MODELING GROWTH STAGE OF TWO SPRING WHEAT CULTIVARS-NEEPAWA AND HY320: 2. MODEL DEVELOPMENT AND PERFORMANCE

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INTRODUCTION

Most agronomic research on wheat in our area has consisted of empirical field trials, where conventional regression analysis is used to produce information specific to the time and location of the trial or series of trials. Though such relationships are easy to develop and use, the information obtained is difficult to extrapolate to areas where the environment differs from that where the relationships were derived. Moreover, because no attempt is made at defining cause-effect relationships, they tend to be inaccurate in abnormal years when concern is often highest. Thus, we at the Swift Current Research Station are attempting to overcome this limitation by using process-oriented plant growth models to analyse wheat crops so that responses to agronomic treatments can be explained, and separated from site and seasonal variability.

The general availability and relatively low cost of modern computers is currently providing scientists with the opportunity to construct process-based crop simulation models to study particular problems of crop production (Ritchie and Otter, 1985; Protopapas and Bras, 1987; Huck and Hillel, 1983; Baker et al., 1985; Childs et al., 1977). A crop simulation model is a formal mathematical statement of assumptions that have been made about the cropping system being studied. These assumptions may be entirely empirical, based on observations of the field performances of crops, or they may be based on an understanding, or knowledge, of the physical or physiological mechanisms underlying crop growth and production. The processes involved in most crop simulation models are very much the same in principle. Differences in these models exist mostly in the details of how radiation, photosynthesis, transpiration, soil moisture movement, and root development are treated.

Of the numerous process-based wheat growth models that have been developed in recent years, the CERES-Wheat model is the one that has been most intensively tested (Otter-nacke et al., 1986). CERES-Wheat is a computer simulation model of the growth development, and yield of spring and winter wheat (Ritchie and Otter, 1985). It was designed to be used in any location throughout the world where wheat can be grown. Because we believe that the CERES-Wheat model is a valuable tool for providing insights into the behaviour of many aspects of a cropping system and could offer a wide range of possible applications, we are presently investigating the feasibility for use of the model in our area.

To assess whether a model is structurally sound and can be used in an area, it should be tested not merely for its overall predictions but also for its component processes using a data base appropriate to the region. In this paper, we report our testing results of one small but important aspect in the CERES-Wheat model, namely, the duration of growth stages as related to plant genetics and weather. The input information needed to run the model was collected from field experiments that were described in the first paper of this series (Cutforth et al., 1988 - this issue).

PLANT GROWTH STAGES

In order to accurately simulate crop growth and yield of a wheat plant, it is necessary to be able to accurately describe the phasic development of the plant. This is so because each contributor to grain yield (e.g., number of heads per plant, number of kernels per head, and kernel weight) is developing over a different part of growing season. Thus, a specific weather event or weather condition may affect grain yield differently depending on the stage of growth at which it occurs.

The physical organs of spring wheat are easily recognized. The plant's parts and structures appear and develop in a consistent and orderly pattern. A growth stage scale indicating the status of plant development during its life cycle through use of numerical or alphabetic designations was devised first by Feekes in 1941 in the Netherlands. Several others have been devised since. Today, commonly used growth stage scales of wheat are those of Feekes (Large, 1954), Robertson (1968), Zadoks et al. (1974), Waldren and Flowerday (1979), and Haun (1973). Those scales differ in method of designation, in detail, and in sensitivity to changes in plant development rate.

The Haun growth stage scale assigns a number to each leaf on the main stem of the plant. The leaves are numbered consecutively in the order in which they appear. Because total number of main stem leaves and leaf appearance rate have been shown to be much more strongly correlated with accumulated thermal units than with chronological time (Gallagher, 1979; Kirby et al., 1982), the Haun scale which provides a more precise measure of leaf appearance than methods involving simply counting number of leaves is considered the most precise and the most sensitive to daily changes in quantifying vegetative development of wheat (Klepper et al., 1985; Baker et al., 1986).

Growth chamber work (Klepper et al., 1982) as well as field experiments (Baker et al., 1986) have shown that each leaf on the wheat plant requires about the same number of thermal units to develop. The number of thermal units required for the production of each successive leaf is referred to as a phyllochron. Thus, the growth stages of wheat after emergence can be determined with high accuracy by knowing the number of leaves on the main stem and the phyllochron of the cultivar and the total accumulated thermal units since emergence. The method is widely adopted in wheat simulation models for determining growth stages (Ritchie and Otter, 1985; Baker et al., 1985).

