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A METEOROLOGICALLY-DRIVEN YIELD REDUCTION MODEL FOR SPRING AND WINTER WHEAT

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A yield-reduction model for spring and winter wheat has been developed for large-area crop

16. Abstract

A yield reduction model for spring and winter wheat has been developed for large-area crop condition assessment. Reductions are expressed in percentage from a base yield and are calculated on a daily basis. The algorithm contains two integral components: a two-layer soil water budget model and a crop calendar routine. Yield reductions associated with hot, dry winds (Sukhovey) and soil moisture stress are determined. Input variables include evapotranspiration, maximum temperature and precipitation; subsequently crop-stage, available water holding percentage and stress duration are evaluated. No specific base yield is required and may be selected by the user; however, it may be generally characterized as the maximum likely to be produced commercially at a location.

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A METEOROLOGICALLY-DRIVEN YIELD REDUCTION MODEL

FOR SPRING AND WINTER WHEAT

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WHEAT YIELD REDUCTION MODEL

PART 1.0   INTRODUCTION

1.1   PURPOSE

This paper documents a yield reduction model for winter and spring
wheat. Reductions are expressed in percentage from a base yield and are
calculated on a daily basis. A synopsis of the model logic and com-
ponents is given.

1.2   SITUATION AND BACKGROUND

U.S. Department of Agriculture (USDA) policy is to provide American
farmers and commodity analysts with timely information concerning world
agricultural conditions. In 1978 USDA's Foreign Agricultural Service
(FAS) created a Foreign Crop Condition Assessment Division (FCCAD) to
aggressively pursue this policy. To further enhance this pursuit, U.S.
government agencies involved in aerospace remote sensing coordinated
their activities in the Agricultural and Resource Inventory Surveys
Through Aerospace Remote Sensing (AgRISTARS).

An Early Warning/Crop Condition Assessment (EW/CCA) element of AgRISTARS
seeks means to detect changes in production quantity and quality of com-
modities and renewable resources. The overall objective of the EW/CCA
Project is to provide better capability for the USDA to identify
environmental and agronomic events which significantly affect crop

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condition and to determine extent and magnitude. Research conducted by
EW/CCA augments and strengthens the capability of FCCAD. Improved crop
condition information even based on subjective criteria is very useful
in assessing crop loss and damage. As research provides better tools,
subjective estimates will iteratively become more objective.

FCCAD operations call for assessments based on convergence of evidence
from available data sources. Information sources include traditional
reports from American embassies and consulates around the world and from
information media. These are coupled to in-house use of agrometeorolog-
ical crop condition indicator models and subjective analysis of remotely
sensed satellite data.

The World Meteorological Organization (WMO) through its global tele-
communications system provides timely exchange of meteorological data
throughout the world. The U.S. Air Force collects meteorological data
from an even larger network of stations and adapts the data to a gridded
system. Environmental parameters, available daily, include in part max-
imum and minimum temperatures, type and quality of precipitation, solar
radiation, snowfall and snow cover, wind direction and speed, vapor
pressure and evapotransipiration.

EW/CCA and FCCAD developed crop stress indicator models and models that
track crop phenology and soil moisture. This paper describes a yield
reduction model which estimates daily stress impact on yield and
particularly the impact of desiccating events as combinations of high
temperature, low humidity, high wind speed and low soil moisture.

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Quantity of water available at specific phases of plant growth and development greatly affects crop yield (Bauer and Young, 1969). Evaporation, as a measure of atmospheric demand, strongly influences crop condition. Primarily, it is a function of temperature, wind speed and humidity (Denmead and Shaw, 1962). Temperature is a major factor due to its effect on vapor pressure - an increase in temperature increases the evaporation rate and decreases the time a given quantity of water can effectively hydrate a plant.

Drought, a prolonged extension of desiccating conditions or soil moisture deficits that disrupt the water balance of plants, affects thousands of square kilometers annually (Ventskevich, 1961). Disruption of the water balance of plants may be induced either by a moisture deficit in the soil or by exceedingly rapid evaporation from plant surfaces. Hot, dry winds (called Sukhovey in the Soviet Union) may cause extreme yield reductions and/or plant death even though soil moisture conditions are optimal (Vitkevich, 1960). Sukhoveys have been roughly characterized as: 1) temperatures greater than 25°C, 2) relative humidity less than 25 percent and 3) windspeeds greater than 3-5 m/sec (CIA, 1974).

