

Dependence of Corn Development from Germination to Silking on Physical  
Environment

by

Herbert Cutforth

A thesis  
presented to the University of Manitoba  
in partial fulfillment of the  
requirements for the degree of  
Doctor of Philosophy  
in  
Department of Soil Science

Winnipeg, Manitoba

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## ABSTRACT

Cutforth, Herbert Wallace. Ph.D., The University of Manitoba, May, 1985. Dependence of Corn Development from Germination to Silking on Physical Environment.

Major Professor: Dr. C.F. Shaykewich, Department of Soil Science.

The effect of physical environment - air and soil temperature, rainfall, photoperiod - on corn development was studied under laboratory and field conditions. Throughout the study, two early maturing hybrids, Pioneer 3995 and Northrup King 403, and one medium maturity hybrid, Pride 1108, were used. Under controlled environment conditions, the duration of germination and emergence phases under varying soil temperature and moisture regimes were studied in two soil types: Almasippi loamy sand and Carroll clay loam. In the field, twelve station years of data were collected from 8 sites throughout central, eastern and south-eastern Manitoba.

Under controlled environment conditions, both germination and emergence rates decreased with decreasing temperature and/or moisture. When soil moisture was expressed as relative available water, the mathematical relationship describing germination rate could be applied to both soils. In the case of emergence rate, one mathematical relationship was adequate for all hybrids in both soils.

During the planting to emergence stage (PE) under field conditions, emergence rates were predominantly controlled by soil temperature, with soil moisture having a minor but significant influence. Accumulated corn heat units (CHU) was a better estimator of stage duration than calendar days but the variability was still very high (coefficient of variation = 20%).

The duration of the emergence to stem elongation stage (ESE) was more closely related to air than to soil temperature. The CHU required for completion of this stage were not constant but increased with the number of days needed for completion. The development models tested were all substantially better estimators of stage duration than calendar days. The best estimator of stage duration of ESE was the iterative model developed during this study and called the IF model.

For the stem elongation to silking stage (SESI), corn heat units were again an inadequate estimator of stage duration because of the dependence of CHU requirement on length of time needed for stage completion. Calendar days was a better estimator of the duration of SESI than were the development models. It appeared that moisture stress significantly influenced the duration of this stage.

For the combined period from emergence to silking (ESI), all development models were more accurate estimators of stage duration than calendar days. However, no model was found to be superior to the CHU model.



#### ACKNOWLEDGEMENTS

I would like to express my appreciation and thanks to a number of individuals without whose support the completion of this project and thesis would not have been possible.

Special mention is extended to my thesis advisor Dr. Carl Shaykewich whose guidance, support and understanding, especially over the last few months of the project, were very much needed and appreciated.

I would like to thank Dr. C. Cho and Dr. W. Woodbury for their helpful suggestions and criticisms during the project; Dr. G. Racz for providing support, both financial and otherwise, when they were needed; Dr. R. Hedlin, Dr. E. Larter and my external examiner, Dr. M. Brown, for reviewing the manuscript; and to the rest of the Department of Soil Science staff and fellow students - Greg, Leesa, Jan Z., Jan M., Monica, Bruce, Don, Jacques, Gordon, Rose, Bill, Jim - for their continued help, concern and support.

Thanks to Lloyd Henders and the Manitoba Corn Committee for their involvement in the project.

I would like to extend my appreciation to the National Science and Engineering Research Council and the University of Manitoba for their financial support.

My family - Mother, Father, Carol and John, Brian, Dauna and Peter - provided much encouragement in times of adversity.

Susan, you were probably the one who not only gave up the most but suffered the most during the project and thesis preparation. For that I am sorry but also very grateful. Thank you.

Last but most definitely not least I would like to offer a very special thank you to members and family involved in The Church of The Way. The last 3 months of the thesis preparation were especially eventful and without the support of the church members and God Himself I'm sure the thesis would not have been completed. Thanks go to John, Brian, Anne, Stan, Ethel, Waldy, Joy and to Alloway group members Kathy, Laura, Steve, Gary, Mitch, Ingrid, Cathy, Rose, Bev, Pam, Miles, Laurie, Shona and especially Dauna, Peter and Lynne. A very special thanks for your prayers and support during an especially difficult and trying time. My prayers are with you always. God bless.

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PART I  
INTRODUCTION

## Chapter 1

### INTRODUCTION

In a previous study of corn growth and development in Manitoba, Tataryn (1974) found that the northerly location of Hamiota required approximately 200 more corn heat units (CHU) than the southerly location of Lyleton. Tataryn further found significant statistical differences between locations and years in the number of heat units required for tasseling and silking. Daynard (1972) found increased accumulated CHU for planting to silking with delayed planting. These studies indicated that the accumulated CHU required for stage completion were not constant but varied with environment.

The purpose of this study was to a) evaluate the CHU equation and compare it to other existing thermal models, b) introduce iterative models that may result in improved accuracy for estimation of stage duration and c) study the influence of air temperatures as well as other environmental variables, such as soil temperature and moisture, on corn development.

To improve accuracy and to quantify the effect of environment on corn phenology, development was studied and analyzed during the planting to emergence (PE) stage under both controlled environment and field conditions; and during the stages emergence to stem elongation (ESE), stem elongation to silking (SESI) and emergence to silking (ESI) for field conditions only.

PART II  
LITERATURE REVIEW

## Chapter 2

### GERMINATION AND EMERGENCE

The duration of the planting to emergence stage can depend on soil temperature, soil moisture and soil aeration. Soil aeration is usually not a problem unless excess soil moisture conditions exist (Wolfe, 1927; Dasberg and Mendel, 1971). For dryland farming, soil temperature and soil moisture are probably the most important environmental conditions influencing germination and emergence of corn.

#### 2.1 SOIL TEMPERATURE

Many controlled environment studies of the effects of soil temperature on the germination and emergence of corn have been conducted. Beauchamp and Lathwell (1967) observed the effects of controlled soil temperature on the early growth of corn. They found days to emergence decreased as soil temperature increased. The relationship between time to emergence and temperature is strongly curvilinear (Warrington and Kanemasu, 1983a; Beauchamp and Lathwell, 1967). However, Warrington and Kanemasu (1983a) found the rate curve (reciprocal of time to emergence versus mean temperature) to be linear between 9 and 30°C. They also concluded that thermoperiodicity (large day/night temperature differentials versus zero day/night temperature differentials) had no marked effect on the length of the emergence stage. Their data also showed that the emergence rates of the two corn belt hybrids used in their



study were equal. Eagles et al. (1983) compared corn belt hybrids used in New Zealand to a yellow dent population developed for highland regions of the tropics. They concluded that the highland populations emerged more rapidly and reliably at low temperatures than did the corn belt hybrids. The differences in emergence times at 20°/15°C were less than one day but were 3 to 4 days at 11°C.

Temperature influences rate of emergence through its effects on germination and shoot growth. Blacklow (1972 a, b; 1973) studied the influence of soil temperature on imbibition, germination, radicle and shoot growth of corn seedlings until emergence. The rate of water uptake (imbibition) was high during the first hours. Even at low temperatures the water content of the seed increased substantially in a short time. Miedema (1982) concluded therefore that temperature would probably not restrict germination by its effects on imbibition.

Blacklow (1972a) showed that elongation of both the radicle and shoot was greatest at 30°C and effectively ceased at 9 and 40°C. The increase in elongation rates of both the radicle and shoot were essentially linear between 9 and 30°C and then decreased rapidly to zero at 40°C. The near constant elongation rate of the primary root was also observed by List (1969). Couchat et al. (1980) observed constant radicle and shoot elongation rates for a temperature regime of 25°/20°C. Other researchers have found varietal differences in the elongation rate of the primary root at low temperatures (Miedema, 1982).

Miedema (1982) found a minimum temperature for germination of about 6°C. He also observed a linear increase in germination rate between 8

and 32°C. Times to 50% germination ranged from 10.6 days at 8° to 18 - 19 hours at 32°C. The minimum shoot elongation rate occurred at a temperature just above 8°C, and the optimum occurred at 32°C. These findings were similar to those of Blacklow (1972b, 1973). Miedema (1982) found that the rate curve could be divided into two linear parts, 8 to 18°C and 18 to 32°C - similar to a division suggested by the data of Lehenbauer (1914). Miedema suggested that shoot elongation was a function of two separate processes, mesocotyl and coleoptile elongation; the former being more temperature sensitive than the latter.

Root direction as well as root length is influenced by soil temperature. Mosher and Miller (1972) studied the effect of soil temperature on the geotropic response of corn roots. They suggested that the soil temperature was the primary factor influencing directional growth. They found roots did not respond to temperature gradients; the roots grew downward regardless of a positive or negative temperature gradient. The angle at which the radicle grew varied from 30° from the horizontal at 18°C to 61° at 36°C. Onderdonk and Ketcheson (1973) found that above and below a constant temperature of 17°C, roots grew in a more vertical direction. They also found the maximum temperature in a fluctuating temperature environment controlled the directional growth of roots. Using a 33°/17°C temperature regime, Sheppard and Miller (1977) found that a single change from 17 to 33°C resulted in more vertical root growth.

Other researchers have observed cardinal temperatures similar to those above for germination (Bierhuizen, 1973; Riley, 1981) and emergence (Warrington and Kanemasu, 1983a; Cooper and Law, 1978). Singh and

Dhaliwal (1972) observed 60% emergence of corn at 40°C but no emergence at either 45°C or 10°C. However, Hough (1972) using linear regression analysis on field data found a base temperature of 5.9°C for emergence. He attached no physiological meaning to this temperature. It was the temperature that gave the best fit of the linear equation to the data. Upon further analysis, he concluded that 10°C was approximately the base temperature for emergence.

In field experiments, various mulch treatments have been used and their effects on soil temperature and emergence have been studied. Miller (1968) compared bare soil to 3 mulches: glass, asphalt and water in clear plastic bags. The differing effects of the mulches on increasing soil temperature - glass > asphalt > water > bare soil - was reflected in emergence rates. In the highland tropics, Cooper and Law (1978) found that a mulch treatment increased soil temperature and decreased time to 75% emergence by 3 days. In England, Iremiren and Milbourn (1979) compared two mulch treatments. Polyethlyene increased soil temperature an average of 4°C over a chalk treatment resulting in a 15 day decrease in time to emergence.

It is important to note that all the above studies were conducted under optimum or near optimum moisture conditions.

## 2.2 SOIL MOISTURE

Although the effects of soil temperature on germination and emergence of corn has been studied extensively such is not the case for soil moisture. In controlled experiments Wolfe (1927) observed a decrease in germination rates with a decrease in soil moisture at 25, 30 and 35°C. Other researchers using field data have alluded to the possible influence of soil moisture on emergence rates. Hough (1972) found soil moisture deficit to be a minor but significant factor influencing emergence rate. Lal (1973) stated that high soil temperature and moisture stress can be serious problems in the tropics. Both forms of stress can act concurrently to decrease both percentage and rate of emergence. Shaw and Thom (1951), Wall and Stobbe (1983, 1984) and Major et al. (1983) have attributed differences in emergence rates unexplained by soil temperature to soil moisture conditions. Major et al. (1983) found calendar days, as opposed to growing degree days (GDD) and corn heat units (CHU) - calculated using air temperatures - to be the best estimator of time to emergence. They concluded that moisture at seed depth, seed depth itself as well as crop residue and soil type influenced the relationship between air and soil temperatures resulting in differing CHU (and GDD) requirements for emergence.

## 2.3 TILLAGE AND SEED DEPTH

Tillage practices and seeding depth can influence the emergence rate of corn. However, in these types of studies it may be difficult to separate the effects of tillage from those attributable to soil moisture and soil temperature. Wall and Stobbe (1983, 1984) studied the effects

of tillage practices (modified versions of zero and conventional tillage) on the soil temperature regime. They found that tillage could have a marked effect on soil temperature but these temperature differences may not be reflected in emergence rates. They indicated there may be confounding effects due to soil moisture and poor seed bed conditions (poor seed - soil contact). Alessi and Power (1971) studied the effects of seeding depth and soil temperature on time to 80% emergence. In controlled studies soil temperature had a much greater effect on emergence than did seed depth; seed depth altering emergence rates only at the lowest temperature ( $13^{\circ}\text{C}$ ). In the field an extra day for each 2.5 cm increment in seed depth was required for emergence. In one experiment 8 days were required for emergence from 7.6 cm whereas 22 days were needed for emergence from 2.5 cm. The difference was attributed to differences in soil moisture stress.

#### 2.4 OTHER FACTORS INFLUENCING GERMINATION AND EMERGENCE

Dasberg (1971) stated that germination is dependent on the rate of seed water uptake, which is determined by the soil water status. Dasberg and Mendel (1971) further concluded that this rate is determined by the matric potential of the soil water, the hydraulic conductivity and the area of contact between the seed and medium. Hadas and Russo (1974a, b) supported the above conclusions but their data also showed that under field conditions the area of water contact would be of minor importance, especially for a relatively large seed such as corn. Williams and Shaykewich (1971) found retarded germination rates and decreased germination percentages of rapeseed with decreasing matric potential. They also concluded that hydraulic conductivity of the soil

system, as compared to a membrane and osmotic system, was a limiting factor in the germination process. In their experiments they used two soil types, a loam and a silty clay, for which there was an order of magnitude difference between respective hydraulic conductivities at low matric potential. However, there were no significant differences between rates for seeds germinated on the two soil types. Similar results were found for germination rates (Pawloski and Shaykewich, 1972) and emergence rates (de Jong and Best, 1979) of wheat seeds planted in various soil types ranging from sandy loam to clay. After reviewing the literature on seed germination, Hadas (1982) concluded that although water potentials and hydraulic conductivity of the soil and of the seeds may affect germination, the limiting influence along the water pathway to the seed is the seed - soil water contact zone and its properties.

## Chapter 3

### EMERGENCE TO SILKING

This stage in corn growth and development can be further subdivided into 3 distinct substages: 1. emergence to tassel initiation (stem elongation), 2. tassel initiation to tassel appearance (tasseling), and 3. tasseling to silking. Before tassel initiation, the apical meristem remains approximately 2 to 3 cm below the soil surface and as such may be strongly influenced by the soil environment at this depth. Very shortly after the apical meristem changes from a vegetative to a reproductive mode (tassel initiation), the stem starts to rapidly elongate moving the now reproductive apical meristem out of the soil into the aerial environment. Because of the position of the apical meristem, prior to stem elongation, three local environments - aerial (shoot), soil surface (apical meristem), subsoil (roots) - may have varying levels of influence on corn growth and development. However, once stem elongation begins and the apical meristem moves above the soil surface, the three local environments may now be combined into two local environments - aerial (shoot) and soil (root). Environmental factors associated with each of the three above environments will determine the rate of development and growth of the corn plant.

### 3.1 SOIL TEMPERATURE

There have been a number of growth room studies dealing with the effects of root temperature on the growth and development of corn plants.

Beauchamp and Lathwell (1966, 1967), using constant root temperatures between 12.5 and 25°C, found that decreasing root zone temperature independent of aerial temperatures increased the duration of the stages used in their study. The duration increased with decrease in root temperature in a curvilinear manner. They also found that the length of the interval from planting to the 2 leaf stage was less affected by low root - zone temperatures than the interval from the 2 to 6 leaf stage. The duration of the 6 to 8 leaf stage was essentially not affected by the root - zone temperature treatments. They concluded that after the 6 leaf stage the apical meristem converted from a vegetative to reproductive phase and with stem elongation, aerial temperatures became more important than root - zone temperatures. They also found the number of leaves at tassel initiation increased slightly with increasing root temperature.