In the CERES-Wheat model,the growth stages are organized around times in the plant life cycle when changes occur in partitioning of assimilate among different plant organs. The growth of spring wheat is divided into 9 phases (Table 1). Stage 1 through 5 are the active above-ground growing stages and the remainder are used to describe other important events in the crop cycle. Comparisons of wheat growth stages, the Haun's scales, and growth stages defined in the CERES-Wheat model are shown in Figure 1.

The primary variables influencing plant development rate are genotype and temperature. The accumulated daily temperature above a base temperature (Tb) is referred to as thermal time or growing-degree-day (GDD). Air temperature is generally used as an indictor. When the daily air temperature is above Tb and the maximum is below 30°C, thermal time for a day is assumed to be the mean of the two values minus Tb. In the CERES-Wheat model, if either the maximum or minimum temperature is outside this range, a separate thermal time calculation is made using the mean temperature and temperature range.

TABLE 1 GROWTH STAGES IN CERES-WHEAT MODEL

STAGE NO.	EVENT	GROWING PLANT PARTS
7	Fallow or Presowing	
8	Sowing to Germination	
9	Germination to Emergence	Roots, Coleoptile
1	Emergence to Terminal Spikelet Initiation	Roots, Leaves
2	Terminal Spikelet to End of leaf Growth	Roots, leaves, Stems
3	End of Leaf Growth to End of Pre-Anthesis Ear Growth	Roots, Stems, Ear
4	End of Pre-Anthesis Ear Growth to Begining of Grain Filling	Roots , Stems
5	Grain Filling	Roots, Stems, Grain
6	End of Grain Filling	

MODEL STRUCTURE

A. Sowing to Germination (stage 8) and Germination to Emergence (stage 9):

The process from sowing to germination in CERES-Wheat is assumed to take place within a day if there is adequate soil moisture in the seed zone. Germination is delayed if the soil moisture is below a threshold value