The operation of the yield reduction model does not require a specific base yield; rather, it measures yield loss. Therefore, any base yield can be selected by the user for final assessment. The base yield may however be generally characterized as the maximum likely to be produced commercially at a location.

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PART 2.0   WHEAT YIELD REDUCTION MODEL

2.1   MODEL COMPONENTS

The yield reduction model contains two integral components; a crop calendar model and a soil moisture model. Both components require daily minimum and maximum temperatures. The crop calendar model uses the Robertson Biometeorological Time Scale (BMTS) (Figure 1) and the soil moisture model is the two-layer or crop moisture index model.

The crop calendar model requires actual or estimated planting dates. It identifies when 50 percent of the crop reaches a particular growth phase. Future refinements may integrate other crop phase increments into the model.

The two-layer soil moisture model requires long term monthly historical mean temperatures, daily rainfall and daily mean temperature and an estimate of the soil's available water-holding capacity.

There are two distinct modules in the operation of the yield reduction model; the ETP/Sukhovey module and the stress module. Sukhovey loss and damage can occur in a matter of minutes or hours while stress from diminishing soil moisture evolves over a longer period. Both can be very destructive.

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2.2   PHENOLOGICAL GROWTH STAGE

The Robertson Biometeorological Time Scale measures phenological phase (Figure 1) and performs in the model as defined below and further described in Figure 1.
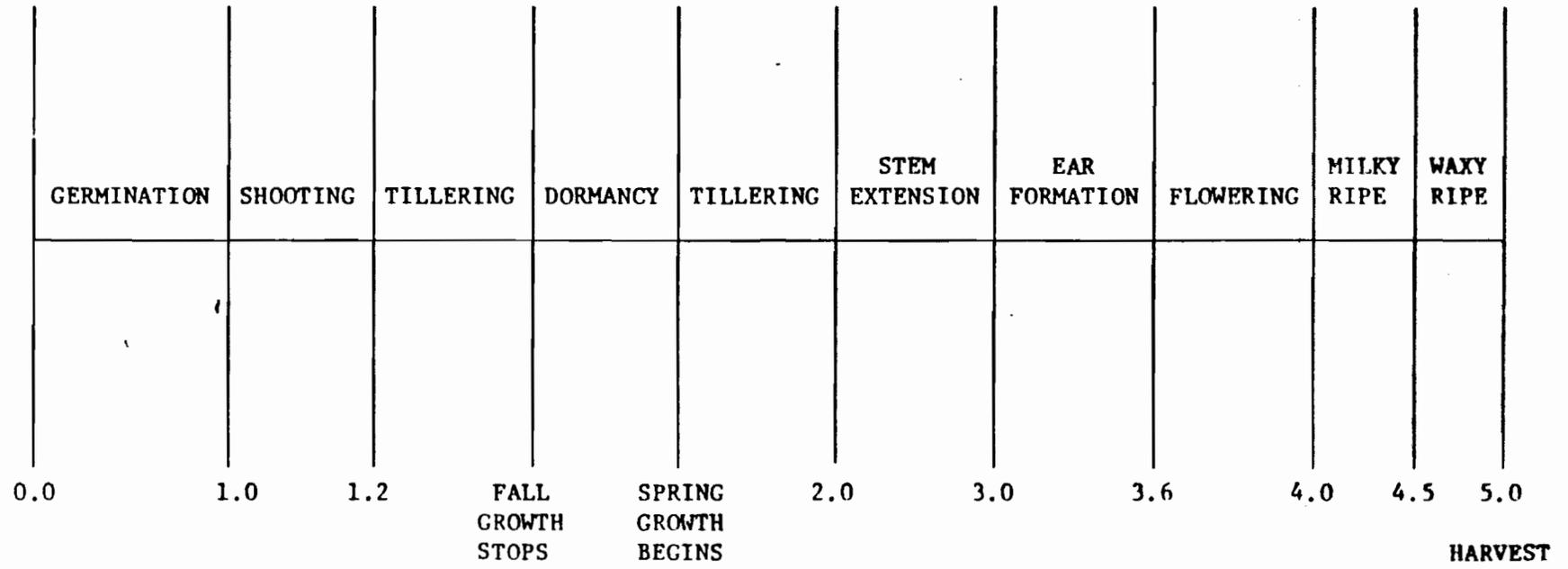
ROBERTSON'S BMTS	PHENOLOGICAL PHASE
0.0	PLANTING
1.0	EMERGENCE
1.5	TILLERING
2.0	JOINTING
2.5	FLAG LEAF
3.0	HEADING
3.5	MILK
4.0	DOUGH
5.0	RIPE