Brouwer et al. (1973) concluded that the temperature of the growing point of the shoot mainly determined the rate of leaf appearance (used as their measure of rate of development). They also found that root temperature controlled the rate of leaf appearance up to the 8 leaf stage, while air temperatures gradually became the controlling factor as the growing point emerged from the soil environment. Once stem elongation had carried the apical meristem away from the influence of the root



temperature, all further development of the inflorescences was controlled by air temperature. They also found that light quality, light intensity and even variations in nutrient supply were of minor importance in determining rate of leaf appearance.

It has been shown that abruptly lowering the root temperature can result in water stress within the plant, lowering leaf growth and extension rates (Watts, 1972; Brouwer et al., 1973). If the temperature drop was not too severe, recovery of both elongation rate and leaf water content could occur gradually through osmotic adjustment (Brouwer et al., 1973) and/or adjustment of root permeability (Miedema, 1982). Miedema (1982) found maize plants reared at root temperatures of 13°C had higher water permeability than plants grown at root temperatures of 20°C. Lowering the temperature of the growing point did not alter the internal water status but could drastically curtail growth and only through release of the temperature stress would recovery occur. Because of these findings it has been assumed by many researchers that root temperature influences the growth of young corn seedlings mainly by affecting the activities of the growing point and additionally by aggravating plant water stress.

The optimum root temperature for leaf and stem growth and extension appears to be between 25 to 30°C. Above this temperature range (Walker, 1969; Lal, 1974) and below this range (Walker, 1969; Watts, 1972) growth rates decreased, i.e., there was a curvilinear response of growth to root temperature. The maximum root temperature for growth varies from 35 to 45°C (Walker, 1969; Lal, 1974). The minimum root temperature for leaf expansion varies from 12.5°C (Barlow et al., 1977) to less than 5°C (Watts, 1972) depending on experimental procedure. Miedema (1982) found

that leaves elongate at temperature less than  $7^{\circ}\text{C}$  but with prolonged exposure to temperatures of  $10^{\circ}\text{C}$  or lower, leaf extension steadily decreased and the apical meristem eventually died.

Watts (1972) found temperature gradients existed within the corn shoot in response to root - shoot temperature differences. With an air/soil temperature regime of  $26^{\circ}/5^{\circ}\text{C}$ , the shoot temperature 1 cm above the soil surface was  $12^{\circ}\text{C}$ ; with temperatures of  $13.5^{\circ}/25^{\circ}\text{C}$ , the shoot temperature was  $21^{\circ}\text{C}$ . The existence of temperature gradients within the plant may have important implications when studying the effect of changing root - shoot temperatures on corn growth and development. The temperature of the apical meristem may be quite different from either the shoot or the root. Watts (1972) measured the apical meristem temperature as the root - shoot temperature environment was changed and leaf extension rates measured. When air temperatures were constant at  $25^{\circ}\text{C}$  and root temperatures varied between 0 and  $35^{\circ}\text{C}$ , the meristem temperature range was between  $10 - 30^{\circ}\text{C}$ ; the same was true when root temperature was held at a constant  $25^{\circ}\text{C}$  and air temperatures were varied between 5 and  $35^{\circ}\text{C}$ . Extrapolation of the meristem temperature curves for both situations yielded base temperatures of between  $10 - 12^{\circ}\text{C}$ , i.e., for the conditions of his experiment, below  $10 - 12^{\circ}\text{C}$  meristem temperature leaf extension rates would be zero.

A number of field trials have been carried out to study the effects of decreased or altered soil temperatures on the growth and development of corn.

Mulching was a common method used to decrease and/or stabilize the soil temperature near the soil surface. In England, Watts (1973) observed the effects of various mulch treatments on soil temperature and corn phenology. The four treatments arranged in order from highest to lowest mean June 5.0 cm soil temperature were glass > black polyethylene > bare soil > perlite. Dates of tassel appearance, anthesis and harvest appeared to be related to this temperature, since they occurred in the same order among treatments. However, between treatments there were only minor differences in the duration (days) from tasseling to anthesis and from anthesis to harvest. Therefore, at stem elongation air temperature may have become the important temperature parameter with the soil temperature differences between the mulch treatments becoming secondary in importance.

It should be noted that for mulch experiments, unless soil moisture levels are monitored and/or controlled, it would be difficult to determine whether moisture, temperature or both, control corn growth. The field plots of Watts (1973) were kept at field capacity. To do so the bare soil plot had to be irrigated 6 times whereas the other plots were only irrigated once.

Other researchers using field experiments similar to those of Watts (1973) have made similar observations. The mulch treatments used by Miller (1968) could be ranked for increased soil temperature at seed depth and also for increased earliness of emergence, silking and harvest in the order: glass > asphalt > water > bare soil. For the very early seeding date, the stage most affected by the mulches was planting to emergence. The duration of this stage was 11, 15, 17, and 27 days for the glass, asphalt, water and bare soil treatments, respectively.

However, for the later seeding date when soil temperatures were less affected by the mulches the duration of planting to emergence was 6, 6, 7, 8 days, respectively. For the next stage, emergence to silking, there was an average 3 to 4 days difference between each successive mulch treatment, i.e., for both early and late seeding silking occurred 3 to 4 days earlier for the glass mulch compared to the asphalt mulch, etc. For both early and late seeding the spread in days between the first and last seedling emerged and the first and last cob silked decreased with increase in average temperature. Similar observations were reported by Iremiren and Milbourn (1979) and Phipps and Cochrane (1975).

Cooper and Law (1978) increased soil temperatures for varying lengths of time by applying a mulch at planting and then removing it at 6 different times: at crop emergence, 1, 2, 3, 4 and 5 weeks after emergence. The number of days from emergence to the 12-leaf stage decreased with increased mulching time up to 3 to 4 weeks after emergence. However, mulching times beyond 3 to 4 weeks did not alter the length of this stage. They concluded that the apical meristem emerged from the soil at this time and was no longer influenced by the enhanced soil temperature caused by the mulches. The number of days from the 12-leaf to tasselling stage was approximately the same for all the mulch trials.

Wall and Stobbe (1984) found tillage practices influenced the soil temperature regime, especially for the surface 10 cm. Zero tillage practices were found to decrease maximum and slightly increase minimum soil temperatures relative to those for conventional tillage. However, these temperature differences were not reflected in days to emergence or

silking. They suggested that soil moisture may have been a confounding factor.

### 3.2 AIR TEMPERATURE

Controlled environments have been used to study the effects of temperature and/or photoperiod on corn growth and development. For a given photoperiod, increasing temperatures from  $< 20$  to  $> 30^{\circ}\text{C}$  will at first decrease and then increase the duration from planting or emergence to tassel initiation (Hunter et al., 1974; Coligado and Brown, 1975a; Breuer et al., 1976; Warrington and Kanemasu, 1983a). The relationship between duration of the stage studied and mean temperature was strongly curvilinear in all the above studies. Warrington and Kanemasu (1983a) found cubic regression equations gave the best fit to their data for both time from planting to tassel initiation and from planting to anthesis. They also found that development rates ( $1/\text{time}$ ) for the two stages increased approximately linearly with temperature from the base temperature to  $28^{\circ}\text{C}$ . Above  $28^{\circ}\text{C}$ , the rates decreased rapidly. For their experiment they found thermoperiodicity did not significantly alter the relationship between rate and mean temperature. Both hybrids used in their studies had the same base temperatures for tassel initiation and anthesis,  $8$  and  $7^{\circ}\text{C}$ , respectively; and both stages had the same optimum temperature,  $28^{\circ}\text{C}$ . Although the cardinal temperatures were similar the earlier hybrid had higher development rates at all the temperatures used in their study. Briefly, the cardinal temperatures were equal and the shape of the rate curves were similar for both hybrids. The only difference between the curves was in the magnitude of the rates at a given temperature.

Coligado and Brown (1975a) divided temperature into two components, mean daily temperature and daily temperature range. Days from emergence to tassel initiation were found to be related to constant temperatures in much the same manner as observed by Warrington and Kanemasu (1983a). Increasing temperatures from 15 to 25°C progressively decreased time to tassel initiation but further increases in temperature from 25 to 30°C did not alter the duration of the stage. Therefore, it was concluded that the optimum temperature was between 25 and 30°C. For the temperature range treatments, temperature ranges of approximately 0, 9, 17°C about mean temperatures of 15, 20 and 25°C were studied. For each mean, days from emergence to tassel initiation increased with increase in range (increase in temperature deviation about mean). The increase in time to tassel initiation with increased range was insignificant at 20°C. Appreciable increase in time occurred at 15 and 25°C only when the range would result in either a minimum temperature,  $T_{min}$ , near or below the base temperature,  $T_{base}$ , or a maximum temperature,  $T_{max}$ , above the optimum (approximately 30°C) (Brown, 1977). Coligado and Brown (1975a) found the response to changes in temperature was hybrid specific. Hunter et al. (1974) reported similar observations with the 4 hybrids of their study. They found that under constant temperature conditions, days from emergence to tassel initiation decreased significantly with temperature increase from 20 to 25°C but that the decrease in time was slight when temperature was increased from 25 to 30°C. The response to temperature increased with increase in maturity rating, i.e., the later the hybrid, the greater the response to a given temperature change.

Struik (1982) found decreased times from emergence to 50% silking as temperatures increased but Struik also observed that the time between 50% anthesis and 50% silking increased with increase in temperature. For a given increase in temperature the decrease in time from emergence to anthesis was greater than the decrease in time from emergence to silking.

Cardinal temperatures have been difficult to determine, especially minimum and maximum base temperatures below and above which development does not occur. Researchers have found maximum development rates for corn under constant or near constant temperature conditions between 25 to 30°C. Deviations from this optimum temperature range will decrease development rate. Warrington and Kanemasu (1983a) found thermoperiodicity did not significantly affect development rate (daylength = 12 h; 12 h at both day and night temperatures) whereas Coligado and Brown (1975a) have concluded that thermoperiodicity can significantly affect development (daylength = 10 h; 10 h at day, 14 h at night temperature).

After emergence, the influence of temperatures below approximately 15°C on development rate is more implied than proven. Hardacre and Eagles (1980) studied the growth of maize populations at constant 13°C (both roots and shoots). They found that all plants grew heterotrophically utilizing seed reserves. However, they found major differences in the ability of the populations to grow autotrophically at 13°C. Although some populations were able to grow very slowly, the three United States corn belt hybrids used in the study did not grow autotrophically at 13°C. Tollenaar et al. (1979) found very poor corn growth at constant 10°C and had to improvise to obtain leaf growth measurements at 10°C. Miedema (1982) and Stevenson and Goodman (1972) found

plants grown at constant  $10^{\circ}\text{C}$ , or under temperature regimes where  $T_{\text{max}} < 10^{\circ}\text{C}$ , eventually died. Taylor and Rowley (1971) found chilling stress damaged the photosynthetic system at daytime temperatures of 10 to  $12^{\circ}\text{C}$ . To study low temperature affects on development rate, alternating temperature regimes have been used where the day temperature may be  $15^{\circ}\text{C}$  or greater with night temperatures below  $10^{\circ}\text{C}$  ( $16^{\circ}/6^{\circ}\text{C}$ ,  $16^{\circ}/11^{\circ}\text{C}$ ,  $23^{\circ}/9^{\circ}\text{C}$  - Warrington and Kanemasu, 1983a;  $15^{\circ}/5^{\circ}\text{C}$ ,  $16^{\circ}/5^{\circ}\text{C}$  - Tollenaar et al., 1979;  $25^{\circ}/8^{\circ}\text{C}$  - Coligado and Brown, 1975a). Development rate may then be estimated for the corresponding mean temperatures (e.g.  $16^{\circ}/6^{\circ}\text{C}$  -  $T_{\text{mean}} = 11^{\circ}\text{C}$ ), assuming thermoperiodicity has negligible influence on development rate (Warrington and Kanemasu, 1983a). Using these methods for low temperature study, researchers have found the base temperature for development to be in the temperature range of  $6$ - $10^{\circ}\text{C}$ .

There have been reports in the literature suggesting that conditions of the previous stage may influence the duration of the next stage. Coligado and Brown (1975a) found increased accuracy in their model to estimate time from planting to tassel initiation when the development rate equation was multiplied by a development potential factor (DP). They assumed that under optimum conditions corn emerges in 5 days. Any delay in emergence after 5 days was considered to decrease the potential for development with the decrease being linearly related to the number of days from planting to emergence minus 5 days. Allison and Daynard (1979) found that temperature conditions from sowing to ear differentiation (SED) would affect the duration from ear differentiation to silking (EDSI). The duration of EDSI decreased as the constant temperature regime of SED increased. This response was cultivar dependent. (A confounding factor in the Allison and Daynard (1979) experiment may have



been the different photoperiods and/or light intensity levels between the two stages studied.)

Landi and Crosbie (1982) studied the response of maize to cold stress (chilling injury) during the vegetative phase. They held corn plants at  $8^{\circ}/3^{\circ}\text{C}$ ,  $10^{\circ}/5^{\circ}\text{C}$ ,  $12^{\circ}/7^{\circ}\text{C}$  day/night temperature regimes for 72 hours and compared these to control plants in a  $16^{\circ}/10^{\circ}\text{C}$  regime. Of the four varieties tested, only one in the lowest temperature regime required significantly more heat units to reach the pollen shedding stage than at the higher regimes. The other varieties were not affected by the temperature stress treatments. Creencia and Bramlage (1971) tested 7 day old corn seedlings for recovery from chilling injury incurred when held from 24 to 36 hours at  $0.3^{\circ}\text{C}$ . No growth occurred at  $0.3^{\circ}\text{C}$  but growth began soon after transfer to  $21^{\circ}\text{C}$ . The chilled seedlings grew at reduced rates during the first 72 hours at  $21^{\circ}\text{C}$  but within 96 hours were growing at the same rate as non-chilled seedlings.

The temperature at the reaction sites (plant temperature) will influence the development and growth of the corn plants. Under controlled environment conditions where light intensities and wind speeds may be low, vapor pressure deficits low and moisture conditions near optimum (compared to field situations) plant temperature may be close to those of the controlled environment. Such may not be the case for field situations. On sunny days the radiation load on a plant at mid-day may be considerably (1.5 to 2 times) more than that experienced by plants in controlled environments. Vapor pressure deficits, wind speeds and moisture conditions may influence the temperature of field grown plants to increase or decrease plant (or canopy) temperature above or below the ambient temperature (Jackson, 1982). Transpirational cooling may play a

major role in the energy balance and temperature control of plant canopies (Jackson, 1982). Choudhury (1983), using simulation modeling, studied the effects of vapor pressure deficit (VPD) on canopy - air temperature difference ( $\Delta T$ ) of corn on clear days. For non-moisture stressed canopies, a linear relationship existed between  $\Delta T$  and VPD; i.e., for  $VPD < 2$  kPa  $\Delta T$  was positive (canopy T greater than air T), for  $VPD > 2$  kPa  $\Delta T$  was negative. With decreasing soil water potential (increasing plant water stress),  $\Delta T$  depended relatively more on wind speed and less on VPD. Gardner et al. (1981a) found corn canopy temperatures to be higher for moisture stressed than non - stressed plants. The midday difference could be as large as  $7^{\circ}\text{C}$  but on average was  $2 - 3^{\circ}\text{C}$ . For the same level in the canopy they found non-stressed canopy temperatures at various positions within the plot to be fairly constant but stressed canopy temperatures varied by up to  $4^{\circ}\text{C}$ . They also found midday temperatures of sunlit leaves of non-stressed and moderately stressed plants to be  $1 - 2^{\circ}\text{C}$  lower than air temperature. Temperature of sunlit leaves in severely stressed plants can be as much as  $4^{\circ}\text{C}$  higher but, on average, were only approximately  $1^{\circ}\text{C}$  higher than air temperatures. However, they also found that corn plants could be subject to water stress and still be cooler than air temperatures.