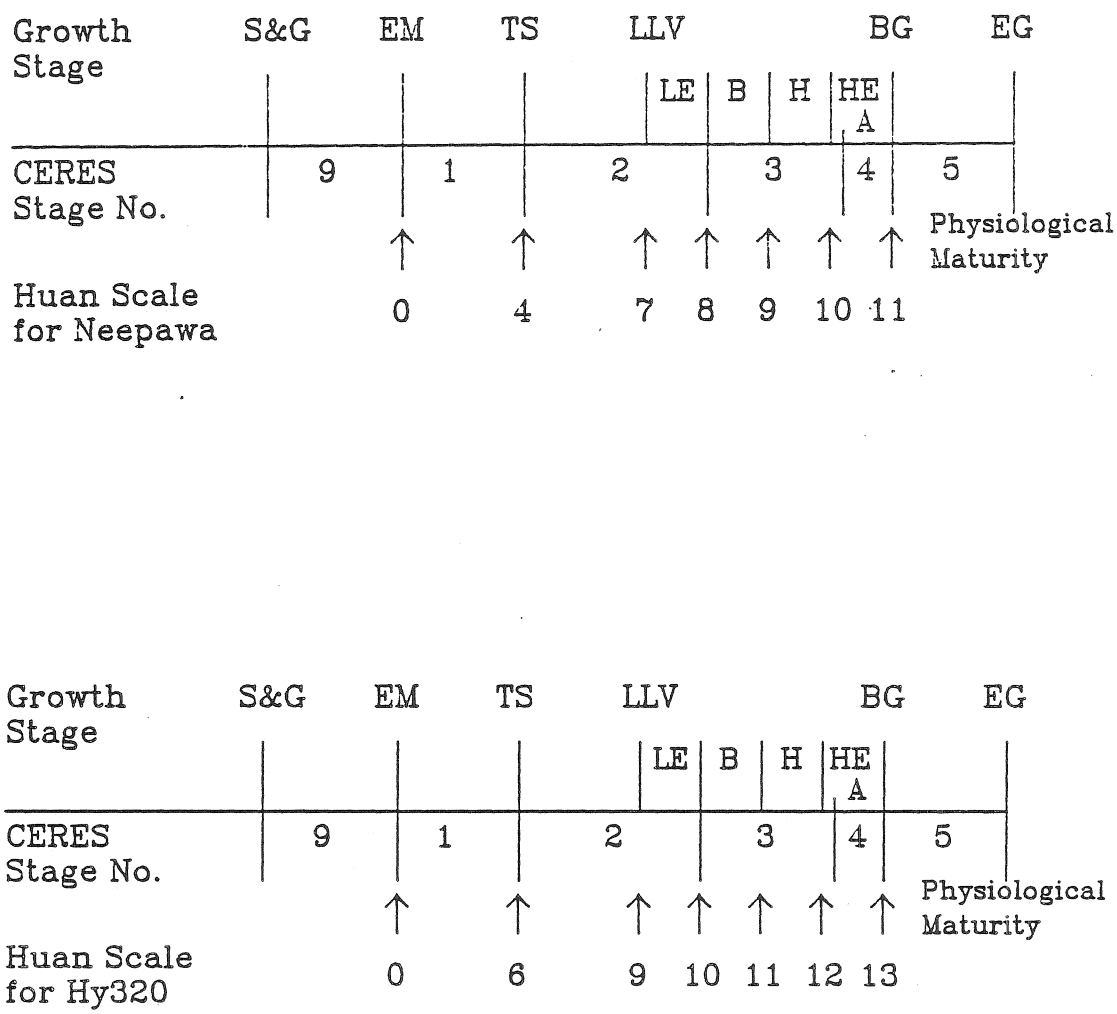

Figure 1. Comparisons of wheat growth stages, the Haun's Scale and growth stages defined in CERES-Wheat model for Neepawa and HY320; S---Sowing, G---Germination, EM---Emergence, TS---Terminal Spikelet, LLV---Ligule Last Leaf Visible, LE---Leaf Extension, B---Booting, H---Heading, HE---Head Extension, A---Anthesis, BG---Beginning of Grain Filling, EG---End of Grain Filling.

(close to wilting point), or if the mean temperature is below 3°C. The thermal time required from germination to emergence (P9) is defined as a function of seeding depth:

$$P9 = 40 + 10.2 * \text{Seeding Depth (cm)}$$

where P9 is the accumulated GDD with Tb = 2°C. Thus, the deeper the seeding depth, the longer it takes the shoot to emerge. When planted in moist soil at a depth of about 5 cm, it takes an accumulation of 91 GDD (Tb = 2°C) from the day after germination to emergence.

B. Emergence to Terminal Spikelet Initiation (stage 1):

In CERES Wheat, the thermal time for stage 1 (P1) varies with genotype and is given as:

$$P1 = (400/95) * \text{PHYLLOCHRON}$$

The thermal time is calculated daily with Tb = 0°C first; the value is then modified by accounting for vernalization and photoperiod factors using values between 0 and 1. These factors are calculated using specific coefficients of vernalization (P1V) and photoperiod (P1D) that depend on the plant genetics. When the ajusted accumulated thermal time reaches P1, stage 1 ends.

We have not determined the sensitivity of Neepawa and HY320 to photoperiod and vernalization yet. However, it is generally believed that spring wheats are not overly sensitive to these two factor. To make the conditions simple for testing our model, we have simply assumed that terminal spikelet initiation occurs at about the time just befor the third-to-last leaf on the main stem has started to emerge.

Neepawa produced a total of 7 or 8 leaves on the main stem and HY320 produced 9 or 10 leaves when they were seeded in mid-May in our area (Cutforth et al., 1988). Of the plants sampled, the majority of Neepawa had 7 leaves and HY320 had 9 leaves. Thus, we set the thermal time for stage 1 (P1) as:

$$P1 = (7 - 3) * \text{PHYLLOCHRON} \;\ldots\; \text{for NEEPAWA,}$$

and

$$P1 = (9 - 3) * \text{PHYLLOCHRON} \;\ldots\; \text{for HY320.}$$

C. Terminal Spikelet to End of Leaf Growth (stage 2):

End of leaf growth is defined as that time just after the flag leaf has fully expanded. In Haun's scale, this is 8.0 for 7-leaved varieties and 10.0 for 9-leaved varieties (Figure 1). Because we assumed that 3 more leaves would develop after terminal spikelet both for Neepawa and HY320, and we also assumed that the number of GDD required for the growth unit of flag-leaf extension is the same as required for a leaf (i.e. one phyllochron), the thermal time for stage 2 (P2) was, therefore, fixed as:

$$P2 = 4 * PHYLLOCHRON$$

for both cultivars.