Attainment of maximum wheat yields is achieved through optimal environmental conditions during each phenological phase. However, if critical environmental factors such as soil, water and temperature are limiting, they reduce yield potential.

2.3   TWO-LAYER SOIL MOISTURE MODEL

The two-layer soil moisture model used by FCCAD and EW/CCA is similar to the Palmer two-layer model (Palmer, 1965). Atmospheric demand and soil water availability determine the amount of water withdrawn from the soil by both direct evaporation from the soil surface and transpiration by plants.

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FIGURE 1. BMTS AND PHENOLOGICAL PHASES

GERMINATION	SHOOTING	TILLERING	DORMANCY	TILLERING	STEM EXTENSION	EAR FORMATION	FLOWERING	MILKY RIPE	WAXY RIPE

0.0   1.0 1.2   FALL   SPRING 2.0   3.0   3.6   4.0 4.5 5.0

GROWTH GROWTH

STOPS   BEGINS

HARVEST

ROBERTSON, G. W. - 1968

Both soil moisture models assume the first inch of available water is held in the surface layer. The actual thickness of the surface layer is variable and depends on soil type, rooting depth and soil permeability.

The Palmer model assumes moisture is removed from the surface layer at a rate equal to potential evapotranspiration, and that moisture is removed from the subsurface layer at a fraction of the potential rate. The model assumes that moisture cannot be removed from the lower layer until the surface layer is completely dry. These assumptions are restrictive and do not adequately represent the soil water budget process.

Stress indicator models require a more accurate representation of the soil water budget, particularly in the surface layer. EW/CCA and FCCAD modified the two-layer model to allow a more gradual and realistic depletion of the surface layer and also allow moisture to be depleted from the lower layer before the surface layer is completely dry.

They also developed a moisture extraction function to allow depletion from the surface at the potential rate of less than or equal to 75 percent of surface capacity. Below 75 pecent, the model extracts moisture from the surface at a reduced rate with the lower layer making up the remaining requirement. It extracts moisture from the lower layer at a fraction of potential and calculates this fraction as a ratio of actual water held to that level held at field capacity.

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Precipitation enters the model by first completely filling the surface layer and then the lower layer. When both layers reach capacity, excess precipitation becomes runoff and/or deep percolation and is lost from the model.

2.4   SUKHOVEY/ETP FUNCTION

This component of the model assigns empirical loss/damage magnitudes based on ETP and maximum temperature. The higher the temperature and ETP, the greater the yield loss (Table 1).

Adjustments are then made for soil moisture (as % of available water-holding capacity) (Table 2), crop phase (both for vulnerability and ETP) and duration of Sukhovey conditions (Table 3). An empirical scale assigns yield reduction by percent available soil water. Further adjustments are applied for crop phase (CSE). As the crop advances through growth and development, its water needs change. The crop becomes more or less vulnerable to environmental impact on yield. The calendar factor increases from small values during early phases of growth and development to a maximum value during early ripening (milk stage); then it decreases as the grain matures. The model calculates yield reduction as:

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TABLE 1 - ETP/MAX TEMPERATURE YIELD REDUCTION

MATRIX

		ETP												
		8	9	10	11	12	13	14	15	16	17	18	19	20
	26	0	0	0	0	0	0	0	0	0	1	2	3	4
	27	0	0	0	0	0	0	0	1	2	3	4	5	6
	28	0	0	0	0	0	1	2	3	4	5	6	7	8
M	29	0	0	0	1	2	3	4	5	6	7	8	9	10
A	30	0	1	2	3	4	5	6	7	8	9	10	11	12
X	31	2	3	4	5	6	7	8	9	10	11	12	13	14
	32	4	5	6	7	8	9	10	11	12	13	14	15	16
T	33	6	7	8	9	10	11	12	13	14	15	16	17	18
E	34	8	9	10	11	12	13	14	15	16	17	18	19	20
M	35	10	11	12	13	14	15	16	17	18	19	20	21	22
P	36	12	13	14	15	16	17	18	19	20	21	22	23	24
	37	14	15	16	17	18	19	20	21	22	23	24	25	26
	38	16	17	18	19	20	21	22	23	24	25	26	27	28
	39	18	19	20	21	22	23	24	25	26	27	28	29	30
	40	20	21	22	23	24	25	26	27	28	29	30	31	32
	41	22	23	24	25	26	27	28	29	30	31	32	33	34
	42	24	25	26	27	28	29	30	31	32	33	34	35	36
	43	26	27	28	29	30	31	32	33	34	35	36	37	38
	44	28	29	30	31	32	33	34	35	36	37	38	39	40
	45	30	31	32	33	34	35	36	37	38	39	40	41	42

CREMINS, W.

TABLE 2 - SOIL WATER AVAILABLILITY FACTOR

% AWHC	YIELD REDUCTION FACTOR
5	1.25
10	1.25
15	1.25
20	1.20
25	1.15
30	1.10
35	1.05
40	1.00
45	0.99
50	0.98
55	0.97
60	0.96
65	0.95
70	0.94
75	0.93
80	0.92
85	0.91
90	0.90
95	0.89
100	0.88

SMIKA, D. - 1982

TABLE 3 - CONTINUOUS DAY ADJUSTMENT

DAY	ADJUSTMENT
1	1.0
2	0.5
3	0.25
4	0.125
5	0.0625
6	0.03125

$$YR = (\text{Table 1 value}) * (\text{Table 2 value}) * (\text{Table 3 value}) * CSE$$

(Crop stage equation)

Prior to BMT 4.0 (milk) the model calculates crop phase effect as:

$$CSE_1 = 8.208 - 9.452X + 3.405 X^2 - 0.3666X^3$$

where $X = BMT$

This second equation determines the milk to ripe crop stage effect:

$$CSE_2 = 16.94 - 6.829X + 0.948X^2 - 0.052X^3$$

The model introduces a duration factor during each crop phase. The first occurrence of a harmful event receives full impact value. Values decrease one-half for the second occurrence during a crop phase, one-fourth for the third and so on (Table 3). These need not be consecutive. The occurrence counter resets to full impact at crop phases 2.5, 3.0, 3.5, 4.0 and 4.5.

An example of the scheme:

If max temperature = 37°C
If ETP = 15

then yield reduction factor (matrix) = 21

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If % AWHC   = 55

then AWHC factor = .97 x 21 = 20.37

If crop phase is flowering the impact factor = 1.3 (from CSE_1)

then 1.3 x 20.37 = 26.48

If it is second day of event in the same crop phase; i.e., .5

then .5 x 26.48 = 13.24

The event would cause a 13.24 point (%) yield reduction from a base yield figure.

2.5   SOIL MOISTURE/DEMAND FUNCTION

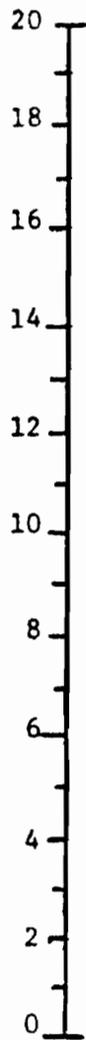If ETP and temperature values do not fall in the ETP/Sukhovey module, the algorithm then defaults to the stress module. The stress module assesses yield reduction for small grains using ETP, available soil moisture and crop phase. The model assumes ETP to be the sum of the demands that are being placed on the plant by the environment and uses it to calculate a stress index. The stress index is a regression equation generated from the Moisture:ETP:Stress nomograph (Figure 2).