In a subsequent study Gardner et al. (1981b) did not find phenological differences among the various moisture treatments until the latter part of the silking stage inspite of canopy temperature differences. During the dry - down stage the stressed plants dried and matured earlier than the non - stressed plants. Mtui et al. (1981) found the hybrids of their study had canopy temperatures lower than the daytime air temperatures. With maximum air temperatures close to  $35^{\circ}\text{C}$ , canopy

temperatures were, on average, 2 - 4°C and 1 - 2°C below maximum air temperatures for irrigated and non - irrigated treatments, respectively. Throughout most of the day, the difference between air and canopy temperature was approximately constant. For the non-irrigated corn, the canopy temperature may be slightly higher than air temperature during the night. Mtui et al. (1981) found that daytime temperature differences could be as high as 2 - 3°C and 4 - 6°C for non-irrigated and irrigated treatments, respectively.

### 3.3 PHOTOPERIOD

Generally, for a given temperature, increasing photoperiod increases the duration of emergence to silking, the magnitude of the increase being genotype dependent (Warrington and Kanemasu, 1983a; Rood and Major, 1980; Kiniry et al., 1983b; Francis et al., 1969). For a change in daylength from 10 to > 16 hours, genotype sensitivity had been observed to range from the relatively insensitive (0 to 4 day increase in duration of the stage) to the very sensitive (> 20 day increase) (Francis et al., 1969; Kiniry et al., 1983a). Because of the general response to photoperiod, maize is classified as a short-day plant although some genotypes are day neutral and there have been reports of one or two long day genotypes (Francis et al., 1969; Russell and Stuber, 1983).

Maize genotypes may be sensitive not only to daylength but also to the light intensity used to extend the daylength (or to alter the photoperiod) (Francis et al., 1970; Francis, 1973). Using mostly tropical genotypes, Francis et al. (1970) found the magnitude of the delay in

time to tassel initiation under long day conditions was related to the intensity of light used to lengthen the naturally short day. They also found that some genotypes showed specific threshold intensity levels above which the delay was very pronounced and below which there was less delay or none at all. Some genotypes were relatively insensitive to the level of light intensity and/or daylength. They suggested that there was genetic variation in the critical light intensity needed for a major delay in floral differentiation. They observed increased leaf numbers with increased daylength for the sensitive genotypes. However, leaf growth and development rates were not affected by daylength or intensity levels during the experiment.

The general response of short-day corn plants sensitive to photoperiod can be divided into three regions: optimal, non-optimal, plateau (Rood and Major, 1980). In the optimal region, the corn plant does not respond to increases in photoperiod (above a minimum value) and the duration of the stage remains at a constant minimum (optimum). In the non-optimal region, the corn plant would be responsive to photoperiod; the duration of the stage would increase with increase in photoperiod up to some critical level. Further increases in photoperiod above the critical photoperiod would not result in increased duration of the stage. This would be the plateau region. The photoperiods over which these 3 regions occur, the sensitivity (rate of increase in duration per hour increase in photoperiod) during the non-optimal region, and whether or not the non-optimal and/or plateau regions exist in the response curve have been found to be genotype dependent (Rood and Major, 1980). Corn genotypes insensitive to photoperiod would only have the optimal region in a response curve.

Warrington and Kanemasu (1983a) found increase in photoperiod lengthened both the time between emergence to tassel initiation and tassel initiation to anthesis in a similar almost equal manner for the hybrids used in their study. Breuer et al. (1976) found the hybrid used in their study was sensitive to a change in photoperiod during the emergence to tassel initiation stage but not during the tassel initiation to silking stage.

Struik (1982) studied the effect on reproductive development of a change in the photoperiod regime at various leaf stages. The corn plants were grown under a 12 h photoperiod until a specified leaf stage was reached. Further growth was completed under a 20 hour photoperiod. The experiments were repeated with the photoperiods reversed, i.e., 20 hours first followed by 12 h. Corn plants were also grown under a given photoperiod with no change in photoperiod throughout the experiment. The rate of development of the reproductive organs of the hybrids was retarded by long days, the female inflorescence more so than the male; i.e. for a given increase in photoperiod, time to 50% silking increased more than time to 50% anthesis. The time between anthesis and silking (desynchronization) increased when short days (12 h) were followed by long days (20 h). The opposite was true when long days were followed by short days. The timing of the photoperiod change influenced the duration between anthesis and silking. For the hybrids of Struik's study, alteration of the photoperiod during the 4 - 5 leaf stage resulted in the largest (for 12 --> 20 h change) or the smallest (for 20 --> 12 h change) desynchronization. Therefore the plants were most sensitive to photoperiod at this particular leaf stage, with sensitivity decreasing

on either side of the leaf stage. Also desynchronization increased with increase in constant photoperiod (daylength). These changes were hybrid dependent. Struik (1982) found even European 'day-neutral' hybrids were sensitive to a switch in photoperiod. The data of Struik (1982) indicates that the corn hybrids were sensitive to photoperiod changes after tassel initiation had occurred.

In an experiment similar to that of Struik (1982), Kiniry et al. (1983a) determined the stage over which cultivars in their study were sensitive to photoperiod; the change in the time from seedling emergence to tassel emergence was used as the measure of sensitivity. The cultivars were insensitive to photoperiod just after seedling emergence and remained so until 4 to 8 days prior to tassel initiation. In general, plants remained sensitive to photoperiod until a few days past tassel initiation. These findings are very similar to Struik (1982) who used leaf stage instead of days after seedling emergence to indicate the start of photoperiod sensitivity.

In a field experiment, Rood and Major (1981) found early maturing maize genotypes adapted to northern latitudes ( $49^{\circ}$  -  $51^{\circ}$  N) had an average photoperiod induced delay in flowering time of approximately 1.5 days when grown under photoperiod conditions similar to those of these northern latitudes. For the early maturing maize genotypes of their study they concluded that photoperiod was only of minor importance with regards to development. In a field experiment, Bonaparte (1975) found an average increase in days to silking of approximately 1 day/ $^{\circ}$ latitude North for the three hybrids in his study.

Generally, for photoperiod sensitive genotypes under a given temperature regime, increasing daylength will eventually result in increased final leaf number (Warrington and Kanemasu, 1983c; Allison and Daynard, 1979; Struik, 1982; Tollenaar and Hunter, 1983; Russell and Stuber, 1983). The above studies also show that, as with duration of a stage, the final leaf number attained under a specified photoperiod regime was genotype dependent. Genotypes insensitive to photoperiod have approximately the same leaf number regardless of the photoperiod regime (Hunter et al., 1974). After reviewing the literature Warrington and Kanemasu (1983c) suggested that the final leaf number may be higher under high intensity light conditions as compared to lower light intensity conditions for a given photoperiod. For the hybrid of their study, Tollenaar and Hunter (1983) found final leaf number to be determined by the photoperiod during the 4 - 7 leaf stage (leaf tip just visible from whorl), regardless of temperature. The hybrid used in the study of Struik (1982) was sensitive to daylength changes prior to the 5.5 leaf stage. The hybrids used in these two studies had approximately equal final leaf number and responded similarly to daylength changes. The leaf stage at which the final leaf number of a corn genotype is sensitive to daylength may be genotype dependent but in all cases must occur before tassel initiation as final leaf number would be set when the vegetative meristem becomes a reproductive meristem (tassel initiation). Final leaf number would be determined by leaf initiation rate and duration of the vegetative phase. Because they found only small increases in leaf initiation rate with photoperiod, Coligado and Brown (1975a) and Warrington and Kanemasu (1983b) concluded that increased leaf number with photoperiod resulted from the increased time to tassel initiation.

### 3.4 PHOTOPERIOD - TEMPERATURE INTERACTION

In the studies of the combined effects of photoperiod and temperature on growth and development of corn there is evidence of the interaction of these two environmental factors. The magnitude of the effect on corn growth and development due to a change in one of these factors is dependent upon the level of the other factor. The interactions have been found to be complicated with no definite patterns apparent.

Several studies indicated that as temperatures increase photoperiod sensitivity may decrease; i.e., for a given change in photoperiod, the change in duration of a stage is less at higher than lower temperatures (Hunter et al., 1974; Struik, 1982; Allison and Daynard, 1979; Coligado and Brown, 1975a). Warrington and Kanemasu (1983a) found little change in photoperiod sensitivity with changes in temperature for time from planting to tassel initiation and to anthesis. Struik (1982) found the decrease in photoperiod sensitivity with an increase in temperature was greater for the time from emergence to anthesis than from emergence to silking. Therefore for the anthesis to silking stage, the apparent photoperiod sensitivity increased with an increase in temperature, contrary to the result for the other two stages. Russell and Stuber (1983) found interactions between photoperiod and temperature for the hybrids of their study to significantly influence the time to tassel initiation but not total leaf number. However, they found the relative importance of this interaction to be minor compared to the effect of photoperiod alone. Warrington and Kanemasu (1983a), after reviewing the literature, stated that for United States corn belt hybrids any interaction between temperature and photoperiod is probably small and hybrid specific.



Stevenson and Goodman (1972) found a significant but small interaction between photoperiod and temperature in determining leaf number. They also found a decrease in photoperiod to be much more effective in decreasing leaf number than were changes in temperature. Coligado and Brown (1975a), Struik (1982) and Tollenaar and Hunter (1983) found similar results. Warrington and Kanemasu (1983b) found leaf initiation and leaf appearance rates to be photoperiod sensitive under low temperature (18°C) but relatively insensitive at high temperature (28°C). They also suggested light intensity may be a third factor interacting with photoperiod and temperature affecting the development and growth of leaves. As with development, the effects and magnitude of the effects of the interaction on leaf growth were hybrid dependent.

Because the effects of photoperiod, temperature and their interactions are genotype specific, researchers have been seeking relationships within and between maize genotypes that can be applied across varied environments. Tollenaar and Hunter (1983) found that for the hybrid used in their study, tassel initiation occurred at a leaf stage equal to approximately 50% of the final leaf number. The coleoptile was not counted as a leaf. This relationship seemed to be relatively independent of temperature and photoperiod. Leaf stages were determined as the tip of the leaf emerged from the whorl. Russell and Stuber (1984) used field and controlled environment studies involving a number of maize genotypes to establish a relationship between total leaf number (TLN) and leaf stage at tassel initiation (LSTI). LSTI was defined by the position of the leaf ligules. A leaf was considered to have emerged when its ligule became visible and was as high as the ligule of the next

lower leaf. A highly significant quadratic relationship was developed ( $R^2 = 0.96$ ) with the linear term accounting for 93% of the variation:

$$\text{LSTI} = 1.59 + .02 (\text{TLN}) + .01 (\text{TLN})^2 \quad (1.1)$$

For the genotypes studied, the relationship was reasonably independent of genotype, photoperiod and temperature. For each genotype the relationship between LSTI and TLN was linear with the later genotypes generally having steeper slopes. This would account for the quadratic term in the overall equation. Warrington and Kanemasu (1983a) found, for the steady - state conditions of their experiment, that time to tassel initiation was highly significantly related to time to anthesis ( $R^2=0.98$ ); the relationship being temperature independent. For a number of genotypes grown under varying photoperiods but constant temperature, Kiniry et al. (1983b) found a linear relationship between thermal time (sum of degrees above base temperature =  $8^\circ\text{C}$ ) to tassel emergence (TTte) and thermal time to tassel initiation (TTti). The relationship was highly significant ( $R^2=0.93$ ) and was independent of the genotype studied and photoperiod. The usefulness of these relationships would be in the estimation of tassel initiation from an easily measurable quantity - either total leaf number or time to tassel emergence. To use these relationships, the appropriate definitions of tassel initiation, leaf stage and tassel emergence would have to be used.

### 3.5 SOIL MOISTURE STRESS

The effects of moisture stress on corn phenology have not been studied as extensively as temperature and photoperiod. Bonaparte (1975) found the three hybrids of his controlled environment study were sensitive to periods of moisture stress prior to tassel emergence. The time from planting to tassel emergence was increased with the application of moisture stress; the more severe the stress, the greater the increase. Under constant temperature conditions (of 26°C), there was an interaction between stress and daylength. Daylength was increased from 12 to 16 h by the use of full lighting. For a given degree of stress, the magnitude (days) of the duration of the stage for the 16 h daylength was approximately twice that for 12 h daylength. For the severest stress, the increase in duration was approximately 4 days for the 12 h daylength and 8 - 10 days for 16 h daylength. All three hybrids used in the study responded in a similar manner.

In field experiments, Herrero and Johnson (1981) studied the effects of moisture stress on the interval between tasseling and silking. The stress treatments - control, mild, severe plant water deficits - were started at tassel emergence. The stress treatments did not alter the time between tassel emergence and pollen shed. Although the treatments increased the duration between tassel emergence and silking, the difference between the stress treatments was minor. For the non-stress treatment, silking and pollen shed occurred at approximately the same time. However, for both stress treatments, silking occurred approximately 3 - 4 days after pollen shed (desynchronization). The duration between tasseling and silking was doubled and the interval between pollen shed and silking was increased approximately 5 fold by the stress treatments.

Moss and Downey (1971) found similar results. The two levels of stress at about tasseling time increased the time from anthesis to silking; the duration of the stage was 3, 13 and 16 days for control, medium and severe stress, respectively. In a field experiment on a loamy sand (field capacity =  $.12 \text{ m}^3 \text{ H}_2\text{O}/\text{m}^3 \text{ soil}$ ), Rhoads and Stanley (1973) found maize flowered earlier as irrigation frequency increased. They kept the surface 20 cm at various soil moisture potentials above -200 kPa. The total amount of irrigation water applied varied from 6 cm to 22 cm. From field observations, Shaw and Thom (1951) concluded that moisture conditions do not significantly influence the duration from emergence to tasseling but moisture stress could significantly increase the duration from tasseling to silking. Mallett (1972 - cited by Shaw, 1977) found that severe stress had little effect on the time to tasseling but silking was delayed 6 to 8 days.

Denmead and Shaw (1962) found that for lower potential transpiration rates, relative transpiration (actual/potential transpiration - AT/PT) for corn was maintained over a greater range of soil water contents than for higher potential transpiration rates. Dwyer and Stewart (1984), in a greenhouse study using large pots and sandy loam soil, found AT/PT started to decline, and other stress indicators began to develop, when available soil water was between 40 to 50% of the maximum available water. Using field lysimeters in clay and clay loam soils Ritchie (1973) found the evaporation from a corn canopy to be practically independent of the available water content for all existing conditions of potential evaporation. He concluded from leaf diffusion resistance and leaf water potential measurements that at least 80% of the extractable water in the rooting zone was freely available to plant roots. He

suggested that in the field, root systems are very dynamic and may be able to change their growth patterns and water uptake patterns in response to soil water deficits within the root zone.

Evidence of the dynamic nature of root growth and water uptake was found by Holt and Van Doren (1961). In a two year study with comparable initial moisture conditions, water removal up to the time of tasseling was confined to the upper 60 cm of soil in the year when evaporative demand was low. In the following year when demand was high, water was being removed from the 120 cm depth at tasseling time. The time from emergence to tasseling was similar for both years.