D. End of leaf Growth to End of Pre-Anthesis Ear Growth (stage 3):

The thermal time required for stage 3 (P3) to be completed is primarily depedent on the genotype and can be determined from field measurements.

E. End of Pre-Anthesis Ear Growth to Beginning of Grain Filling (stage 4):

The accumulated GDD for stage 4 (P4) is set to be 50 (for dryland) and 70 (for irrigation) with Tb=0°C for both Neepawa and HY320 cultivars. Those values were derived from field observations in our area.

F. Grain Filling (stage 5):

The thermal time for stage 5 (P5) is also only dependent on the genotype. GDD in stage 5 is calculated with Tb = 1°C in the model.

MODEL PERFORMANCE AND DISCUSSION

Calibration, validation, and sensitivity analysis are three different steps of evaluating models. Calibration is normally the first and validation the last step in model testing. The purpose of calibration is to allow adjustment of some parameters using a data base appropriate to the area such that the model behaviour matches the real world. The results presented in this paper were primarily used for model calibration.

The model was calibrated with a data set obtained from field measurements. The data set includes 4 years of experiments under irrigation and 3 years under dryland (Cutforth et al., 1988). The genetic specific constants needed in the model were derived by matching the predicted growth stages to the field measured growth stages. This was carried out for each year and each treatment. The optimum value for a special genetic constant (Table 2) was assumed to be the average of all estimates of the genetic constant in question. The predicted growth stages using the values presented in Table 2 are shown in Figures 2 (Neepawa under irrigation), 3 (HY320 under irrigation), 4 (Neepawa under dryland), and 5 (HY320 under dryland).

TABLE 2. THERMAL TIME FOR DETERMINATION OF GROWTH STAGES IN CERES-WHEAT MODEL FOR NEEPAWA AND HY320

genetic constant	Irrigation		Dryland	
	Neepawa	HY320	Neepawa	HY320
	GDD+			
Phyllochron	88	75	80	69
P9	91	91	91	91
P1	352	450	320	414
P2	352	300	320	276
P3	95	153	94	120
P4	70	70	50	50
P5	720	730	620	620
Total from sowing to End of Grain Filling	1680	1794	1495	1571

+ Values are the average of all estimates of the specific constant in question from a data set including 4 years of experiments under irrigation and 3 years under dryland.

The growth stages predicted from the model agreed reasonably well to the actual measurements for the 4 years of experiments (Figures 2, 3, 4, and 5), especially under irrigation. In most cases, the growth stages were accurately predicted within 2 or 3 days of their occurrence. The phyllochrons obtained from model calibration for Neepawa and HY320 were very close to the measured results obtained in 1987 (Cutforth et al., 1988); the biggest difference (5 GDD) was for Neepawa on dryland.

The predicted emergence dates for Neepawa and HY320 were within 1 or 2 days of their occurrence. Both cultivars required approximately 91 GDD (with Tb = 2°C) for emergence when seeded about 5 cm deep in our area. However, for seedbeds with surface residues, dry soil surface, or temperature close to threshold value (i.e., 2°C), the model may not work as well and may require some adjustments.

It would be advantageous if a single set of genetic constants for each cultivar could be derived to cover a wide range from dry to wet conditions instead of one set for irrigation and one for dryland. However, we were unable to do this. This indicates that the so called "genetic constants" are not truly constants that depend on solely genotype. The values seemed

