_{et}.

A.4. Analysis of variance of wheat yield data

Analysis of variance (AOV) on final dry matter and grain yields showed that the application of nitrogen significantly affected final dry matter ($\alpha = 0.05$). Otherwise the treatments were not significant (Table 5.2). Final dry matter significantly varied from year to year. The only significant source of variation on grain yield was the yearly variation.

Annual AOV on grain yield showed that generally the treatments and replications were not significant. Mulch mainly decreased yields. Therefore, variations from year to year were the major factors affecting grain yield.

A.5. Dry matter yield models

Linear and quadratic dry matter yield models were formulated and tested for dry land hard red winter wheat. The independent variables include W_{et}, W_t, W_r, and $\frac{W_t}{E_o}$. Wheat total dry matter was highly correlated with each of these (Table 5.3). The linear models with marginal productivities of 195 kg ha^{-1} cm^{-1} for W_{et}, 228 kg ha^{-1} cm^{-1} for W_t, 100 kg ha^{-1} for W_r, and 140 kg ha^{-1} day^{-1} for $\frac{W_t}{E_o}$ appear accurate enough for predicting dry matter yields (Figures 5.1 - 5.4).

W_r is obtained by scaling daily ET or daily T by corresponding potential ET or potential T for the crop. The scaling is believed to

reconcile climatic differences. However, the applicability of the reconciling technique presented here must be validated by conducting comparative tests on different climatic regions.

Use of W_t has great conservation implications. Comparison of W_t with W_{et} indicates the amount of water that can potentially be saved if soil surface evaporation is reduced through proper conservation measures.

$\frac{W_t}{E_o}$ was computed to test the applicability of model (3.1) to field data. The model was developed by de Wit (1958) using container data. Although the linearity of the model holds for the field data, the marginal product $m_1 = 140$ kg ha^{-1} day^{-1} is higher than $m = 115$ given by de Wit. Yet m_1 falls within the range $90 \leq m \leq 160$ kg ha^{-1} day^{-1} obtained by Hanks et al. (1969).

No definite trends were apparent in the relationship between interstage dry matter and interstage stress days (Figures 5.5 - 5.8).

A.6. Linear grain yield models

Since grain yield can only be sampled after crop maturity, selection of independent variables for grain yield is extremely difficult. Linear and nonlinear models were formulated and tested.

The linear models include (6.1), (6.2), (6.3), and (6.4). Model (6.1) relates grain yield to final dry matter, model (6.2) relates to dry matter production the preceding fall and interstage dry matter, model (6.3), relates grain yield to dry matter production the preceding fall, final dry matter, and tillers, and model (6.4) adds the number of days $T_{max} \geq 27^oC$ and $U_a \geq 10$ kph to model (6.3). The coefficients of determination ranged from 0.48 to 0.75 and were all significant at $\alpha = 0.01$. Model (6.1) was tested by excluding the extremely low yield of 1963.

The value of $g = 0.44$ in model (6.1) was compared with other independent estimates. A value of $g = 0.36$ with a very high coefficient of determination ($R^2 = 0.96$) was obtained for the one year Texas data (Figure 6.2). Yet, the two year western Kansas date indicate curvilinear

relationship between grain yield and final dry matter (Figure 6.3). Therefore, the linearity may not hold when combining different years as was indicated by the data analyzed in this study.

Model (6.2) which relates grain yield to interstage dry matter involved negative coefficients which imply a decrease in grain yield with an increase in interstage dry matter during the first and fourth interstages. The first interstage included periods established to be critical. Therefore, it appears that negative coefficients for the first interstage and possibly the last are not reasonable. However, further tests may be necessary before rejecting the model.

Grain yield and seasonal water use were poorly and negatively correlated. However, models which relate grain yield to water use or other related variables can be derived by substituting any one of the dry matter yield models (5.1) through (5.4) into the linear grain yield models (6.1), (6.3), or (6.4). The derived marginal product for model (6.1), 85.8 kg ha^{-1} cm^{-1}, was coincidentally identical with the estimated water use efficiency. But the variability from the estimated lines was still large (Figure 6.4). Models (6.3) and (6.4) appear to have physical basis. Particularly model (6.4) indicates that climatic extremes may affect grain yield severely. The effects of such extremes can only be evaluated by comparing data from different years. Therefore, field experiments must be conducted for several years if the analytical results are to incorporate annual variations due to the uncertain climatic effects.

A.7. Nonlinear grain yield models

The nonlinear multiplicative model (3.7) was tested using wheat and grain sorghum data. The parameter λ_i is equivalent to the elasticity of relative yield $\frac{G}{G_o}$ with respect to the interstage relative water use $\left(\frac{W_{et}}{W_{oc}}\right)_i$. The physical significance of $\lambda_i > 0$ is that for a given level of relative stress $\left(\frac{W_{et}}{W_{oc}}\right)$, the greater the stress parameter λ_i, the greater the yield reduction. $\lambda_i < 0$ implies that grain yield increases

with increasing stress. Thus, only $\lambda_i > 0$ and not $\lambda_i < 0$ can have physical relevance.