More direct evidence of altered growth patterns by imposed water stress was obtained by Sharp and Davies (1979). Maize plants at the 4 - 5 leaf stage were stressed for 7 days. Leaf growth ceased after 5 days of stress. At the beginning of the experiment leaf growth rate was equal during the light and dark periods (day/night temperature of 25°/25°C - 16 h daylength). However, as stress period progressed, the growth rate decreased at a faster rate during the light than during the dark. On stress day 4, leaf extension rate during the light period was half that during the dark period. Leaf area of the stressed plants decreased almost immediately when compared to the non-stressed plants. However, root growth (both root length and weight) at the end of the 7 day stress period was almost equal for the stressed and non-stressed plants, but the pattern of growth during the stress period had changed. Between days 3 - 5 root growth was substantially higher for the stressed treatment. Maximum root length and weight was achieved by day 5 and remained fairly constant thereafter whereas the non-stressed maize roots grew at fairly constant rates through to the end of the experiment.

There was a shift in growth pattern by the stressed plants in favor of the roots resulting in a brief period where root growth was greater than that of the non-stressed plants.

Bonaparte (1975) found moisture stress had little influence on the final number of leaves. With severe stress leaf number was decreased by approximately one leaf. The decrease was hybrid dependent, some hybrids more affected by a given stress period than others.

During the latter part of the emergence to silking stage, maize has the ability to withstand extended periods of flooding (excess moisture) with little affect on growth or yield. Wenkert et al. (1981) found maize plants grown on a clay loam soil flooded at various times of the year for varying durations (3 - 13 days) with nutrient rich animal waste solution (190 - 370 Kg/ha added N) showed normal growth rates, leaf color and nitrogen content. The recovery of growth rates may be associated with adventitious roots. These roots are short and may be porous enough to allow oxygen diffusion to their meristems from the above ground environment. These roots have high conductivity to water and may be able to supply the plant with water and nutrients as long as they are in contact with nutrient rich water or high moisture soil (Wenkert et al., 1981). Ritter and Beer (1969) found flooding for 96 hours just before tasseling and at silking did not reduce growth in soil with a high N level. Under low N conditions, the reduction in yield was greatest when corn was flooded at tasseling rather than at silking.

### 3.6 SOIL FERTILITY

Bonaparte (1975) found a highly significant increase in duration from planting to tassel emergence under low fertility compared to high fertility conditions. The response was hybrid dependent and the magnitude of the increase was independent of the temperature regime for all the hybrids in the experiment. The increase in duration ranged from 5 to 14 days depending on hybrid. Fertility level had only a minor influence on the total leaf number; the influence increased with temperature and was again, hybrid dependent. The high fertility treatment had an average of 1 - 2 more leaves than the low fertility treatment. By contrast, Hesketh et al. (1969) found changes in nutrient level did not alter final leaf numbers.

Peaslee et al. (1971) found high levels of phosphorus decreased time to silking but had little effect on time from silking to maturity. High levels of potassium decreased time to silking and increased time from silking to maturity.

## Chapter 4

### MODELING CORN DEVELOPMENT

There are many methods that can be used to estimate the duration of a stage during the development of a corn plant. Most of these methods are temperature related and are referred to as thermal or heat unit formulae.

#### 4.1 HEAT UNITS

Most heat unit formulae used in recent years are modifications of the general formula:

$$GDD = [(T_{max} + T_{min})/2] - T_{base} \quad (1.2)$$

where GDD = growing degree day (daily thermal units);  $T_{max}$ ,  $T_{min}$  = daily maximum, minimum temperatures ( $^{\circ}C$ ), respectively;  $T_{base}$  = base temperature ( $^{\circ}C$ ) below which development does not occur (Gilmore and Rogers, 1958; Cross and Zuber, 1972).

Brown (1963, 1969) developed the corn heat unit equation where the contribution of  $T_{max}$  to the daily development was represented by a quadratic equation developed from soybean data (Brown, 1960). The contribution of  $T_{min}$  was assumed to be linear and was represented by a linear equation with a base temperature of  $4.4^{\circ}C$ . The base temperature for  $T_{max}$  was  $10^{\circ}C$ . The corn heat unit equation is of the form:

$$CHU = [3.33(T_{max}-10) - 0.084(T_{max}-10)^2 + 1.8(T_{min} - 4.4)]/2 \quad (1.3)$$



where CHU = corn heat units (daily thermal unit);  $T_{max}$ ,  $T_{min}$  = daily maximum, minimum temperature ( $^{\circ}C$ ), respectively. The optimum temperature for the quadratic is  $30^{\circ}C$ , there is no optimum for the linear ( $T_{min}$ ) equation. When  $T_{max}$  and/or  $T_{min}$  fall below their respective base temperatures, the contribution of the quadratic and/or linear equations to the daily heat unit is assumed to equal zero.

Gilmore and Rogers (1958) found accumulated daily heat units were more reliable than calendar days for predicting silking dates for different planting dates. They used modified forms of equation 1.2 to calculate the daily heat units. Of the equations tested they concluded that the equation modified in the following manner was the best estimator of the time from planting to silking:

$$GDD = [(T_{max} + T_{min})/2] - R - 10 \quad (1.4)$$

where  $T_{min} = T_{min}$  if  $T_{min} > 10^{\circ}C$ ;  $T_{min} = 10$  if  $T_{min} < 10^{\circ}C$ ;  $R = 0$  if  $T_{max} < 30^{\circ}C$ ;  $R = T_{max} - 30$  if  $T_{max} > 30^{\circ}C$ . Cross and Zuber (1972) tested 22 different methods of computing heat units for their ability to account for variation in date of pollen shedding. They found that daily ( $T_{max}$ ,  $T_{min}$ ) temperature measurements gave results approximately as accurate as hourly readings. They found the daily heat stress equation:

$$GDD = [(T_{max} + T_{min})/2] - 10 \quad (1.5)$$

where  $T_{max} = T_{max}$  if  $T_{max} < 30^{\circ}C$ ;  $T_{max} = 30 - (T_{max} - 30)$  if  $T_{max} > 30^{\circ}C$ ;  $T_{min} = T_{min}$  if  $T_{min} > 10^{\circ}C$ ;  $T_{min} = 10$  if  $T_{min} < 10^{\circ}C$  accumulated from planting to pollen shed was the best estimator of this stage. This method was only slightly superior to the corn heat unit equation and the adjusted average equation:

$$GDD = [(T_{max} + T_{min})/2] - 10 \quad (1.6)$$

where  $T_{max} = T_{max}$  if  $T_{max} < 30^{\circ}\text{C}$ ;  $T_{max} = 30^{\circ}$  if  $T_{max} > 30^{\circ}\text{C}$ ;  $T_{min} = T_{min}$  if  $T_{min} > 10^{\circ}\text{C}$ ;  $T_{min} = 10^{\circ}\text{C}$  if  $T_{min} < 10^{\circ}\text{C}$ .

The corn heat unit or growing degree day equations can be used to rate geographic regions (Major et al., 1976; Bunting, 1979) and hybrids (Carter and Poneleit, 1973; Major et al., 1983) according to the heat units available or needed to reach a given stage. One of the assumptions associated with this type of rating is that, for a given hybrid, the same number of heat units are required to reach a given stage regardless of the year or location. Daynard (1972) found accumulated CHU and GDD (equation 1.5) increased for planting to silking and decreased for silking to maturity with delayed planting. However, days for planting to silking and for silking to maturity decreased and increased, respectively, with delayed planting. Peaslee et al. (1971) and Duncan et al. (1973) found approximately equal accumulated heat units for planting to silking with either early or late seeding dates but Peaslee et al. (1971) found decreased heat units for silking to maturity with delayed seeding.

Bunting (1976) found that CHU estimated the duration from planting to silking and from silking to maturity with slightly better precision than did GDD and both were more precise than the use of calendar days. Daynard (1972) concluded that both CHU and GDD were of comparable precision and were better estimators of the duration from planting to silking than were calendar days. However, to estimate the duration from silking to maturity (black layer formation) neither heat unit equation was superior to calendar days. Major et al. (1983) evaluated CHU and various GDD equations for their accuracy in estimating growth stage

duration for hybrids grown across Canada. They found calendar days to be the best estimator of the duration of planting to emergence. Emergence to anthesis was equally predictable by either CHU, calendar days or GDD with any base temperature between 5 to 15°C. From anthesis to 45% ear moisture the heat unit equations were significantly better estimators of the duration of this stage than were calendar days. GDD with  $T_{base} = 8^{\circ}\text{C}$  was a slightly better estimator than either CHU or GDD with  $T_{base} = 10^{\circ}\text{C}$ . Major et al. (1983) found almost constant coefficient of variation for GDD with base temperatures varied between 5 to 15°C used to estimate the duration of emergence to anthesis. This also occurred for the anthesis to 45% ear moisture stage when base temperatures varied from 5° to 11°C. Wang (1960) also reported no improvement in the heat unit system when  $T_{base}$  was varied from 0 to 10°C.

Gardner et al. (1981b) substituted canopy temperature into equation 1.2.  $T_{max}$  was the midday canopy temperature,  $T_{min}$  the minimum canopy temperature and  $T_{base}$  was set equal to 10°C. This method was highly correlated with stage of development and provided an excellent means of estimating the duration of the growth stages.

#### 4.2 OTHER METHODS

Coelho and Dale (1980) represented the relative growth rate curve based on the data of Lehenbauer (1914) by fitting 4 linear equations to various portions of the data. To obtain the relative growth rate curve from the Lehenbauer (1914) data, the maximum seedling extension rate (which occurred at 30-31°C) was divided into the extension rates occurring at the other temperatures (<30°C and >31°C) used in the study. Coelho and Dale (1980) concluded that the use of the 4 regression equa-

tions to estimate maize development (planting to 75% silking) was significantly better than the heat unit equations tested in their study. The procedure of Coelho and Dale (1980) was similar to that used by Gilmore and Rogers (1958) who arrived at much the same conclusion - relative growth rates calculated using Leheubauer's data were slightly better estimators of planting to silking than the heat unit equations.

Daughtry et al. (1984) tested various models for accuracy in estimating silking and maturity dates for corn grown over a large area. The models tested were (a) the model proposed by Coelho and Dale (1980) (called the FT model), (b) equation 1.2 with  $T_{base} = 10^{\circ}\text{C}$ , (c) equation 1.5, (d) equation 1.6 and (e) calendar days. They determined that the thermal models were more accurate than calendar days in estimating silking date but found no significant differences among the thermal models. This contrasts with the report of Coelho and Dale (1980) which indicated that the FT model was superior to the other models. Daughtry et al. (1984) found calendar days was the best estimator of the duration from silking to maturity. There were no significant differences between the thermal models when estimating the time from planting to maturity. When thermal models were used to estimate silking and calendar days were used to estimate the duration from silking to maturity, the accuracy in estimating maturity was increased significantly. There was no significant difference in accuracy among these mixed models.

Coligado and Brown (1975b) developed a bio-photo-thermal model to predict time to tassel initiation. The model incorporated a genetic factor, mean daily temperature, photoperiod, daily temperature range and a development potential factor. The genetic factor was the time

required to reach tassel initiation under optimum environmental conditions -  $T_{\text{mean}} = 25^{\circ}\text{C}$ ,  $T_{\text{range}} = 0^{\circ}\text{C}$ , 10 h photoperiod. Any deviation from these optimal conditions resulted in increased times to tassel initiation. The effects of the three defined variables were assumed to be independent and therefore additive.

The resulting development equation, determined from growth chamber data, was iteratively fit to field data with the use of the development factor. It was assumed that any delay in emergence beyond 5 days resulted in decreased development potentials. The bio-photo-thermal model was found to be slightly more accurate than the CHU or GDD models.

## Chapter 5

### SUMMARY OF LITERATURE

#### 5.1 PLANTING TO EMERGENCE

1. The duration from planting to 50% emergence has been found to be very dependent upon soil temperature. Under optimum moisture conditions the relationship between soil temperature ( $ST \leq 30-35^{\circ}\text{C}$ ) and emergence rate has been found to be approximately linear with a base temperature  $ST_{\text{base}}$ , between 8 to  $10^{\circ}\text{C}$ .

2. Compared to soil temperature, the effect of soil moisture on germination and emergence of corn seedlings has received little attention. It has been suggested that decreased soil moisture availability resulted in slower emergence rates.

3. Environmental factors other than soil temperature may influence the germination and emergence of corn seedlings. Increasing mechanical impedance, and poor soil aeration may decrease rates of germination and emergence. However, in a field situation soil temperature and, to a lesser degree, soil moisture are likely the two most limiting environmental factors affecting germination and emergence.

4. Soil temperature may indirectly control moisture availability by influencing both elongation rates and directional growth of the roots of a corn seedling. However, elongation and direction of root growth are

also directly influenced by mechanical impedance and soil moisture stress.

5. Major et al. (1983) found calendar days, as opposed to growing degree days and corn heat units calculated using air temperatures to be the best estimator of time to emergence.

## 5.2 EMERGENCE TO SILKING

1. Prior to stem elongation, growth room and field experiments have shown that soil temperatures, as opposed to air temperatures, may be the controlling influence on the growth and development of corn. When leaf number or leaf extension rates were used as the measure of phenology, lower soil temperatures resulted in slower development rates.

2. For the emergence to silking stage the temperature response function relating development rate to temperature has been found to be curvilinear. The critical temperatures below and above which development will not occur have been found to be between 6 to 10°C and 35 to 45°C, respectively. The optimum temperature for development is approximately 30°C.

3. Phenological development depends on plant, not air, temperatures. The interaction between the plant and the aerial environment (radiation load and transpirational cooling) influence plant temperature and therefore phenology. Depending upon moisture conditions and evaporative demand, plant temperatures may be significantly higher or lower than air temperatures.

4. Corn hybrids have been found to be either sensitive or insensitive to changes in photoperiod. Increasing photoperiod (daylength) will decrease development rates for sensitive hybrids. For early maturing hybrids adapted to northern latitudes, Rood and Major (1981) concluded that the effect of photoperiod on development was relatively minor.

5. Moisture stress has been found to delay development. From tassel emergence to silking, development is very sensitive to even mild moisture stress. Prior to tassel emergence, moisture stress may or may not delay development. Growth room studies indicate moisture stress may delay development from planting to tassel emergence (Bonaparte, 1975) but field studies suggest that moisture stress may not delay tassel emergence (Ritchie, 1973).

6. The response of hybrids to temperature, photoperiod and moisture stress has been found to be hybrid dependent.

7. Numerous mathematical models involving temperature (thermal models) and/or photoperiod have been tested and used to estimate the development rate of corn. For small geographic regions thermal models have been found to be better estimators of the time from planting or emergence to silking than calendar days (average duration in days of the stage under study). However, Major et al. (1983) found that for large geographic regions (Canada) thermal models were not significantly better than calendar days in estimating the duration from emergence to silking.



PART III

CONTROLLED ENVIRONMENT STUDY

## Chapter 6

### MATERIALS AND METHODS

Three corn hybrids (Zea mays L.), Pioneer 3995, Northrup King (NK) 403 and Pride 1108 were used in this study. Pioneer 3995 and NK 403 are early maturing hybrids while Pride 1108 is a later maturing hybrid for Manitoba conditions. Surface soil of two soil types, Almasippi loamy sand and Carroll clay loam were used as growth media. Moisture characteristic curves were determined for each soil using the pressure membrane method. The upper and lower limits of available water were calculated from the 33 and 1500 kPa gravimetric water contents using the following equations (Shaykewich, 1965):

$$\%FC = 8.28 + 0.654 (33 \text{ kPa } \%) \quad (2.1)$$

$$\%PWP = 0.021 + 0.775 (1500 \text{ kPa } \%) \quad (2.2)$$

Soil characteristics are given in Table 1.

TABLE 1

Soil characteristics for Carroll clay loam and Almasippi sandy loam soils.