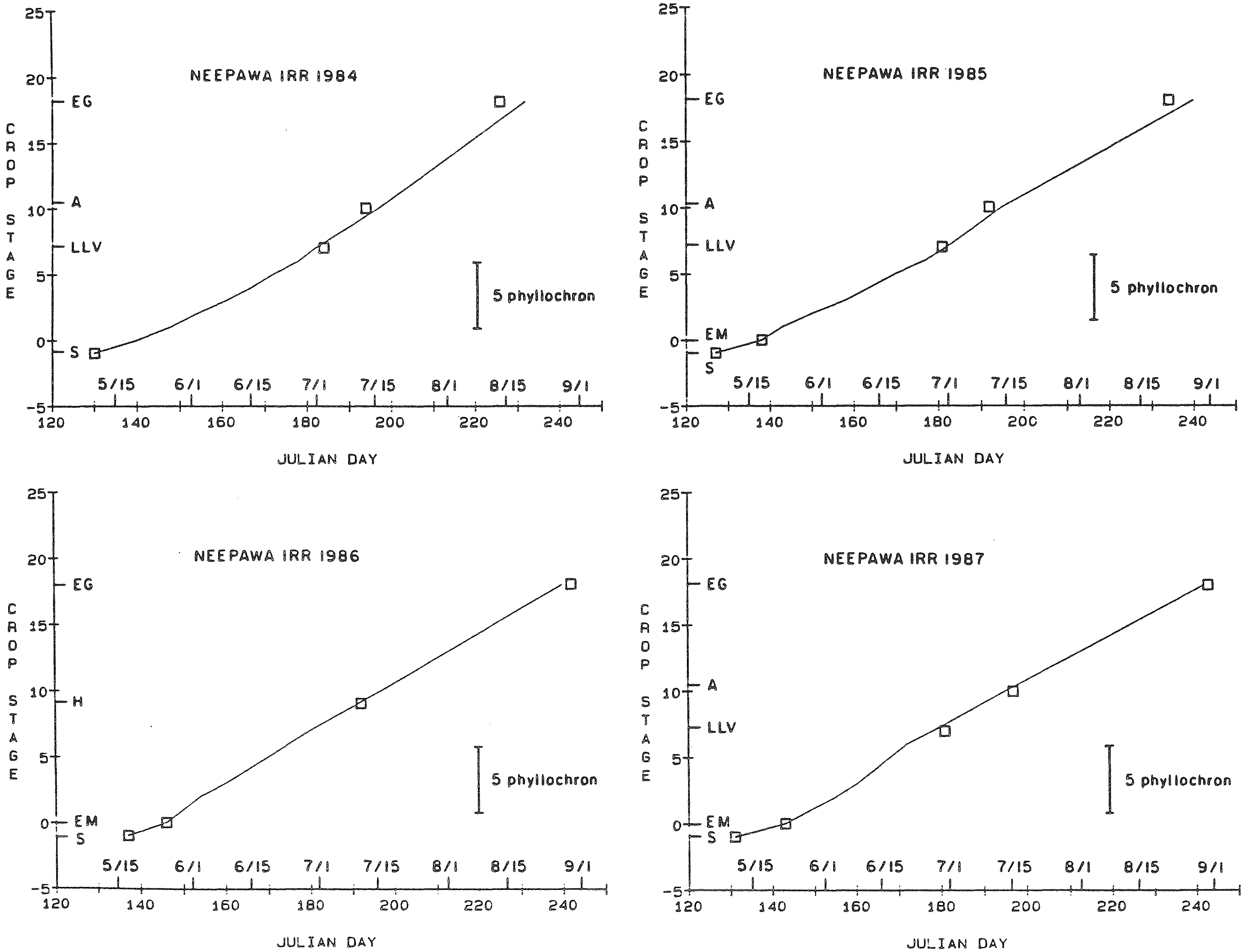

Figure 2. Model predictions of growth stages (———) vs. measured values (□) for Neepawa under irrigation; S---Sowing, EM---Emergence, LLV---Ligule last leaf visible,H---Heading, A---Anthesis and EG---End of grain filling.