The statistical estimates of negative λ_i during the first and third interstages (Table 6.4) make model (6.6) inapplicable for the winter wheat yield. Although the estimates of the parameters λ_i for grain sorghum were all positive, the insensitivity of the model to the range of λ_i (Figure 6.8) make the applicability of the model for singular inputs of water questionable. The model is commonly used with aggregate inputs in which the $(\frac{W_{et}}{W_{oc}})_i$ are replaced by discrete and unique input variables.

B. Conclusions

1. Number of days, growing degree days, solar thermal units, and potential ET were compared as phenological indices for wheat. The number of days was the least variable.

2. Crop evapotranspiration was shown to be predictable with sufficient accuracy from climatic, crop, and soils data by the combination method with proper regional and crop calibrations.

3. Wheat dry matter yields were highly correlated to W_{et}, W_t, W_r, and $\frac{W_{et}}{E_o}$. The linear models with the respective marginal products of 195 kg ha^{-1} cm^{-1}, 228 kg ha^{-1} cm^{-1}, 100 kg ha^{-1}, and 140 kg ha^{-1} day^{-1} may be sufficient for predicting dry matter yields when soil water is limiting. The scaling of the crop ET or T by the corresponding daily potential ET_o or T_o to obtain W_r is believed to reconcile climatic differences.

4. Grain yield models are extremely difficult to formulate. Winter wheat grain yields may be predicted using dry matter production the preceding fall, tillers, final dry matter, and number of days $T_{max} \geq 27^oC$ and $U_a \geq 10$ kph:

$$G = 232 + 1.27\ DM_p + 0.91\ N_t + 0.31\ DM_f - 114.12\ M.$$

The coefficient of determination $R^2 = 0.75$. DM_p may be considered a proxy for the factors affecting growth during the fall. DM_f may be

replaced by one of the variables in the dry matter yield models. Yield increases with increasing DM_p, N_t, and DM_f (W_{et}) and decreases with increasing exposure to temperature and wind extremes M.

5. Relating grain yield to interstage dry matter involved negative coefficients which imply a decrease in grain yield with an increase in dry matter production during the first and fourth interstages. The first interstage included periods established to be critical. Apparently negative coefficients for the first interstage are not reasonable.

6. The multiplicative nonlinear model was inapplicable for dry land winter wheat production. Its negative elasticities ($\lambda_i < 0$) imply that grain yield increases with severity of stress. Although the elasticities were positive for grain sorghum, the model appears to be relatively insensitive.

C. Recommendations

The production model is the basis to efficient allocation of resources on the farm or on a larger scale. Planning and management of farms can properly be executed using production models. Estimates of the production isoquant and marginal rate of technical substitution for multiple factors of production along with input and output price relationships can be used to derive the most profitable combination of farm inputs.

Therefore, the selection of the proper yield model is of paramount importance. The model that predicts best should be selected at a given stage of technological development. Great care must be exercised not to substitute elegance for substance.

It must be emphasized that water is only one of the many variables that affect yield of crops. Year to year variation in climate alone can cause great variation in yield, thus the need for conducting experiments for more than one year. Inclusion of all or many of the known processes that influence crop yield requires enormous resources for thorough validation. Simpler models must be used while adding further complications as confidence in the structure is established.

Realizing that this study dealt with secondary analysis of the data, experiments with crop yield response to the soil-water-climate environmental complex may be designed considering the following points:

1. A model incorporating the major factors that affect the plant processes of photosynthesis, respiration, and transpiration should be built to simulate on a daily basis.

2. In addition to accounting for the total energy, the model must consider the effect of climatic extremes such as temperature above and below the thresholds, and the duration of the extremes.

3. The model must be constructed so that parts can be removed and replaced with better process relationships.

4. Since year to year variation in climate can significantly affect the results, the experiments must be conducted for several years under field conditions.

5. Various interactions of the controllable inputs of irrigation water and fertilizer should be considered. Water stresses may be imposed between tillering and booting, booting and heading, and heading and soft-dough stages for wheat. The amounts of water applied should range from optimum to critical levels.

In addition to the above, further studies are needed to:

6. Test the applicability of scaling daily ET by corresponding potential for the crop to reconcile climatic differences; and