Soil Type	Bulk density (Kg/m <sup>3</sup> )	Water Content (m <sup>3</sup> m <sup>-3</sup> ) at			
		33 kPa	FC	1500 kPa	PWP
Carroll CL	1050	.500	.430	.159	.130
Almasippi LS	1380	.268	.356	.052	.056

Water was thoroughly mixed (using a plant mister and cement mixer) with each soil to obtain 5 to 7 water contents distributed within the corresponding available water range. The soil plus water mixture was then stored in covered plastic 6 litre pots in the desired temperature regime for 1 week before planting. The constant temperature regimes were  $15^{\circ} \pm 0.5^{\circ}$ ,  $19^{\circ} \pm 1.0^{\circ}$ ,  $25^{\circ} \pm 0.5^{\circ}$  and  $30.5^{\circ} \pm 0.5^{\circ}\text{C}$ .

Thirty seeds, 10 of each hybrid, were planted in each seed layer. Each seed layer was divided into 3 equal parts, each part occupied by the seeds of one hybrid. The soil - water mixtures were uniformly packed to bulk densities of  $1050 \text{ Kg m}^{-3}$  (clay loam) and  $1380 \text{ Kg m}^{-3}$  (loamy sand).

#### 6.1 GERMINATION

Approximately 5000 g (clay loam) or 6000 g (loamy sand) of soil with the appropriate amount of water were added to the pots. For water contents greater than 50% of the maximum available, 4 layers of seeds (separated by approximately 4 cm of soil) were sown per pot, each water content replicated twice. For the lower water contents, 3 layers of seeds (approximately 6 cm soil separated each layer) were sown per pot, each water content replicated 3 times. At each harvest, 20 seeds of each hybrid (2 layers) were sampled. Those that showed any sign of radicle protrusion through the seed coat were counted as germinated. This allowed 4 individual harvests per water content. At the higher temperatures (25 and  $30.5^{\circ}\text{C}$ ) samplings had to be taken every 6 to 24 hours depending on water content; at the lower temperatures (15 and  $19^{\circ}\text{C}$ ) every 12 to 48 hours. The pots were covered to prevent evaporation and were opened twice daily for aeration purposes.

## 6.2 EMERGENCE

The seeds were sown 5 cm deep in 12 cm of soil. At each temperature, each water content was replicated twice. Four daily emergence counts were made until a constant emergence count for all hybrids was observed for 3 to 7 days. A  $10^0 \pm 1^0\text{C}$  temperature treatment was added for the Carroll clay loam soil.

## 6.3 ROOT LENGTHS

At completion of the emergence phase, the seedlings were carefully removed from the soil - water mixtures and radicle root lengths were measured and recorded.

## Chapter 7

### RESULTS AND DISCUSSION

A controlled environment study of the effects of soil moisture and soil temperature on germination and emergence of corn was undertaken.

The objectives of the study were:

1. to observe the effect of soil moisture and soil temperature on the time to, and rate of, germination and emergence.
2. to mathematically describe the combined influence of moisture and temperature on germination and emergence. A measure of the usefulness of a mathematical equation to estimate the time to emergence would be its versatility - ease of use under varying conditions, such as with different soil types and hybrids. With this in mind, two soil types - an Almasippi loamy sand and a Carroll clay loam - and 3 hybrids - two early maturing hybrids, Pioneer 3995 and Northrup King 403 and one medium maturity hybrid, Pride 1108 - were used in the study.
3. to observe the effect of moisture and temperature on root growth and morphology. The ability of the emerging seedling to meet its water requirements depends to a large degree on the ability of the roots to grow under stress conditions - both moisture and/or temperature. If the roots can grow through the drying surface soil layers to wetter soil layers below, the water status of the seedling will improve. A measure of this ability is root elongation rate.

### 7.1 PLANTING TO 50% EMERGENCE (PE)

Time (hours) to 50% emergence for the different soil temperature - soil moisture combinations are recorded in Table 2. For a given temperature, emergence times increased with a decrease in volumetric water content,  $\theta$ . The difference in emergence times between the highest and lowest  $\theta$  varied from 7 to 14 days, the range increasing with decreasing temperature. For the clay loam soil, seedlings emerged from soil with  $\theta$  less than that at -1500 kPa potential (compare Table 2 with Table 1). However, the emergence times were long and the seedlings much less vigorous than those at the higher water contents.

For a given temperature, NK 403 required less time for emergence than did 1108, followed by 3995. The difference in emergence times between hybrids may occur because of an interaction between seed size, moisture uptake and critical water content needed for germination. Pioneer 3995 is the larger seed, .39 g/seed, compared to 403 and 1108, .25 g/seed. Being the larger seed, 3995 may require relatively more water per seed to reach the critical water content needed for germination than would the two smaller seeds. More time would be needed to take up the extra water thus increasing the emergence time.

For 15°C in the Almasippi loamy sand, the order of hybrids in times to emergence was reversed. Pioneer 3995 now emerged slightly sooner than did 403 or 1108, the difference increasing with decreasing moisture content. The roots of the hybrids were shorter and thicker than those grown at 15°C in the Carroll clay loam. 3995 was less affected by the soil conditions than were 403 and 1108. The roots were similar in appearance to those described by Boone and Veen (1982). Root and shoot

extension rates are influenced by bulk density - moisture potential changes within a given soil (Bilanski and Varma, 1976). Under the conditions of this experiment, the adverse influence of bulk density on the extension rates may not be significant until soil temperatures are low enough; there may be a 3 factor - bulk density, soil temperature, moisture potential (soil strength) - effect on the shoot and root extension rates. This interaction may be hybrid dependent. Visually seedlings of 3995 were more vigorous than those of 403 and 1108, this difference was more noticeable as moisture contents decreased. Seed size, through its influence on seed protein content, has been shown to influence seedling vigor (Bulisani and Warner, 1980). At low temperatures enhanced seedling vigor through larger seed size may result in decreased times to emergence under certain conditions (increased soil strength due to high bulk density).

For a given moisture content, time to emergence increased with a decrease in temperature. For example at field capacity, times to emergence at 30.5°C and 15°C were 2.5 and 11.0 days, respectively. Near the wilting point the time to emergence ranged from 9 to 25 days depending on temperature.

Time to emergence was influenced by both temperature and moisture in approximately the same manner for all 3 hybrids. The variation between the hybrids in times to emergence was generally less than 15%.

The total number of seeds emerging as a function of temperature and moisture are shown in Table 3. Only near the PWP at the lower temperatures did the final emergence percentage decrease. Although there was

TABLE 2

Hours to 50% emergence as a function of volumetric water content and temperature.

Temperature (°C) Hybrid		Volumetric water content (cc water/cc soil)					
Carroll clay loam							
30.5		.436	.341	.286	.215	.184	.149
	Pioneer 3995	63	70	74	90	130	241
	Northrup King 403	56	59	63	85	119	214
	Pride 1108	59	61	65	84	127	242
25			.366	.294	.225	.176	.156
	Pioneer 3995		89	100	124	187	262
	Northrup King 403		82	87	109	161	248
	Pride 1108		85	92	116	169	248
19		.418	.310	.254	.199	.167	.159
	Pioneer 3995	151	164	178	249	351	453
	Northrup King 403	131	146	165	224	305	429
	Pride 1108	135	150	173	248	424	-
15		.335	.315	.238	.200	.186	.161
	Pioneer 3995	284	285	303	385	378	643
	Northrup King 403	269	268	283	361	376	-
	Pride 1108	277	286	292	361	376	-
Almasippi loamy sand							
30.5			.331	.228	.153	.108	.095
	Pioneer 3995		63	70	84	161	186
	Northrup King 403		60	69	86	147	183
	Pride 1108		60	62	82	147	183
25		.346	.225	.152	.120	.091	.086
	Pioneer 3995	85	96	121	147	291	407
	Northrup King 403	74	84	107	137	274	311
	Pride 1108	80	84	105	141	285	-
19			.348	.222	.155	.123	.097
	Pioneer 3995		156	179	192	243	455
	Northrup King 403		142	150	178	239	437
	Pride 1108		145	153	162	213	463
15			.327	.237	.166	.135	.111
	Pioneer 3995		258	285	327	416	543
	Northrup King 403		258	298	356	455	617
	Pride 1108		270	303	381	527	650



TABLE 3

Number of emerged seedlings, out of 20 seeds planted, as a function of temperature and volumetric water content.

Temperature (C)	Hybrid	Volumetric water content (cc water/cc soil)						
Carroll clay loam								
30.5		.436	.341	.286	.215	.184	.149	
	Pioneer 3995	18	20	20	17	17	18	
	Northrup King 403	20	18	20	20	20	18	
	Pride 1108	17	19	16	17	17	14	
25		.366	.294	.225	.176	.156	.129(644)+	
	Pioneer 3995	19	20	20	19	18	0	
	Northrup King 403	19	20	18	20	18	0	
	Pride 1108	18	18	16	16	17	0	
19		.418	.31	.254	.199	.159	.129(1000)+	
	Pioneer 3995	19	19	20	19	20	2	
	Northrup King 403	19	19	20	20	14	4	
	Pride 1108	17	19	19	18	10	0	
15		.335	.316	.238	.2	.186	.161	.156
	Pioneer 3995	20	19	20	15	19	19	16
	Northrup King 403	20	18	19	19	15	12	11
	Pride 1108	15	19	20	15	17	7	5
10(1248 hours)		.374	.326	.279	.200	.167		
	Pioneer 3995	7	2	0	0	0		
	Northrup King 403	5	2	0	0	0		
	Pride 1108	3	4	0	0	0		
Almasippi loamy sand								
30.5		.331	.228	.153	.108	.095		
	Pioneer 3995	17	20	17	18	17		
	Northrup King 403	20	20	19	20	20		
	Pride 1108	19	19	20	20	18		
25		.346	.225	.152	.12	.091	.086(585)+	
	Pioneer 3995	20	20	17	19	17	17	
	Northrup King 403	20	19	20	18	16	17	
	Pride 1108	19	19	18	18	16	9	
19		.348	.222	.155	.123	.097	.079(833)+	
	Pioneer 3995	20	18	16	20	16	10	
	Northrup King 403	20	20	17	17	15	13	
	Pride 1108	16	15	16	17	10	5	
15		.327	.237	.166	.135	.111		
	Pioneer 3995	19	18	18	19	17		
	Northrup King 403	19	18	20	19	15		
	Pride 1108	20	18	17	16	14		

† hours from planting to harvest

some emergence at  $\theta$  below PWP calculated using equation 2.2, the % emergence was very low. At  $10^{\circ}\text{C}$  the % emergence did not reach 50% after 1248 hours (52 days). Until the young seedlings can photosynthesize, the metabolites needed for growth come from the seed reserves. The longer times required for emergence at the low temperature ( $10^{\circ}\text{C}$ ) and low moisture ( $< \theta(\text{pwp})$ ) values may have resulted in respiratory depletion of these seed reserves before emergence could occur. At  $10^{\circ}\text{C}$ , the seeds at the time of sampling (52 days) were small and shriveled. The seedlings had various lengths of shoot and root growth. The maximum % emergence was attained 10 days earlier. It would seem the seedlings had used their seed reserves and were now "not viable".

The inverse of time to emergence is a measure of emergence rate. Before data were used in calculating emergence rate, certain criteria had to be met. At least 14 seedlings had to emerge before the hybrid at the specified moisture - temperature combination would be included in the analysis. This limit was used because an emergence % of at least 70% was thought to be required for economic yields. Also the statistical population would change if the number of seeds emerging was too small.

The rate curves for all 3 hybrids grown in Carroll clay loam and Almasippi loamy sand are represented by Figures 1 and 2, respectively. The rate of emergence was plotted against the volumetric water content. As temperatures decreased, the plateau region of the curves extended to include progressively lower soil moisture contents. As temperatures decrease, moisture may become progressively less significant to the measured growth process (stem extension). The  $Q_{10}$  for the temperature

controlled portion (biochemical) of the emergence processes may be higher than the  $Q_{10}$  for the moisture controlled portion (biophysical). Therefore as temperatures decrease that portion controlled by temperature would decrease at a faster rate than that controlled by moisture. This would cause the plateau region to extend towards lower moisture levels as temperatures decrease. The curves also seem to be approaching approximately the same threshold water content below which emergence rates would be zero.

The shape of the curves suggest an equation of the form:

$$\text{Rate} = R_{\max} (1 - \text{EXP}[-k(\theta - \theta_0)]) \quad (3.1)$$

where Rate = emergence rate  
 $R_{\max}$  = maximum emergence rate at optimum moisture  
 $k$  = rate constant  
 $\theta$  = volumetric moisture content  
 $\theta_0$  = threshold moisture content below which  
 Rate is zero.

$R_{\max}$ , being relatively independent of moisture, would depend on temperature only while the exponential part of the equation would be the reduction factor due to decreased moisture availability.  $\theta - \theta_0$  is in effect the moisture available for emergence.

An iterative procedure employing the Gauss - Newton method of curve fitting was used to calculate  $R_{\max}$ ,  $k$  and  $\theta_0$  in equation 3.1. The derived parameters are listed in Table 4 (p. 58). For a given soil, there was little change in  $\theta_0$  with temperature both within and between hybrids. For the clay loam,  $\theta_0$  was approximately equal to the calculated  $\theta(\text{pwp})$  of Table 1 (p. 46). For the loamy sand,  $\theta_0$  was slightly higher than  $\theta(\text{pwp})$ . The -1500 kPa potential volumetric moisture content

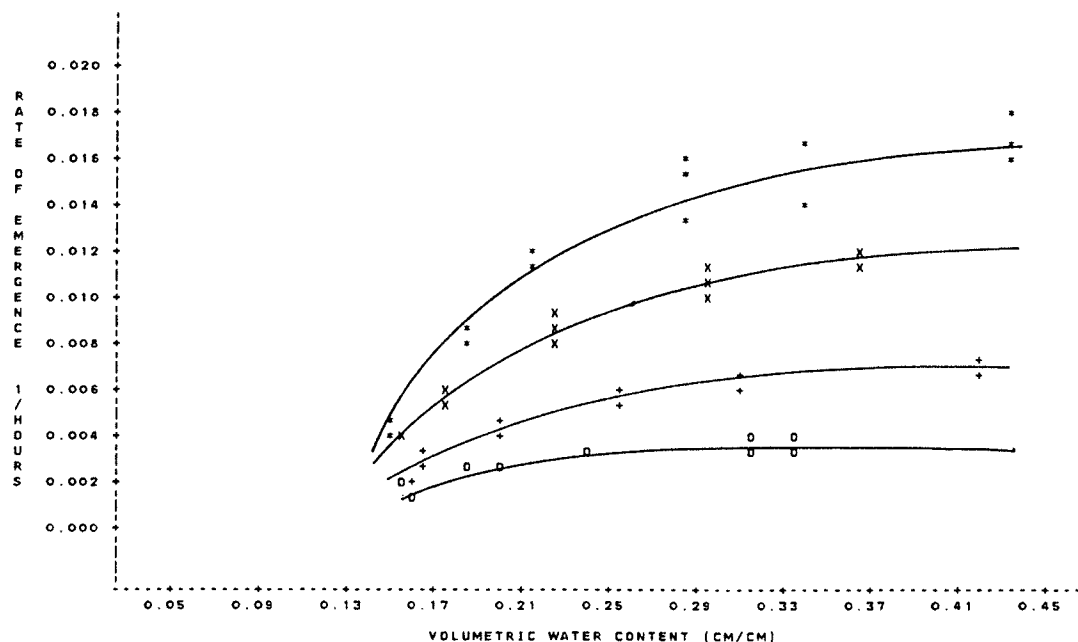


Figure 1: Emergence rate for all 3 hybrids as a function of water content and temperature in Carroll clay loam (\* - 30.5°C, X - 25°C, + - 19°C, O - 15°C).