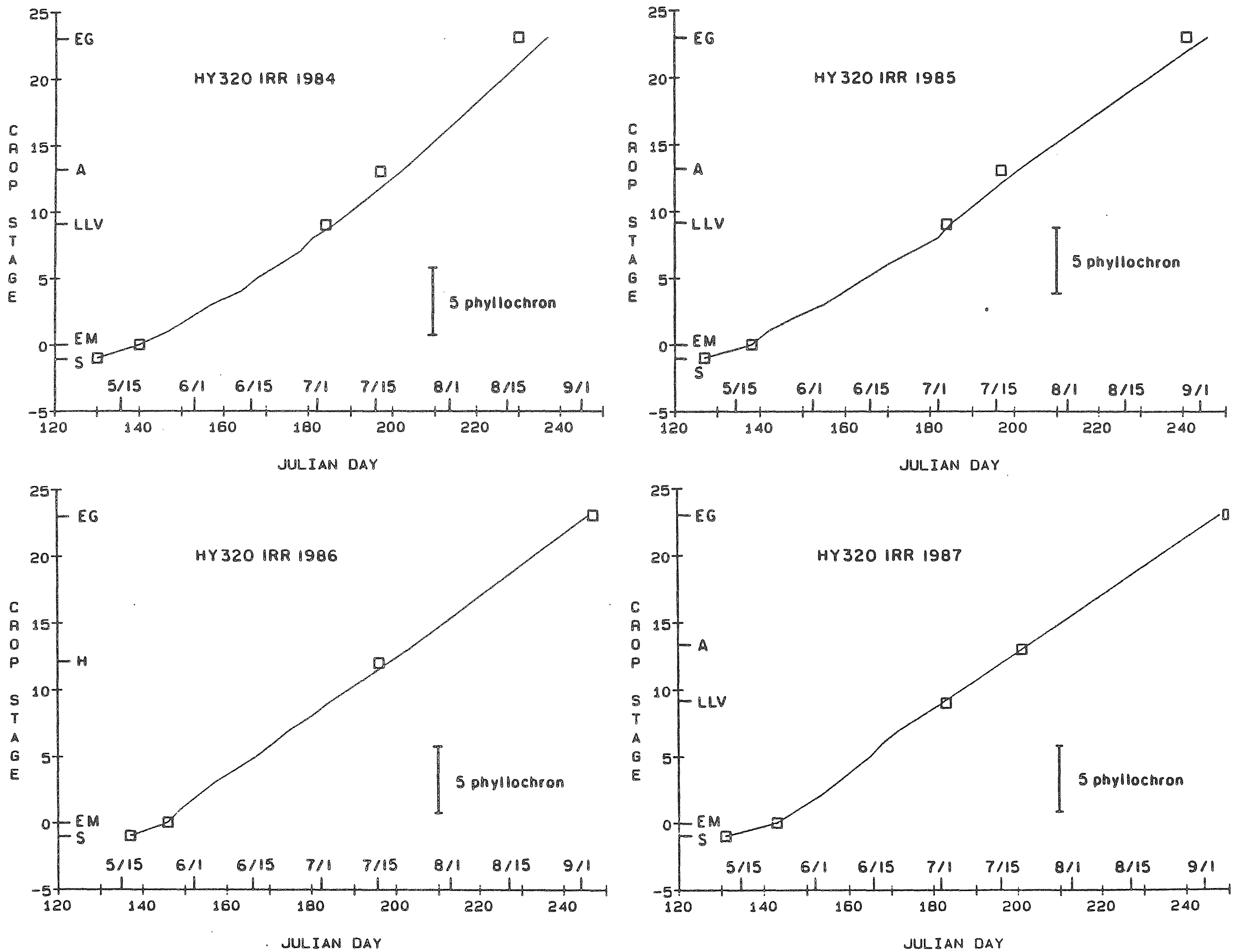

Figure 3. Model predictions of growth stages (——) vs. measured value (□) for HY320 under irrigation: S---Sowing, EM---Emergence, LLV---Ligule last leaf visible, H---Heading, A---Anthesis, and EG---End of grain filling.