7. Validate the transpiration model developed in this study.

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APPENDIX

COMPUTER PROGRAM LISTING

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      PROGRAM ETEST(INPUT,OUTPUT,FILMPL,TAPE5=INPUT,TAPE6=OUTPUT,PUNCH,
     1TAPE1)
      COMMON TMAX(366),TMIN(366),RS(366),P(366),WIND(366),ETPR(366),ETPS
     A(366),RSO(366),G(366),ETPP(366),RN(366),NDIR(100),RIG(100),PREC(36
     16),C(8,8),D(8),VPD(366),TAVG(366),VP(366),RLO(366),RNRS(366),D1(8)
      COMMON KSA,KSB,MEND
      COMMON/A/ R(4),HEAD(8),LABY(4),LABX(4),DATE(8),SPEC(8)
      COMMON/B/ XA(20),YA(20),AP,NDB,NN,GR,HEADS
      COMMON/C/ ETX(366),XXA(50),DXA(50),DYA(50),DXXA(50),ETRE(50)
      COMMON/D/ ETRM(50) , DM(50), ETRET(50),ETRMT(50)
      COMMON/E/ TE(366), GDD(10), DGDD(10), STU(10), DSTU(10),STUD(366)
      COMMON/F/ CPANE(10),PANE(366) ,DDM(10), DAYS(10),DCETKCO(10)
      COMMON/G/ SD(50),DSD(50) ,ETRETC(50), AKCO(366),ETC(366)
      COMMON/H/ RAIN(50),T(366),CTA(50),ETKCO(366),CETKCO(50)
      COMMON/O/ ETRD(366),E(366),CEA(50),ETR(366),AKCOT(366),AKC(366)
      COMMON/P/ AKCT(366),AKS(366),AKA(366),TKCOT(366),CTKCOT(20)
      COMMON/Q/ CETRD(20),CTRD(20) ,ASW(366),ET(366),TRD(366)
      INTEGER HEAD
*************************************************************************
***** *******************************************************************
MM*** DEFINITIONS OF MAJOR TERMS                                      ******
***** TAVG IS AVERAGE TEMPERATURE                                      ******
***** VPD IS SATURATION VAPOR PRESSURE OF WATER                        ******
***** VPS IS   VAPOR PRESSURE IN MILLIBARS                             ******
***** WIND OR UA IS WIND RUN                                           ******
***** RS IS OBSERVED SOLAR RADIATION                                   ******
***** RSO IS CLEAR SKY SOLAR RADIATION                                 ******
***** RLO  IS NET OUTGOING LONGWAVE RADIATION                          ******
***** RN IS DAILY NET RADIATION                                        ******
***** G IS SOIL HEAT FLUX                                              ******
***** ETPP IS POTENTIAL EVAPOTRANSPIRATION                             ******
***** ET IS ACTUAL EVAPOTRANXPIRATION                                  ******
***** ETR IS INCREASE IN ET DUE TO RAIN                                ******
***** E IS DAILY EVAPORATION FROM THE SOIL SURFACE                     ******
***** CEA IS CUMULATIVE EVAPORATION                                    ******
***** T IS ESTIMATED DAILY TRANSPIRATION                               ******
***** CTA IS CUMULATIVE ESTIMATED TRANSPIRATION                        ******
***** NDB IS BEGINNING DATE                                            ******
***** NDP IS DATE OF PLANTING                                          ******
***** NDE IS DATE OF EFFECTIVE COVER                                   ******
***** NDH IS DATE OF HARVEST                                           ******
***** NDS IS STOP DATE                                                 ******
***** KSA IS PLANTING DATE, KSA=IPDA                                   ******
***** KSB IS HARVEST DATE KSB=IPDB                                     ******
***** IPDA IS THE BEGINNING DATE                                       ******
***** IPDB IS THE ENDING DATE                                          ******
***** MEND IS THE BLGINNING DATE WHERE CLIMATIC DAT  RECORD            ******
*****   BECOMES COMPLETE                                              ******
***** XXA IS CUMULATIVE POTENTIAL ET                                   ******
***** XA IS CUMULATIVE ESTIMATED ET                                    ******
***** P IS DAILY PRECIPITATION                                         ******
***** RAIN IS CUMULATIVE RAIN FALL OR PREECIPITATION                   ******
***** ASW=SAVB IS DAILY AVAILABLE SOIL WATER                           ******
***** AKCO IS BASIC CROP COEFFICIENT                                   ******
***** AKCT IS ACTUAL CROP COEFFIENT FOR TRANSPIRATION                  ******
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***** AKA IS CROP COEFFICIENT ADJUSTMENT FOR LIMITED SOIL WATER ******
***** AKS IS CROP COEFFICIENT MODIFIER FOE SURFACE WETNESS      ******
***** AKC IS CROP COEFFICIENT                                   ******
***** CETKCO IS CUMULATIVE CROP POTENTIAL ET                    ******
***** ETRD IS DAILY RELATIVE ET                                 ******
MM**** TRD IS DAILY RELATIVE TRANSPIRATION                      ******
***** CTKCOT IS CUMULATIVE POTENTIAL TRANSPIRATIOM              ******
***** TKCOT IS THE DAILY POTENTIAL TRANSPIRATION                ******
***** PANE IS DAILY PAN EVAPORATION                             ******
***** CPANE IS CUMULATIVE EVAPORATION                           ******
***** STU IS DAILY SOLAR THERMAL UNIT                           ******
***** GDD IS DAILY GROWING DEGREE-DAY                           ******
***** SAVB IS AVAILABLE SOIL WATER                              ******
***** SAVT IS HOLDOING CAPACITY FOR AVAILABLE SOIL WATER        ******
***** GR IS GRAIN YIELD                                         ******
***** DM IS DRY MATTED YIELD AT SAMPLING DATES                  ******
***** ***************************************************************
*********************************************************************
  200 PERC=0.0
      READ(5,202)IPD,IPDA,IPDB,(HEAD(I),I=1,4)
      READ (5,201) KSA8KSB,MEND
      M=63
      N=212
      CALL INPUT
***** THE STATEMENT BELOW RETAINS THE VALUE OF ETPP (PAN EVAP) BEFORE IT *******
***** GOES ANY TRANSFORMATION.  THE VALUE IS STORED UNDER PANE.          ******
      DO 100 K=MEND,KSB
100   PANE(K)=ETPP(K)
      CALL RSOC
      CALL PSC(M,N)
      CALL PENET(KSA,KSB)
      IF(MEND.GT.KSA) GO TO 101
      GO TO 1022
101   DO 102 K=KSA,MEND
***** WIND IS ASSIGNED  A DUMMY VALUE TO AVOID ERROR MODE 2 IN THIS LOOP  ******
      WIND(K)=10.00
      PANE(K)= ETPP(K)
102   CONTINUE
***** CONVERSION TO METRIC UNITS IS DONE BELOW                   ******
1022  DO 1021 I=KSA,KSB
      TAVG(I)= (TAVG(I)-32.0)/1.8
      WIND(I)=WIND(I)*1.609
      ETPP(I)=ETPP(I)*2.54
      P(I)=P(I)*2.54
      PANE(I)=PANE(I)*2.54
      TE(I)=TAVG(I)-2.8
      IF(TE(I).LT. 0.0) TE(I) =0.0
      IF(TE(I).GT.24.0) TE(I)= 24.0
      IF(I.LT.MEND) GO TO 118
      STUD(I)= TE(I)*RS(I)
      GO TO 1021
118   STUD(I)= TE(I)*190.
1021  CONTINUE
****  NN IS TREATMENT NUMBER AND HEADING NUMBER
103   READ(5,203)NN,(HEAD(I),I=1,8)
```