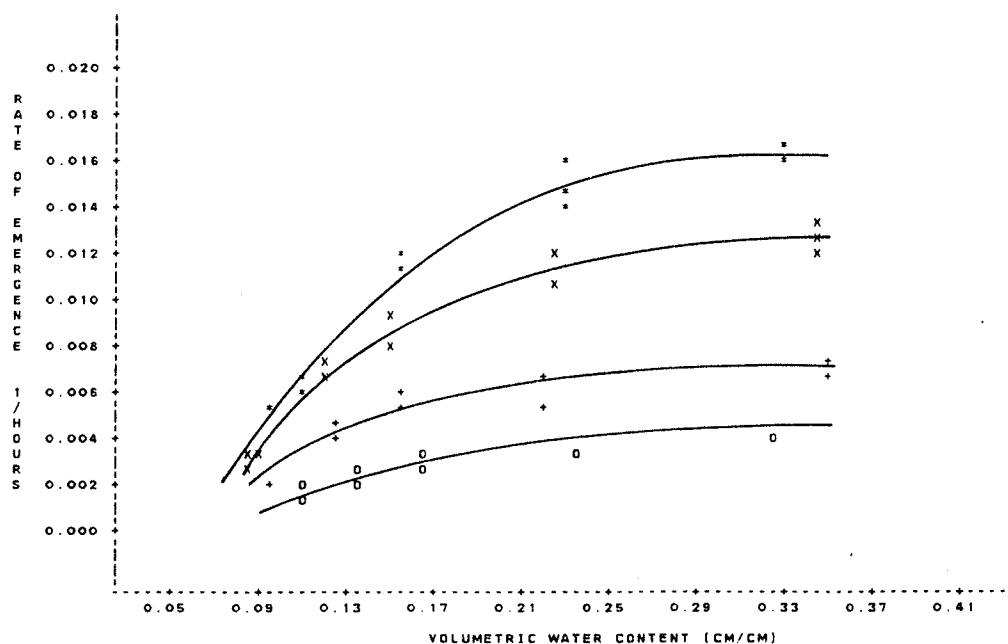


Figure 2: Emergence rate for all 3 hybrids as a function of water content and temperature in Almasippi loamy sand (\* - 30.5°C, X - 25°C, + - 19°C, O - 15°C).

of the clay loam was substantially greater than  $\theta_0$ ; this difference would probably increase with increasing silt and clay content. Based on the close approximation of  $\theta_0$  to the calculated  $\theta(\text{pwp})$ , equation 2.2 was used throughout the rest of the experiment to estimate  $\theta_0$ .

The maximum rates,  $R_{\text{max}}$ , decreased with decreasing temperature (Table 4). For a given temperature and hybrid,  $R_{\text{max}}$  does not differ significantly between soils.  $R_{\text{max}}$  differs slightly between hybrids; 403 emerging slightly faster, under optimum moisture, than 1108 followed by 3995.

The rate constant,  $k$ , is a measure of the changing slope with increase in moisture from  $\theta_0$ . Larger  $k$  indicates steeper curves. Any factor influencing the availability or movement of water to the roots or seed and any factor influencing the response of the seedling to this available water would affect the magnitude of  $k$ . For a given change in water content, the rate of change in both water potential and hydraulic conductivity will help determine availability and therefore influence  $k$ . These rate changes with water content are probably soil dependent. The faster these changes occur, the steeper will be the slope of the rate curves - larger  $k$  values.

These changes are likely to be hybrid specific. Temperature influences both the physical properties of water and the biological processes involved in growth and development. Viscosity and surface tension increase with a decrease in temperature resulting in decreased flowability and increased water contents at a given potential (Taylor and Ashcroft, 1972; Constantz, 1982). These changes are also soil (texture) dependent. However such physical changes may not be as important as the

TABLE 4

Threshold volumetric water content,  $\Theta_0$ , rate constants,  $k$ , and maximum rate of emergence,  $R_{max}$ , as obtained by iterative fitting of the model  
 $R_{emer} = R_{max}\{1 - \exp[-k(\Theta - \Theta_0)]\}$ .

Hybrid	Temperature (°C)	$\Theta_0$ (m <sup>3</sup> m <sup>-3</sup> )		$k$		$R_{max}$ (hr <sup>-1</sup> )	
		Carroll	Almasippi	Carroll	Almasippi	Carroll	Almasippi
Pioneer 3995	30.5	.124	.069	11.77	14.82	0.0160	0.0161
	25	.118	.069	9.96	15.62	0.0122	0.0117
	19	.125	.077	12.80	23.15	0.0068	0.0062
	15	.128	.067	20.41	14.26	0.0036	0.0039
Average		.124	.071	13.74	17.00		
Northrup King 403	30.5	.124	.064	10.79	11.93	0.0187	0.0173
	25	.127	.067	13.30	13.55	0.0128	0.0137
	19	.125	.078	11.38	20.06	0.0079	0.0071
	15	.136	.064	23.10	10.98	0.0038	0.0041
Average		.128	.068	14.64	14.13		
Pride 1108	30.5	.129	.072	12.37	15.15	0.0176	0.0173
	25	.122	.073	11.51	17.58	0.0125	0.0127
	19	.136	.085	11.78	31.66	0.0077	0.0068
	15	.134	.065	24.44	9.99	0.0036	0.0040
Average		.130	.074	15.03	18.60		
Overall Average		.127	.071	14.47	16.50		

biological responses to temperature. Given time, the seedlings may be able to adjust or adapt to the new temperature environment. There are reports in the literature of increased permeability of roots with decrease in temperature (Miedema, 1982). The literature review of Miedema (1982) indicated the confusion that exists among researchers with regards to the response of corn seedlings to low temperature treatments. The conflicting findings are an indication of the adaptability of plants to changing environmental conditions. Mechanical impedance (soil strength) can also influence the response of roots and shoots to changing soil moisture conditions (Bilanski and Varma, 1976; Boone and Veen, 1982). There is also evidence in the literature that plants can adjust in some degree to moisture stress through osmotic adjustment (Turner, 1980). This response to moisture stress is cultivar specific as, probably, is the response to temperature.

Generally at the 3 higher temperatures,  $k$  values for the clay loam were lower than those for the loamy sand. This may in part have reflected the pore size distribution. The sandy loam would have larger water holding pores than the clay loam. These larger pores would empty abruptly with decreasing potential and this would result in steeper slopes for the emergence rate curves, i.e. larger  $k$  values. At 15°C the reverse occurred,  $k$  being larger for the clay loam soil. If there is an interaction of bulk density, temperature, and moisture potential affecting the growth of corn seedlings at low temperatures, this may help explain the observations regarding  $k$  at 15°C. The sandy soil had a bulk density of 1380 Kg/m<sup>3</sup> which may have, under the conditions of this experiment, approached the limiting bulk density for unhindered seedling growth and development (Taylor and Ashcroft, 1972). The differences in

root morphology among seedlings grown in the clay loam and those in the loamy sand may give an indication of the ability of roots to extract water from the soils. Roots from the sandy soil were short, thick and had little, if any, branching and root hairs. Those from the clay loam were longer, thinner, were more branched and had much more root hair growth than those from the sandy soil. Because of the increased root growth (length and root hairs) of the roots from the clay loam, water would be relatively more available to these seedlings than those grown in the sandy soil. The seedlings from the sandy soil probably had to rely more on the movement of water from the bulk soil to the roots and less on the ability of roots to proliferate in areas of greater water availability.

For a given hybrid, the rate curves for both soils were plotted as a function of relative available water. Relative available water was defined as:

$$RAW = \frac{\theta - \theta(pwp)}{\theta(FC) - \theta(pwp)} \quad (3.2)$$

where RAW = relative available water

$\theta$  = existing volumetric water content

$\theta(FC)$  = calculated volumetric field capacity

$\theta(pwp)$  = calculated volumetric permanent wilting content.

The curves for the 3 hybrids - Pioneer 3995, NK 403, Pride 1108 - are represented by Figures 3, 4 and 5, respectively. For a given temperature, the rate curves from the two soil types correspond very closely. This was similar to the findings of de Jong and Best (1979) in their study of wheat emergence. The rate curves were mathematically described by an equation of the form:

$$Rate = Rmax \{ [1 - EXP(-S RAW)] \} \quad (3.3)$$



where Rate = emergence rate  
 Rmax = maximum emergence rate (optimum moisture)  
 S = rate constant  
 RAW = relative available water (equation 3.2).

The derived parameters of equation 3.3 are shown in Table 5. As previously stated, Rmax was strongly dependent upon temperature and only slightly dependent upon hybrid. Decreasing temperature decreased Rmax. The rate constant, S, increased slightly with decreasing temperature, reflecting both the changing properties of water and the water - matric medium and the changing biological responses to water availability. The rate constants at each temperature did not differ substantially among hybrids.

Because of the similarities in Rmax and S among hybrids, the rate curves for the hybrids were plotted together on a single graph (Figure 6). Equation 3.3 was again used as the model for the relationship between rate of emergence and relative available water. The parameters are listed in Table 5. As before, Rmax decreased substantially and S increased slightly with decrease in temperature. The equations fit the data very well -  $R^2 \geq .99$ .

The values of Rmax for the individual hybrids and for the combined data (Table 5) were plotted versus temperature (Figure 7). The relationships were best described by linear equations of the form:

$$R_{\max} = (1/H_{50}) (T - T_{\text{base}}) \quad (3.4)$$

where Rmax = maximum rate (under optimum moisture)  
 T = temperature ( $^{\circ}\text{C}$ )  
 Tbase = base temperature (below which emergence rate is zero)  
 H<sub>50</sub> = degree-hours to 50% emergence.

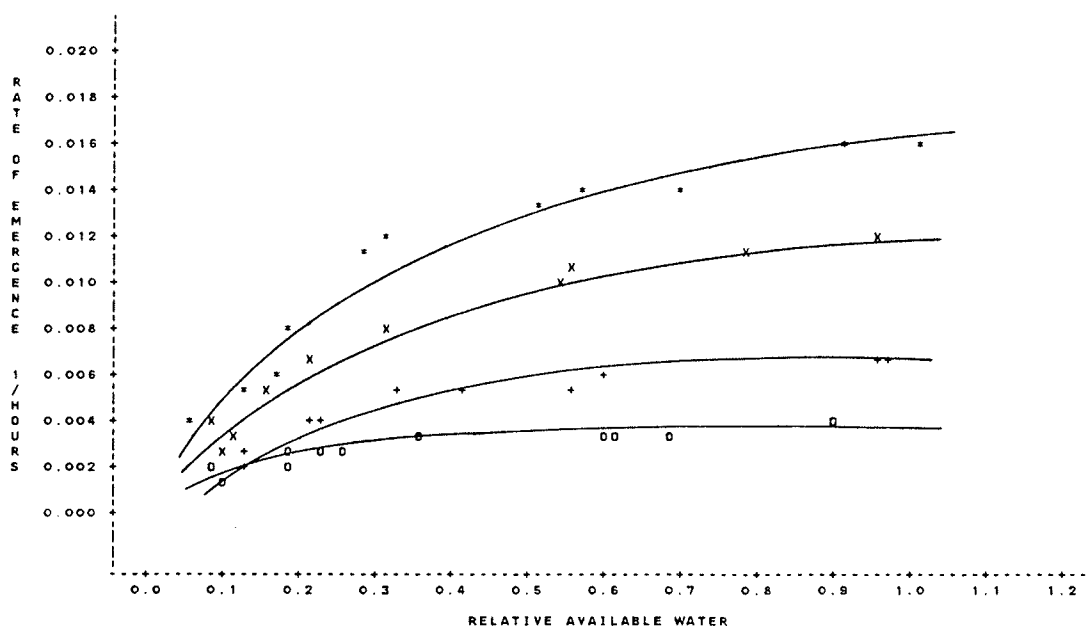


Figure 3: Emergence rate of Pioneer 3995 as a function of relative available water and temperature in both soils (\* - 30.5°C, X - 25°C, + - 19°C, O - 15°C).

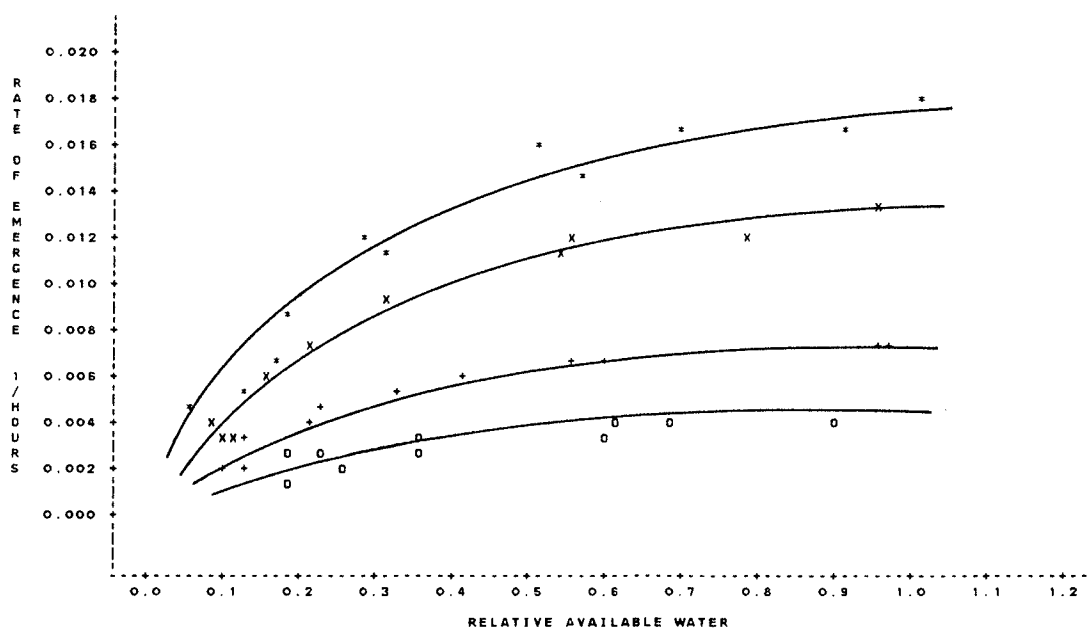


Figure 4: Emergence rate of Northrup King 403 as a function of relative available water and temperature in both soils (\* - 30.5°C, X - 25°C, + - 19°C, O - 15°C).

TABLE 5

Maximum emergence rate (Rmax) and rate constant (S) for each hybrid-temperature combination for the model:

$$\text{Remer} = \text{Rmax}\{1 - \exp[-S \text{ RAW}]\}.$$

Temperature	Rmax (h <sup>-1</sup> )	Ratio†	S	R <sup>2</sup>
Pioneer 3995				
30.5	.0163	.36	3.60	0.99
25	.0121	.38	3.53	0.99
19	.0066	.31	4.13	0.99
15	.0037	.25	5.12	0.99
Northrup King 403				
30.5	.0182	.26	3.30	0.99
25	.0136	.21	3.51	0.99
19	.0076	.22	3.78	0.99
15	.0039	.17	4.31	0.97
Pride 1108				
30.5	.0179	.29	3.43	0.99
25	.0128	.26	3.84	0.99
19	.0075	.24	3.74	0.99
15	.0037	.22	4.30	0.98
ALL HYBRIDS COMBINED				
30.5	.0175		3.44	0.99
25	.0128		3.62	0.99
19	.0072		3.88	0.99
15	.0037		4.61	0.99

† Ratio = Ratio of Rmax for emergence divided by Rmax for germination.