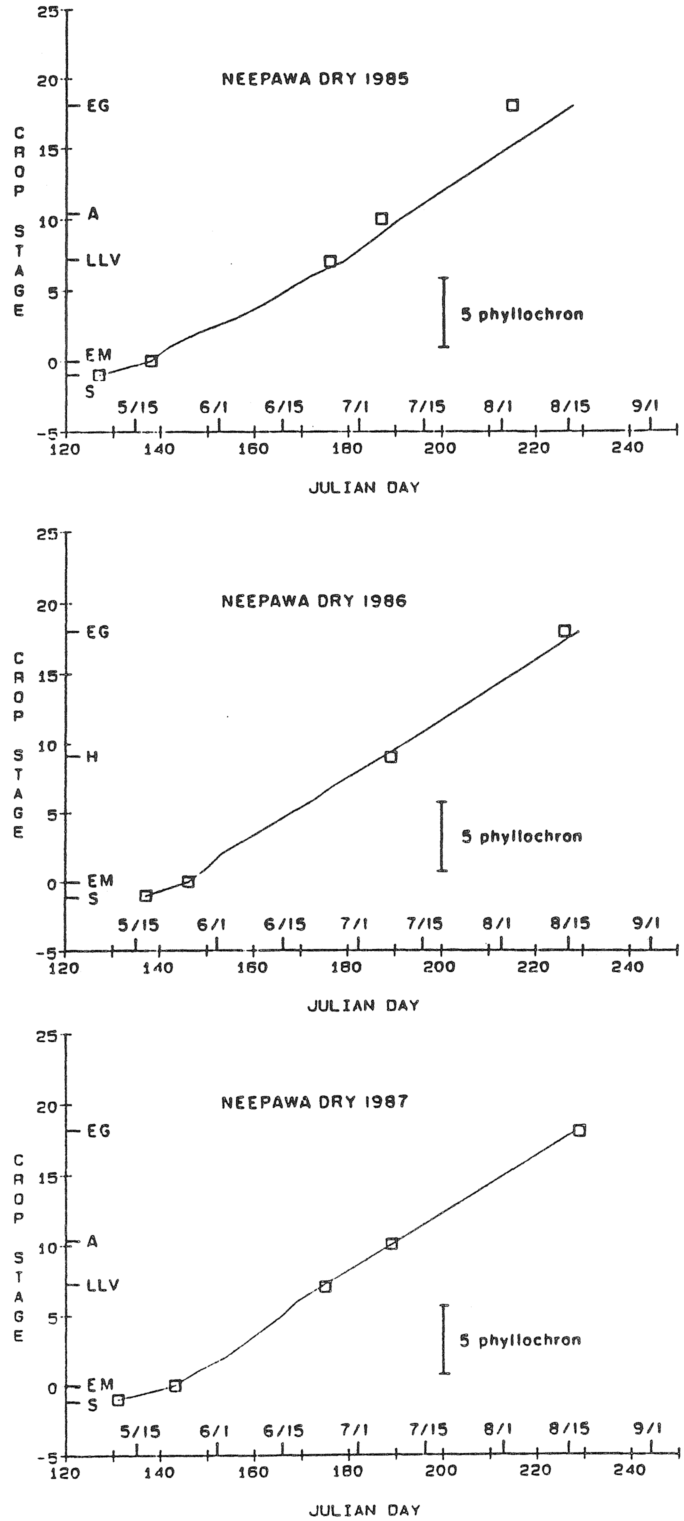

Figure 4. Model prediction of growth stage (——) vs. measured values (◻) for Neepawa under dryland; S---Sowing, EM---Emergence, LLV---Ligule Last Leaf Visible, H---Heading, and EG---End of grain filling.