```
      IF(NN.EQ.20)GO TO 200
      IF (NN.EQ.0) CALL ETREL
      IF(NN.EQ.0) CALL EXIT
      IF (NN.EQ.1) WRITE (6,204)
      IF (NN.EQ.1) WRITE(6,205) HEAD
      IF (NN.EQ.1)WRITE(6,2052)
C     NDB-BEGINNING DATE, NDP-PLANTING DATE,NDE-DATE OF EFFECTIVE COVER,
C     NDH-DATE OF HARVEST, NDS-STOP DATE, SAVB-AVAILABLE WATER,
C     SAVT-SOIL CAPACITY FOR A.W.
      READ(5, 206)NDB,NDP,NDE,NDH,NDS,SAVB,SAVT,KLYS
*     STORE INFORMATION ON TAPE
      WRITE(1) NN, HEAD,NDB,NDS
      SAVB=SAVB*2.54
      SAVT=SAVT*2.54
      AB=NDB
      AP=NDP
      AE=AP+73.00
      READ(5,207) M,(DATE(J),SPEC(J),J=1,M)
      DO 1041 J=1,4
1041  SPEC(J)=SPEC(J)*2.54
      READ(5,208) GR,GRMAX,DMMAX,(DM(J),J=1,M),HEADS
      IB=NDB-1
      YA(1)=SAVB - SPEC(1)
***** R IS A TERM USED TO ACCOUNT FOR RAIN IN DAYS 1, 2, 3, 4   ******
      R(4)=P(NDB-3)
      R(3)=P(NDB-2)
      R(2)=P(NDB-1)
      R(1)=P(NDB)
C     CALCULATES A CROP COEFFICIENT
      DO 119 I=NDB,NDS
      ETR(I)=0.0  $ RX=R(1)
      IF(I.LT.NDP) GO TO 117
      IF(I.GE.AE) GO TO 105
      AI=I
       PCT=100.*(AI-AP)/(AE-AP)
      AKCO(I)=C(N,1)+C(N,2)*PCT+C(N,3)*PCT**2+C(N,4)*PCT**3
      IF(PCT.LT.20.) AKCO(I)=0.09
      IF (AKCO(I).GT.1.00) AKCO(I)=1.00
      AKCOT(I)=AKCO(I)*(PCT-10.0)/100.0
      IF (PCT.LT.10.0) AKCOT(I)=0.04
      GO TO 106
105   DT=I-AE
      AKCO(I) =C(N,5)+C(N,6)*DT+C(N,7)*DT**2+C(N,8)*DT**3
      IF (AKCO(I).GT.1.00) AKCO(I)=1.00
      AKCOT(I)=0.90*AKCO(I)
106   IF (AKCO(I).GT.1.00)AKCO(I)=1.00
****  ETX IS POTENTIAL ET FROM A CROP OF ALFALFA                  ******
      IF(ETPP(I).LT. 0.00) ETPP(I)=0.00
      ETX(I)= ETPP(I)
      ETKCO(I)=AKCO(I)*ETPP(I)
      TKCOT(I)=AKCOT(I)*ETPP(I)
      IF(SAVB.GT.SAVT) GO TO 107
***** AKA IS AN ADJUSTING FACTOR FOR LIMITED SOIL WATER          ******
      AKA(I)= ALOG(100.*SAVB/SAVT+1.)/ALOG(101.)
      AKC(I)=AKCO(I)*AKA(I)
```