$$Index = .9998 + (.108 \ ETP) + (.0145 \ AWC) - (.3536 \ (AWC)^{.5})$$
$$- (.0001)$$

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PERCENT
CAPACITY

100 ━
80 ━
70 ━
60 ━
50 ━
40 ━
35 ━
30 ━
25 ━
20 ━
15 ━
10 ━
7.5 ━
5 ━
2.5 ━

ETP
m/m
DAY

20 ━
18 ━
16 ━
14 ━
12 ━
10 ━
8 ━
6 ━
4 ━
2 ━
0 ━

SOIL MOISTURE
STRESS
INDEX

1.0 ━
.9 ━
.8 ━
.7 ━
.6 ━
.5 ━
.4 ━
.3 ━
.2 ━
.1 ━
0.0 ━
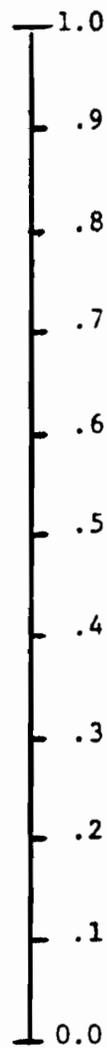
NOMOGRAPH

MOISTURE:ETP:STRESS

FIGURE 2

ASHBURN, P.

where

Index = the crop stress index (between 0 and 1)

ETP   = the evapotranspiration potential

AWC   = the percent of soil water available to the plant

A daily Yield Reduction Index is then adjusted for crop phase (See
Figure 3). This is accomplished by multiplying the Index and the
maximum daily reduction.

An example:

If maximum temperature = 28°C

ETP   = 10

% AWC   = 10

then Index = 1.10

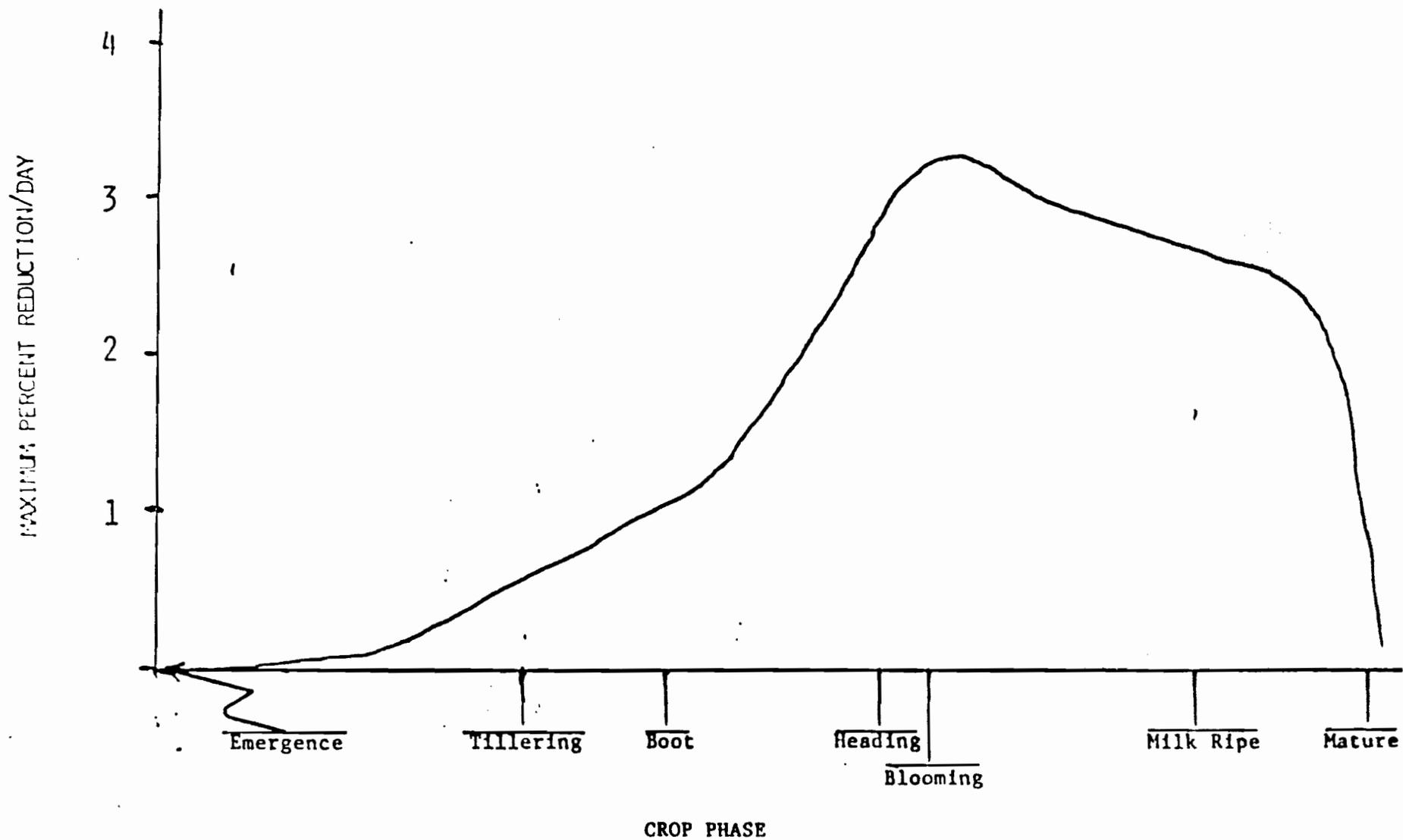and if the crop phase is at heading, then the stage factor is 3.4.