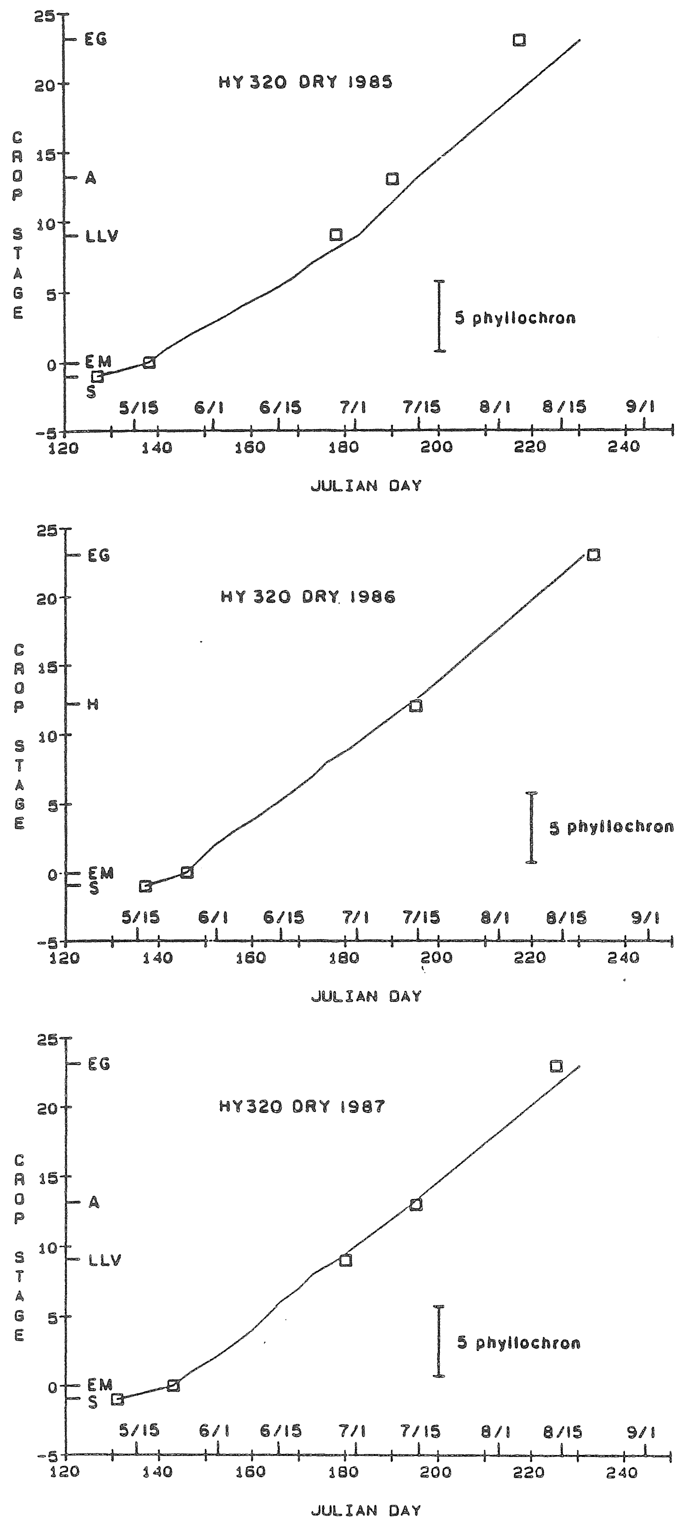

Figure 5. Model prediction of growth stages (——) vs. measured values (□) for HY320 under dryland; S---Sowing, EM---Emergence, LLV---Ligule last leaf visible, A---Anthesis and EG---End of grain filling.

to vary with environmental conditions. This may cause some problems when we want to apply the constants derived from this study to other areas.

The effect of seeding date on phyllochron was reported by Delécolle et al. (1985). They suggested that the rate of daylength change at emergence may affect the rate of leaf appearance. Our data were obtained from experiments with seeding date in mid-May. Thus, application of the model to early or late seeded wheat may cause some errors.

The effect of moisture stress on decreasing phyllochron interval was also reported by Baker et al. (1986). The reduction in phyllochron interval was thought to be the result of the drought-stressed plants accumulating thermal units faster because they were warmer than the well-watered plants.

The effect of drought on canopy temperature has been documented (Waker and Hatfield, 1979; Idso et al., 1981; Jackson, 1982). The difference between the canopy temperature and the air temperature depends on several environmental factors such as soil moisture availability, air vapor pressure, net radiation, and wind speed. Transpirational cooling plays a major role in the energy balance, and therefore in determining plant canopy temperature (Jackson, 1982). In certain condictions, canopy temperature of well-watered plants can be 7 to 9°C lower than air temperature, while canopy temperature of moisture-stressed plants can be 3 to 4°C higher than air temperature. This may explain why our model parameters change for different conditions. The use of air temperatures in meteorologically based plant growth models may cause error in our area. We are now attempting to derive a relationship between air temperature and canopy temperature as influenced by several environmental factors, for use in our area. We hope that when canopy temperatures are used in the model as an index for plant growth the model parameters will be constant and will be applicable to different climates.

CONCLUSIONS

The CERES-wheat model provides a conceptual framework for the formulation and testing of theories regarding plant adaptation to a variable environment. This study showed that by using Haun's Scale, phyllochron interval and the accumulated thermal units enables quantification of wheat growth stage with precision previously unavailable in other methods. Much testing, however, must be done before a complex model of this sort can be considered valid, even in a limited sense.

It is believed that a good model is not one that embodies a perfect depiction of reality, for such is not possible, but one that spurs further efforts toward the acquisition of more knowledge and greater understanding of the system. Only after extensive experimental validation and no doubt after numerous modifications, can a model of this sort eventually become an actual working tool capable of providing guidance in the practical management of the real system.

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