```
      AKCT(I)=AKCOT(I)*AKA(I)
      ET(I)=AKC(I)*ETPP(I)
      T(I)=AKCT(I)*ETPP(I)
      GO TO 1071
107   ET(I)=AKCO(I)*ETPP(I)
      T(I)=AKCOT(I)*ETPP(I)
1071  IF (AKC(I).GT.0.90) GO TO 115
C ***THIS GROUP OF CARDS ACCOUNTS FOR PRECIP ON DAYI ******************
      IF(R(1).LE.0.0)GO TO 108
***** AKS IS AN ADJUSTMENT FACTOR DUE TO SURFACE WETNESS        ******
      AKS(I)= 0.90-AKC(I)
***** ETR IS INCREASE IN ET DUE TO RAIN                          ******
      ETR(I)=AKS(I)*ETPP(I)
      R(1)=R(1)-ETR(I)
      IF(R(1).GE.0.0)GO TO 114
      R(2)=R(2)+R(1)
      R(1)=0.0
      GO TO 109
108   IF(R(2).LE.0.0)GO TO 112
      AKS(I)=0.80*(0.90-AKC(I))
      ETR(I)=AKS(I)*ETPP(I)
      R(2)=R(2)-ETR(I)
109   IF(R(2).GE.0.0)GO TO 114
      R(3)=R(3)+R(2)
      R(2)=0.0
110   IF(R(3).GE.0.0)GO TO 114
      R(4)=R(4)+R(3)
      R(3)=0.0
111   IF(R(4).GE.0.0)GO TO 114
      ETR(I)=ETR(I)+R(4)
      R(4)=0.0
      GO TO 114
112   IF(R(3).LE.0.0)GO TO 113
      AKS(I)=0.5*(0.90-AKC(I))
      ETR(I)=AKS(I)*ETPP(I)
      R(3)=R(3)-ETR(2)
      GO TO 110
113   IF(R(4).LE.0.0)GO TO 114
      AKS(I)=0.3*(0.90-AKC(I))
      ETR(I)=AKS(I)*ETPP(I)
      R(4)=R(4)-ETR(I)
      GO TO 111
114   IF (ETR(I).LT.0.00)ETR(I)=0.00
*     ETC IS CROP EVAPOTRANSPIRATION
      ETC(I)=ET(I)
115   ET(I)=ET(I)+ETR(I)
      SAVB=SAVB+RX-ET(I)
      IF(SAVB.LT.0.0)SAVB=0.0
      IF(SAVB.LE.SAVT)GO TO 116
      PERC=SAVB-SAVT
      SAVB=SAVT
116   IF (ET(I).LT.0.005)  ET(I)=0.005
      IF(ETX(I).LT.0.01) ETX(I)=0.01
      TRD(I)=T(I)/TKCOT(I)
      ETRD(I)=ETC(I)/ETKCO(I)
```

```
      ASW(I)=SAVB
      PREC(I)=PERC
117   R(4)=R(3)
      R(3)=R(2)
      R(2)=R(1)
      R(1)=P(I+1)
      PERC=0.0
119   CONTINUE
      DO 120 I=NDB,NDS
      ETPP(I)=ETX(I)
      E(I)=ET(I)-T(I)
*     WRITE INFORMATION ON TAPE
      WRITE(1)PANE(I),ETX(I),ET(I),T(I),E(I),P(I),ETRD(I),TRD(I),AKCO(I
     1),AKCOT(I),AKA(I),AKC(I),ETKCO(I),TAVG(I),TE(1),STUD(I),ASW(I),
     2TKCOT(I)
      IF (NN.NE.1) GO TO 120
      IF(I.LT. MEND) GO TO 1161
      IF((I-NDB).EQ.50.OR.(I-NDB).EQ.103) WRITE (6,2051)
      IF((I-NDB).EQ.50.OR.(I-NDB).EQ.103) WRITE (6,2052)
      WRITE(6,209)I,TAVG(I),VP(I),VPD(1),WIND(I),RS(I),RSO(I),RLO(I),
     1RN(I),G(I),RNRS(I),ETPS(I),ETPP(I),ET(I),T(I),E(I),P(I),PREC(I),
     BASW(I)
      GO TO 120
1161  WRITE(6,210)I,TAVG(I),ETPP(I),ET(I),T(I),E(I),P(I)
120   CONTINUE
      CALL CUMLTV
      GO TO 103
201   FORMAT (2X,3I3)
  202 FORMAT(3I3,4A10)
203   FORMAT(I2,4A10,/,4A10)
204   FORMAT(1H1)
205   FORMAT(49X,4A10,/,44X,4A10,//,1X,*DATE  TAVG   VPS   VPD    UA
     1RS   RSO   RLO    RN   G  RN/RS  ETP/RN   ETP    ET    T      E  R
     2AIN  DRAIN  ASW*)
2051  FORMAT ( 1H1,//,1X,                *DATE  TAVG   VPS   VPD    UA
     1RS   RSO   RLO    RN   G  RN/RS  ETP/RN   ETP    ET    T      E  RA
     2IN  DRAIN  ASW*)
2052  FORMAT (      *           C   MB     MB   KPH    CAL. PER CM SQ. PE
     1R DAY                    CM    CM    CM    CM    CM    CM    CM*,/
     2)
206   FORMAT(5I5,2F5.2,I5)
207   FORMAT(I2,/,(4(F5.0,F5.2)))
208   FORMAT(F7.2, 7F7.0)
209   FORMAT(1X,I4,F6.1,2F6.2,F6.1,5F6.0,F6.3,F7.3,7F6.2)
210   FORMAT(1X,I4,F6.1,61X,5F6.2)
      END