1.10 X 3.4 = 3.74 yield reduction.

The model calculates ETP using the albedo is specified as a function of
crop phase.

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$$ETP = (A-1) \; ETP, + ETP2$$

Phase	(A-1)
0 - .99	.9 - .14 phase
1 - 2.99	.76
3 - 5.00	.76 + .14 (phase - 3.0)

FIGURE 3 - DAILY YIELD REDUCTION

STEGMAN, E. C., AND H. BAUER. 1970. Canad. J. Ag. Eng. 12(2):92.

APPENDIX I

SOIL MOISTURE EQUATION

Top Layer $=$ Contains 1 inch of plant available water.

Lower Layer $=$ Normally contains between 5 and 10 inches of available water.

$$L_s = S'_s - (ETP-P) D_f$$

$$L_u = (ETP-P-L_s) \frac{S'_u}{AWC} : L_u \_ S'_u$$

D_f $=$ Surface moisture extraction function.

D_f $=$ 1 if P   ETP

D_f $=$ $(S'^s \div .75) : .1 \_ D_f \_ 1.$

D_f $=$ .1 if D_f .1 and $D_f = 1. : D_f$ 1.

R $=$ Excess P after both layers are filled.

ETP $=$ ETP'(d) [Thornwaite, 1948]

    If T less than 0°
    ETP' $= 0$

    If $0^oC.$ T 26^oC
    ETP' $= 1.6 \ (\overline{10T/I})^a$

    If T 26^oC
    ETP' $=$ Sin $(T - 9.5) -.76$

a $= 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + .01792 I + .49239$

$$I = \sum_{i=1}^{12} (T/5)^{1.514}$$

d $= -0.767 \tan (.410117 Cos(.0172264(JDAY-172)))$

DEFINITION OF TERMS

L_s =   Moisture loss from surface

S'_s =   Available water in surface layer at start

P   =   Daily precipitation

L_u =   Loss from lower layer

S'_u =   Available moisture stored in lower layer

AWC   =   Combined available water capacity; i.e., $MAX(S'_s + S'_u)$

R   =   Runoff

D_f =   Surface moisture extraction function

ETP   =   Evapotranspiration Potential – "The amount of water transpired in unit time by a short, green crop completely shading the ground, of uniform height and never short of water."

d   =   Day length adjustment for ETP

$\dot{T}$ =   Average daily temp degree C

I   =   Annual heat index

JDAY   =   Julian date

a   =   Coefficient

CSE   =   Crop stage equation

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