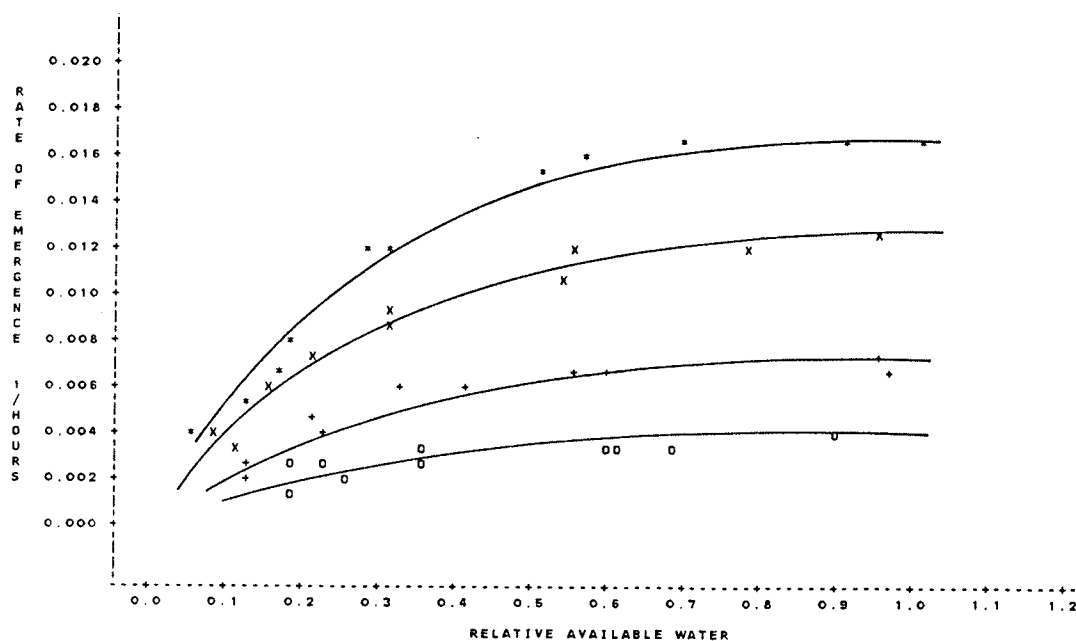


Figure 5: Emergence rate of Pride 1108 as a function of relative available water and temperature in both soils (\* - 30.5°C, X - 25°C, + - 19°C, O - 15°C).

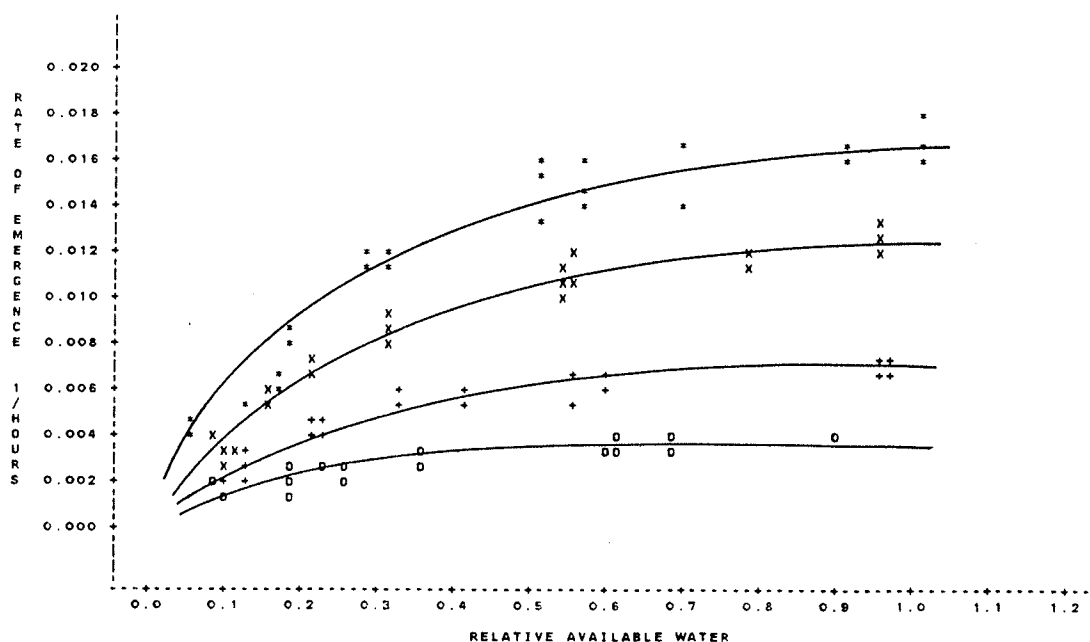


Figure 6: Emergence rate for all 3 hybrids as a function of relative available water and temperature in both soils (\* - 30.5°C, X - 25°C, + - 19°C, O - 15°C).

The parameters for equation 3.4 as they relate to emergence are shown in Table 6. This relationship was similar to those reported for field data (Hough, 1972; Feddes, 1972) and controlled environment data (Warrington and Kanemasu, 1983a). The base temperatures,  $T_{base}$ , for the different hybrids were essentially equal to  $10.8^{\circ}\text{C}$ . At  $10^{\circ}\text{C}$ , the total emergence percentage after 52 days was less than 40%, lending support to the above determined base temperature.

$T_{base}$  was close to that reported in the literature (Cooper and Law, 1978; Warrington and Kanemasu, 1983a). The differences that occur among the reported base temperatures may be because of the different definitions of emergence and different seeding depths. A seeding depth of 5 cm was used in our experiments. Warrington and Kanemasu (1983a) used a seeding depth of 2.5 cm and obtained a base temperature for 50% emergence of  $8.9^{\circ}\text{C}$ . In our studies 50% emergence did not occur at  $10^{\circ}\text{C}$  with a seeding depth of 5 cm. However, emergence as defined would have occurred if the seeding depth were 2.5 cm. For each hybrid at the highest  $\theta$ , more than 14 of 20 seeds had greater than 2.5 cm of shoot growth. Therefore seeding depth may determine  $T_{base}$  for emergence. There were slight differences in slope between the hybrids but the relationship of  $R_{max}$  versus temperature was adequately described using the combined data for all 3 hybrids ( $R^2=0.99$  - Table 6).

The inverse of the slope divided by 24 is equivalent to the (growing) degree - days needed for emergence ( $H_{50}$  (DAY-C) in Table 6).  $47^{\circ}\text{C-day}$  above  $10.8^{\circ}\text{C}$  was needed for emergence. Warrington and Kanemasu (1983a) reported degree day requirements for the hybrids of their study to be approximately  $62.5^{\circ}\text{C-day}$  above  $9^{\circ}\text{C}$ . Their times for emergence were measured to the nearest day, ours to the nearest hour.

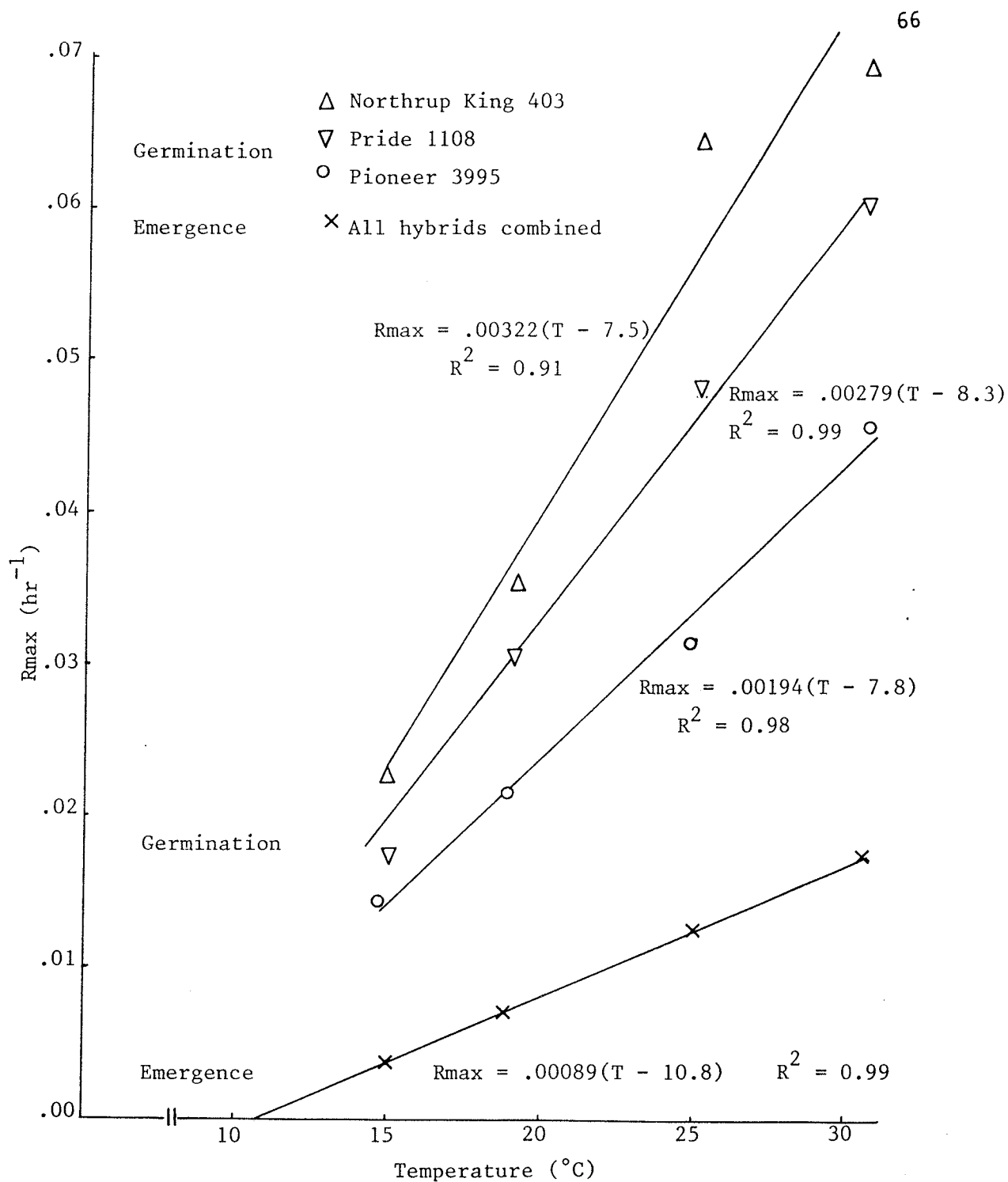


Figure 7: Maximum germination and emergence rates as a function of temperature.

TABLE 6

Parameters for the equations describing the relationships of the maximum rates,  $R_{max}$ , to temperature.  $R_{max} = (1/H_{50}) (T - T_{base})$ .

Hybrid	$1/H_{50}$ (h-C) <sup>-1</sup>	$H_{50}$ (DAY-C)	$R_{max}$ $T_{base}$ (°C)	$R^2$
planting to 50% germination				
3995	.00194	21	7.8	.98
403	.00322	13	7.5	.91
1108	.00279	15	8.3	.99
planting to 50% emergence				
3995	.00082	51	10.6	.99
403	.00093	45	10.8	.99
1108	.00091	46	10.9	.99
combined	.00089	47	10.8	.99
50% germination to 50% emergence				
3995	.00136	31	11.6	
403	.00127	33	11.4	
1108	.00132	32	11.5	

The values of the rate constant,  $S$ , showed a definite increase with decreasing temperature (Table 5). The regression equation expressing this relationship is:

$$S(PE) = 8.1965 - 0.3229 T + 0.0055 T^2 \quad R^2 = 0.99 \quad (3.5)$$

in which  $T$  is temperature in degrees Centigrade. If one examines the model (equation 3.3), one observes that  $S$  occurs in the negative exponential, and thus as soil temperature decreases, emergence becomes less sensitive to changes in relative available water.

The equations used to describe the rate curves are listed in Table 7. The emergence rate for all the soils and corn hybrids used in this study can now be adequately described by a single function of temperature and moisture.



TABLE 7

Equations used to describe the relationship of germination and emergence to temperature and moisture.

$$\text{Rate} = R_{\max} \{1 - \exp[-S \text{ RAW}]\}$$

$$R_{\max} = (1/H_{50}) (T - T_0)$$

$$S(\text{PE}) = 8.1965 - 0.3229T + 0.0055T^2$$

$$S(\text{PG}) = mT + d$$

$$\text{RAW} = [\theta - \theta(\text{pwp})] / [\theta(\text{FC}) - \theta(\text{pwp})]$$

$$\theta(\text{FC}) = \text{BD} [(1/100) (8.28 + 0.654(33 \text{ kPa}\%))]$$

$$\theta(\text{pwp}) = \text{BD} [(1/100) (0.021 + 0.775(1500 \text{ kPa}\%))]$$

where BD = bulk density

33 kPa % = 33 kPa gravimetric water content as %

1500 kPa % = 1500 kPa gravimetric water content as %

RAW = relative available water

S(PE) = rate constant for emergence with all hybrids combined

S(PG) = rate constants for germination for each hybrid  
separately

R<sub>max</sub> = maximum development rate (at optimum moisture)

Rate = development rate (as function of T and moisture).

## 7.2 PLANTING TO 50% GERMINATION (PG)

Time (hours) to germination for Carroll clay loam (CL) and Almasippi loamy sand (LS) are shown in Table 8. For both soils a decrease in temperature and/or moisture content increased times to germination. Comparing Table 2 (p. 52) with Table 8, approximately 20 to 40% of the time to emergence involved the germination process. The percentage varied with hybrid, temperature and to a lesser degree,  $\theta$ . Generally less time was needed for germination of 403 compared to 1108 while 3995 required the longest time to germinate. Pioneer 3995 was the larger seed, .39 g/seed compared to .25 g/seed for both 403 and 1108. Apparently, longer times may be needed to take up enough water to start the germination process. For the clay loam soil, at the lower temperatures and higher moisture contents there were slight delays in germination of 403 and 1108 but not 3995 as moisture content increased. The delay may indicate aeration problems for the smaller seeds at low temperatures and high moisture levels.

The inverse of time to germination is the germination rate. The same procedures used to mathematically describe the rate curves for emergence were used to describe the germination rate curves. An example of the rate curves for germination is given in Figure 8. The shapes of the curves resemble those for emergence. The parameters obtained when equation 3.1 was iteratively fitted to the data are listed in Table 9.  $\theta_0$ ,  $k$  and  $R_{max}$  behave similarly to those for emergence. For a given soil  $\theta_0$  increased slightly with a decrease in temperature but, as was the case with emergence,  $\theta_0$  can be estimated with equation 2.2.  $\theta_0$  for the loamy sand was greater than the corresponding -1500 kPa  $\theta$ , while  $\theta_0$  for the

TABLE 8

Hours to 50% germination as a function of volumetric water content and temperature.