      SUBROUTINE CUMLTV
      COMMON TMAX(366),TMIN(366),RS(366),P(366),WIND(366),ETPR(366),ETPS
     A(366),RSO(366),G(366),ETPP(366),RN(366),NDIR(100),RIG(100),PREC(36
     16),C(8,8),D(8),VPD(366),TAVG(366),VP(366),RLO(366),RNRS(366),D1(8)
      COMMON KSA,KSB,MEND
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      COMMON/A/ R(4),HEAD(8),LABY(4),LABX(4),DATE(8),SPEC(8)
      COMMON/B/ XA(20),YA(20),AP,NDB,NN,GR,HEADS
      COMMON/C/ ETX(366),XXA(50),DXA(50),DYA(50),DXXA(50),ETRE(50)
      COMMON/D/ ETRM(50) , DM(50), ETRET(50),ETRMT(50)
      COMMON/E/ TE(366), GDD(10), DGDD(10), STU(10), DSTU(10),STUD(366)
      COMMON/F/ CPANE(10),PANE(366) ,DDM(10), DAYS(10),DCETKCO(10)
      COMMON/G/ SD(50),DSD(50) ,ETRETC(50), AKCO(366),ETC(366)
      COMMON/H/ RAIN(50),T(366),CTA(50),ETKCO(366),CETKCO(50)
      COMMON/O/ ETRD(366),E(366),CEA(50),ETR(366),AKCOT(366),AKC(366)
      COMMON/P/ AKCT(366),AKS(366),AKA(366),TKCOT(366),CTKCOT(20)
      COMMON/Q/ CETRD(20),CTRD(20) ,ASW(366),ET(366),TRD(366)
      DIMENSION TOET(20),CETC(10),DCETC(10)
***** XXA IS ACCUMULATED POTENTIAL ET ********************
****  GDD IS  ACCUMULATED GROWING DEGREE-DAYS *************
****  STU IS ACCUMULATED SOLAR THERMAL UNITS  ************
****  CPAE IS CUMULATIVE EVAPORATON  ***********
      IB=NDB-1
      CTA(1)=0.0
      SD(1)=0.00
      RAIN(1) = 0.00
      CPANE(1)=0.00
      GDD(1) =0.0
      STU(1) =0.0
      CETKCO(1)=0.00
      XXA(1)=0.0
      XA(1)=0.0
      CETC(1)=0.0
      CTRD(1)=0.00
      CETRD(1)=0.00
      CTKCOT(1)=0.0
      CEA(1)=0.0
      CETKCO(1)=0.0
      M=4
      DO 126 II=1,M
      IA=IB+1
      IB=DATE(II)+.001
      IB=IB-1
      IF(II.EQ.1)GO TO 121
      CETKCO(II)=CETKCO(II-1)
      CTA(II)=CTA(II-1)
      GDD(II)=GDD(II-1)
      STU(II)=STU(II-1)
      RAIN(II)= RAIN(II-1)
      XXA(II)=XXA(II-1)
      CPANE(II)=CPANE(II-1)
      XA(II)=XA(II-1)
      CTRD(II)=CTRD(II-1)
      CETRD(II)=CETRD(II-1)
      CEA(II)=CEA(II-1)
      CTKCOT(II)=CTKCOT(II-1)
      YA(II)=(SPEC(II-1)-SPEC(II) + YA(II-1))
121   DO 123 JJ=IA,IB
      CTA(II)=CTA(II)+T(JJ)
      RAIN(II)= RAIN(II) + P(JJ)
      CETC(II)=CETC(II)+ETC(JJ)
      XA(II)=XA(II) + ET(JJ)
      YA(II)=YA(II)+P(JJ)-PREC(JJ)
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```
      CETKCO(II)=CETKCO(II)+ETKCO(JJ)
      XXA(II)=XXA(II)+ETX(JJ)
      GDD(II)=(GDD(II) + TE(JJ))
      STU(II) =(STU(II) + STUD(JJ))
      CPANE(II)=CPANE(II) +PANE(JJ)
      CTRD(II)=CTRD(II) +TRD(JJ)
       CETRD(II)=CETRD(II) +ETRD(JJ)
      CEA(II)=CEA(II) +E(JJ)
      CTKCOT(II)=CTKCOT(II)+ TKCOT(JJ)
123   CONTINUE
      IF(II.EQ.1) GO TO 124
      DCETC(II)=CETC(II)-CETC(II-1)
      DXA(II)=XA(II)-XA(II-1)
      DYA(II)=YA(II)-YA(II-1)
      DXXA(II)=XXA(II)-XXA(II-1)
      DCETC(II)=CETC(II-1)
      DGDD(II) =GDD(II)-GDD(II-1)
      DCETKCO(II)=CETKCO(II)-CETKCO(II-1)
      DSTU(II) = STU(II)- STU(II-1)
      DAYS(II) =DATE(II)-DATE(II-1)
      DDM(II)=DM(II)-DM(II-1)
      GO TO 125
124   DXA(II)=XA(II)
      DCETC(II)=CETC(II)
      DYA(II)=YA(II)
      DCETKCO(II)=CETKCO(II)
      DXXA(II)=XXA(II)
      DSTU(II) = STU(II)
      DGDD(II) = GDD(II)
      DDM(II)=DM(II)
      DAYS(II)=DATE(II)-AP
125   ETRE(II)=DCETC(II)/DCETKCO(II)
      ETRM(II)=DYA(II)/DCETKCO(II)
126   CONTINUE
      DO 127  II=1,4
      STU(II) =STU(I1)/710000.
       GDD(II)= GDD(II)/1300.
      DGDD(II)=DGDD(II)/1300.
      DSTU(II)=DSTU(II)/710000.
      TOET(II)=CTA(II)/XA(II)
127   CONTINUE
      IF(NN.GT.1.AND.NN.LT.5) GO TO 128
      WRITE(6,2111)HEAD
      WRITE(6,212)
      GO TO 129
128   WRITE(6,213) HEAD
129   DO 130 II=1,4
130   WRITE(6,214)DATE(II),XA(II),YA(II),XXA(II),CPANE(II),ETRE(II),
     1ETRM(II),CETKCO(II),RAIN(II),        CTA(II),CEA(II),CETRD(II),
     2CTRD(II),TOET(II)
*     WRITE INFORMATION ON TAPE
*     WRITE(1)      (DATE(II),XA(II),YA(II),XXA(II),CPANE(II), CTA(II),
*    ADM(II),GDD(II),STU(II),DGDD(II), DSTU(II),DAYS(II),CEA(II),CETRD(I
*    BI),CTRD(II),CTKCOT(II),SPEC(II),CETKCO(II), II=1,4),GR,HEADS
2111  FORMAT(1H1,47X,4A10,/,44X,4A10)
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212   FORMAT(1H0,17X,*ACCUMULATED ET*,18X,*STAGE ET RATIO*,12X,*      *,
     1/,2X,*DAY*,2X,*ESTIMATED*,2X,*MEASURED*,2X,*POTENTIAL*,2X,*PAN EVA
     2P*,2X,*ESTIMATED *,2X,*MEASURED*,2X,*CETKCO     *,2X,*RAIN *,6X,*CT
     3A*,6X,*CE *,6X,*CETRD*,6X,*CTRD*,*    T/ET*)
213   FORMAT(1H0,47X,4A10,/,44X,4A10)
214   FORMAT(1H0,F4.0,6F10.3, 2F11.2, 4F10.3 ,F6.3)
      RETURN
      END

      SUBROUTINE INPUT
      DIMENSION DP(366)
      COMMON TMAX(366),TMIN(366),RS(366),P(366),WIND(366),ETPR(366),ETPS
     A(366),RSO(366),G(366),ETPP(366),RN(366),NDIR(100),RIG(100),PREC(36
     16),C(8,8),D(8),VPD(366),TAVG(366),VP(366),RLO(366),RNRS(366),DI(8)
      COMMON KSA,KSB,MEND
      VPP(T)=10.**(-7.9028*(373.16/(5.*(T-32.0)/9.+273.16)-1.)+5.02808*A
     ALOG10(373.16/(5.*(T-32.0)/9.+273.16))-1.3816E-7*(10.**(11.344*(1.-
     B373.16/(5.*(T-32.)/9.+273.16)))-1.)+8.1328E-3*(10.**(-3.49149*(373
     C.16/(5.*(T-32.)/9.+273.16)-1.))-1.)+3.00571)
C**** CROP COEFF. BEFORE EFFECTIVE COVERFOR SMALL GRAINS (WHEAT)
      C(1,1)=0.160$ C(1,2)=-1.140E-2$ C(1,3)=4.843E-4$ C(1,4)=-2.893E-6
C***   CROP COEFF. AFTER EFFECTIVE COVER FOR SMALL GRAINS (WHEAT)
      C(1,5)=1.250$ C(1,6)=8.532E-3$ C(1,7)=-7.261E-4$ C(1,8)=4.44E-6
C ***   INPUT FOR NORTH PLATTE
C       READS PERCENT SUNSHINE, RS
      READ(5,13)(RS(I),I=63,212)
   13 FORMAT(5X,25F3.2)
C       READS SATURATION VAPOR PRESSURE, VPD.
      READ(5,14)(VPD(I),I=63,212)
   14 FORMAT(5X,25F3.1)
C       READS THE FOLLOWING
C       TMAX= MAXIMUM TEMPERATURE
C       TMIN= MINIMUM TEMPERATURE .
C       P= PRECIPITATION OR RAIN
C       ETPP= PAN EVAPORATION
C       WIND= DAILY WIND RUN IN MILES
      READ(5,15)(TMAX(K),TMIN(K),P(K),ETPP(K),WIND(K),K=63,212)
   15 FORMAT(5X,2F3.0,F3.2,F3.3,F3.1,2F3.0,F3.2,F3.3,F3.1,2F3.0,F3.2,F3.
     13,F3.1,2F3.0,F3.2,F3.3,F3.1,2F3.0,F3.2,F3.3,F3.1)
      RETURN
      END
      SUBROUTINE PENET(N,M)
C     CALCULATES PENMAN POTENTIAL E.T.
      COMMON TMAX(366),TMIN(366),RS(366),P(366),WIND(366),ETPR(366),ETPS
     A(366),RSO(366),G(366),ETPP(366),RN(366),NDIR(100),RIG(100),PREC(36
     16),C(8,8),D(8),VPD(366),TAVG(366),VP(366),RLO(366),RNRS(366),DI(8)
      COMMON KSA,KSB,MEND
      VPP(T)=10.**(-7.9028*(373.16/(5.*(T-32.0)/9.+273.16)-1.)+5.02808*A
     ALOG10(373.16/(5.*(T-32.0)/9.+273.16))-1.3816E-7*(10.**(11.344*(1.-
     B373.16/(5.*(T-32.)/9.+273.16)))-1.)+8.1328E-3*(10.**(-3.49149*(373
     C.16/(5.*(T-32.)/9.+273.16)-1.))-1.)+3.00571)
      NN=KSA-3
```

```
      DO 5 J=NN,KSB
    5 TAVG(J)=(TMAX(J)+TMIN(J))/2.
      IF(MEND.GT.KSA)CALL JENET(M,N)
      DO 10 I=MEND,KSB
      VPS1=VPP(TMAX(I))
      VPS2=VPP(TMIN(I))
      IF(VPS2.LE.0.0)VPS2=0.0
      VP(I)=(VPS1+VPS2)/2.0
      IF(I.LE.3) RETURN
      G(I)=(TAVG(I)-(TAVG(I-1)+TAVG(I-2)+TAVG(I-3))/3.0)*5.
      TEN=((TMIN(I)-32.)/1.8 + 273.)/ 100.
      TAX=((TMAX(I)-32.)/1.8 + 273.)/100.
      RLO(I)=(0.37-0.044*VPD(I)**0.50)*11.71*(TAX**4+TEN**4)*0.5
      RN(I)=0.77*RS(I)-(0.9 *RS(I)/RSO(I)+0.1 )*RLO(I)
      T1=.041+.0125*TAVG(I)-4.534*TAVG(I)**2/10.0**5
      T2=.959-.0125*TAVG(I)+4.534*TAVG(I)**2/10.0**5
      ETPP(I)=(T1*(RN(I)-G(I))+T2*15.36*(1.0+0.36*WIND(I))*(VP(I)-
     1VPD(I)))*0.000673
      RNRS(I)=RN(I)/RS(I)
      ETPS(I)=ETPP(I)/(RN(I)*0.000673)
   10 CONTINUE
      RETURN
      END


      SUBROUTINE RSOC
      COMMON TMAX(366),TMIN(366),RS(366),P(366),WIND(366),ETPR(366),ETPS
     A(366),RSO(366),G(366),ETPP(366),RN(366),NDIR(100),RIG(100),PREC(36
     16),C(8,8),D(8),VPD(366),TAVG(366),VP(366),RLO(366),RNRS(366),D1(8)
      COMMON KSA,KSB,MEND
C     CALCULATES CLEAR SKY SOLAR RADIATION
C       THE CARDS SET THAT FOLLOW INITIALIZES RSO
      DO 1 I=1,366
    1 RSO(I)=0.0
C ***   INPUT FOR NORTH PLATTE
      RSO(1)=270.
      RSO(32)=350.
      RSO(61)=460.
      RSO(92)=575.
      RSO(122)=670.
      RSO(153)=725.
      RSO(183)=720.
      RSO(214)=640.
      RSO(245)=590.
      RSO(306)=340.
      RSO(336)=265.
      RSO(366)=270.
      IA=1
      IB=IA
    4 IB=IB+1
      IF(RSO(IB).EQ.0.0)GOTO4
      A=IA
      B=IB
```

```
      SL=(RSO(IB)-RSO(IA))/(B-A)
      DO10 J=IA,IB
      CX=J-IA
   10 RSO(J)=RSO(IA)+SL*(CX)
      IA=IB
      IF(IA.LT.366)GO TO 4
      RETURN
      END


      SUBROUTINE JENET(M,N)
****  CALCULATES JENSEN-HAISE POTENTIAL ET
      COMMON TMAX(366),TMIN(366),RS(366),P(366),WIND(366),ETPR(366),ETPS
     A(366),RSO(366),G(366),ETPP(366),RN(366),NDIR(100),RIG(100),PREC(36
     16),C(8,8),D(8),VPD(366),TAVG(366),VP(366),RLO(366),RNRS(366),D1(8)
      COMMON KSA,KSB,MEND
      DO 41 I= KSA,MEND
   41 ETPP(I)=(0.014*TAVG(I)-0.37) *RS(I)*0.000673
      RETURN
      END
      SUBROUTINE PSC(M,N)
      COMMON TMAX(366),TMIN(366),RS(366),P(366),WIND(366),ETPR(366),ETPS
     A(366),RSO(366),G(366),ETPP(366),RN(366),NDIR(100),RIG(100),PREC(36
     16),C(8,8),D(8),VPD(366),TAVG(366),VP(366),RLO(366),RNRS(366),D1(8)
      COMMON KSA,KSB,MEND
      DO 5 I=M,N
      RS(I)=RSO(I)*(.35+.61*RS(I))
    5 CONTINUE
      RETURN
      END
0000000000000000000000
```