Temperature (°C)		Hybrid	Volumetric water content (cc water/cc soil)					
Carroll clay loam								
30.5			.405	.302	.264	.205	.156	.126
	Pioneer 3995		25	25	29	36	61	133
	Northrup King 403		15	16	18	24	45	114
	Pride 1108		18	19	22	29	53	158
25			.430	.321	.278	.222	.170	.137
	Pioneer 3995		31	33	37	45	58	116
	Northrup King 403		17	17	19	27	46	123
	Pride 1108		23	26	30	37	65	123
19			.440	.316	.272	.214	.173	.140
	Pioneer 3995		47	45	54	57	94	179
	Northrup King 403		32	28	35	39	60	149
	Pride 1108		37	34	43	52	91	171
15			.413	.315	.271	.215	.171	.137
	Pioneer 3995		65	72	77	86	133	-
	Northrup King 403		54	50	48	57	97	426
	Pride 1108		67	62	60	81	135	-
Almasippi loamy sand								
30.5			.352	.210	.134	.106	.087	
	Pioneer 3995		22	21	40	48	73	
	Northrup King 403		15	17	20	36	57	
	Pride 1108		18	21	30	41	75	
25			.342	.227	.146	.126	.104	
	Pioneer 3995		33	35	43	56	72	
	Northrup King 403		17	19	26	35	48	
	Pride 1108		22	25	40	47	66	
19			.324	.235	.161	.104	.081	
	Pioneer 3995		49	50	55	100	180	
	Northrup King 403		28	31	34	66	151	
	Pride 1108		33	36	43	90	186	
15			.368	.222	.146	.115	.097	
	Pioneer 3995		70	74	86	121	172	
	Northrup King 403		41	42	53	85	123	
	Pride 1108		57	61	68	106	168	

clay loam was substantially less than the corresponding  $-1500 \text{ kPa } \theta$  reflecting the influence of hydraulic conductivity on the biological permanent wilt point.  $\theta_0$  for germination was approximately equal to  $\theta_0$  for emergence.

The rate constant,  $k$ , generally increased with decrease in temperature. The rate constants for the loamy sand were generally slightly greater than those for the clay loam, suggesting an influence of texture on the rate constant. On the whole, the rate constants for germination were not significantly different from those for emergence. However, the rate constants at  $15^\circ\text{C}$  for the loamy sand were very different. During germination there may be relatively little biological growth able to respond to changing soil environmental conditions. Interaction among growth, temperature, moisture, and bulk density would not be limiting during the germination stage. Temperature and moisture availability limit germination but under the same conditions soil strength may be a third limiting factor affecting emergence. These combined limitations would influence the slope of the rate curves and therefore the magnitude of  $k$ .

$R_{\max}$  decreased with decreasing temperature. For a given hybrid and temperature,  $R_{\max}$  was reasonably independent of soil type. For a given temperature the differences in  $R_{\max}$  between hybrids was substantial. This was contrary to results obtained for emergence.

As was done for emergence, the rate curves of both soils were plotted together on the same graph, a separate graph for each hybrid (e.g. Figure 9). Germination rate was plotted as a function of relative

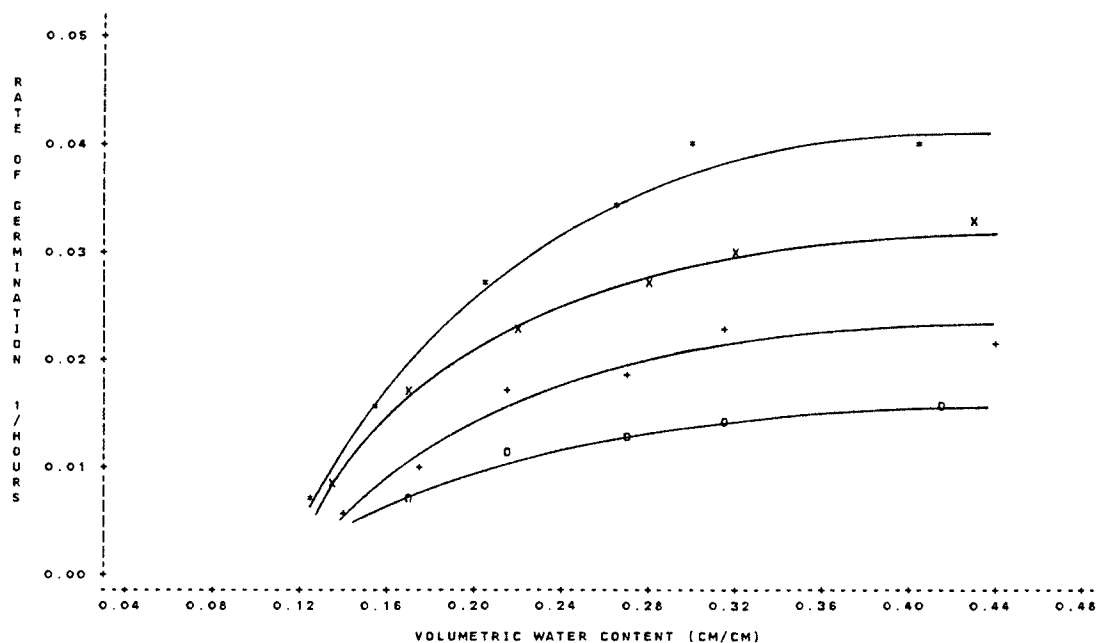


Figure 8: Germination rate of Pioneer 3995 in Carroll clay loam as a function of water content and temperature (\* - 30.5°C, X - 25°C, + - 19°C, O - 15°C).

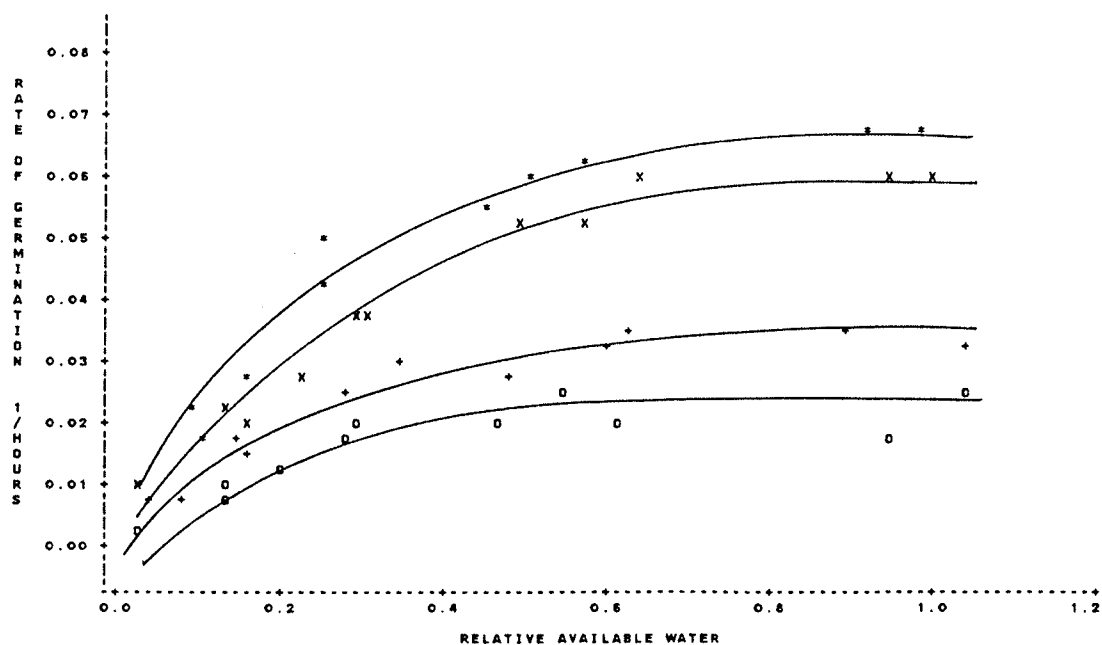


Figure 9: Germination rate of Northrup King 403 as a function of relative available water and temperature (\* - 30.5°C, X - 25°C, + - 19°C, O - 15°C).

TABLE 9

Threshold volumetric water content,  $\theta_0$ , rate constants,  $k$ , and maximum rate of germination,  $R_{\max}$ , as obtained by iterative fitting of the model  $R_{\text{germ}} = R_{\max}\{1 - \exp[-k(\theta - \theta_0)]\}$ .

Hybrid	Temperature (°C)	$\theta_0$ ( $\text{m}^3 \text{ m}^{-3}$ )		$k$		$R_{\max}$ ( $\text{hr}^{-1}$ )	
		Carroll	Almasippi	Carroll	Almasippi	Carroll	Almasippi
Pioneer 3995	30.5	.109	.065	11.16	13.54	0.0428	0.0489
	25	.104	.070	9.88	17.36	0.0336	0.0306
	19	.122	.066	14.72	19.21	0.0221	0.0208
	15	.118	.074	13.21	22.16	0.0154	0.0142
	Average	.113	.069	12.24	18.07		
Northrup King 403	30.5	.114	.072	9.56	19.33	0.0725	0.0659
	25	.122	.073	9.41	13.01	0.0653	0.0608
	19	.127	.070	16.11	17.28	0.0335	0.0356
	15	.132	.079	22.03	19.92	0.0212	0.0248
	Average	.124	.072	14.28	17.39		
Pride 1108	30.5	.116	.062	9.68	10.92	0.0603	0.0609
	25	.113	.067	7.17	9.58	0.0488	0.0495
	19	.124	.068	11.57	13.69	0.0295	0.0313
	15	.147	.081	25.39	25.67	0.0160	0.0173
	Average	.125	.081	13.44	14.97		
Overall Average		.121	.070	13.32	16.80		

available water. For a given hybrid and temperature the rate curves for the two soils coincide reasonably well. Approximately equal germination rates between different soil types has been observed for wheat (Ward and Shaykewich, 1972). The parameters obtained from fitting equation 3.3 to the data for each of the 3 hybrids are given in Table 10.

As was the case with emergence rate curves, the plateau region of the germination rate curves extended to lower moisture contents as temperature decreased. Generally at higher RAW the loamy sand curves were slightly above those for the clay loam but as RAW decreased the position of the curves was reversed.

In the model  $R = R_{\max} \{1 - \exp(-S \text{ RAW})\}$ ,  $S(\text{PG})$  generally increased slightly with decreasing temperature (Table 10).  $R_{\max}$  again decreased with decreasing temperature.  $R_{\max}$  for 403 and 1108 at 25°C was greater than  $R_{\max}$  for 3995 at 30.5°C. The rate curves were thus hybrid dependent and could not be combined further as was done for emergence.  $R_{\max}$  for germination were substantially larger than  $R_{\max}$  for emergence, reflecting the shorter times needed for germination than emergence.

The variable called Ratio (Table 5, p. 63) is the ratio of time to germination:time to emergence under conditions with optimum moisture. The values of Ratio for 3995 were larger than those for 403 and 1108, due in part to the larger seed size of 3995. One would expect that longer times would be needed to attain the critical water content needed for germination. Within hybrids, Ratio decreased with decreasing temperature. With decreasing temperature, the time required for germination increased at a slower rate than the time required for emergence, i.e., the  $Q_{10}$  for germination was less than the  $Q_{10}$  for emergence. The lower

TABLE 10

Maximum germination rate (Rmax) and rate constant (S) for each hybrid-temperature combination in the model:  $R_{\text{germ}} = R_{\text{max}}\{1 - \exp[-S \text{ RAW}]\}$ .

Temperature (°C)	Rmax (h <sup>-1</sup> )	S	R <sup>2</sup>
Pioneer 3995			
30.5	0.0455	3.79	0.98
25	0.0312	4.38	0.99
19	0.0216	4.85	0.99
15	0.0149	4.59	0.99
Northrup King 403			
30.5	0.0694	3.74	0.99
25	0.0643	2.98	0.99
19	0.0351	4.28	0.99
15	0.0228	4.58	0.98
Pride 1108			
30.5	0.0605	3.18	0.99
25	0.0483	2.62	0.99
19	0.0308	3.43	0.99
15	0.0173	4.51	0.99



$Q_{10}$  for germination may reflect the much larger portion of that stage that was dependent on water movement to, and uptake by, the seed (physical processes). On the other hand, the processes occurring during germination to emergence are more biological. This is supported by the view that physical processes have a much lower  $Q_{10}$  than biological processes (Miedema, 1982).

Plots of  $R_{max}$  and  $S$  for germination as a function of temperature are given in Figures 7 (p. 66) and 10, respectively. For each hybrid there was a definite linear relationship between  $R_{max}$  and temperature. To determine the relationship of  $R_{max}$  to temperature, linear regression analysis was used to fit equation 3.4 to the data. The parameters are listed in Table 6 (p. 67). For  $S$ , the only noticeable trend for all 3 hybrids was an overall decrease in  $S$  with an increase in  $T$  (Figure 10). For each hybrid, the relationship of  $S$  to  $T$  was significant at the 0.05 level.

The base temperatures,  $T_{base}$ , for germination were approximately equal to  $7.9^{\circ}\text{C}$ . Miedema (1982) observed minimum temperature for germination slightly above  $6^{\circ}\text{C}$ . Bierhuizen (1973) reported  $T_{base}$  may range between  $8^{\circ} - 10^{\circ}\text{C}$ .  $T_{base}$  for germination was lower than  $T_{base}$  needed for emergence. As stated earlier, this may reflect the importance of biological processes involved in emergence as opposed to the importance of physical processes involved in germination.

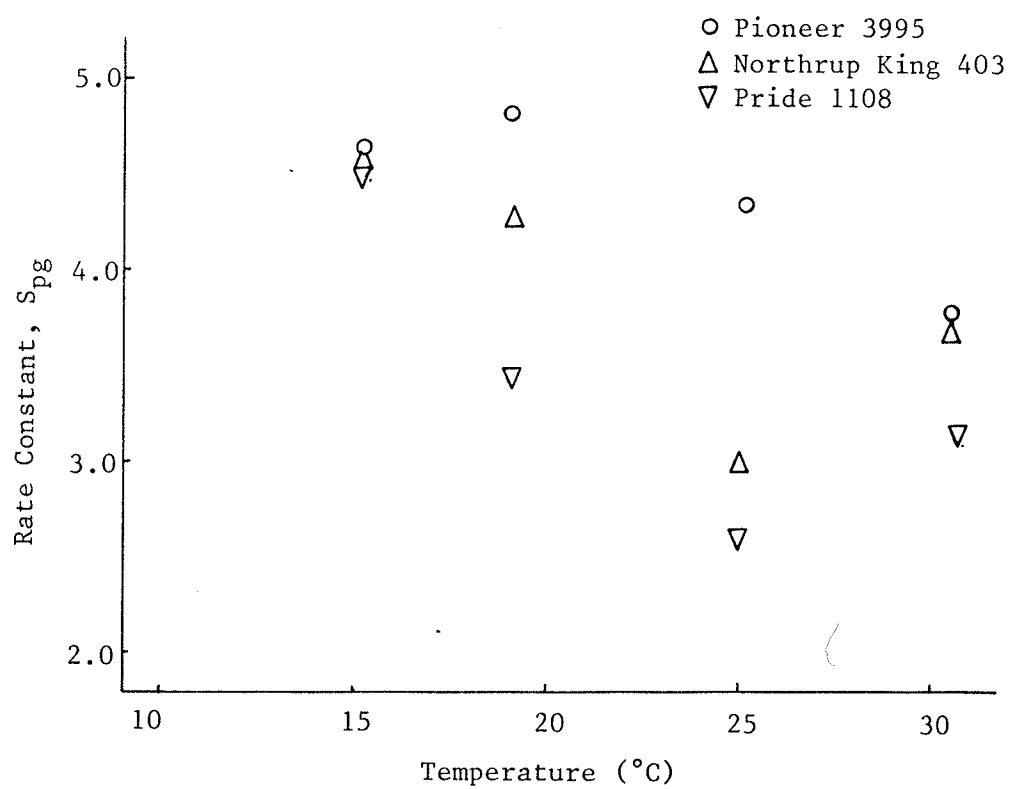


Figure 10: Rate constant,  $S(PG)$ , for germination plotted as a function of temperature.

### 7.3 50% GERMINATION TO 50% EMERGENCE (GE)

Using the equations developed from the emergence and germination data, the rate of germination to emergence (GE) was determined by subtracting the calculated time to germination from the calculated time to emergence. From the calculated times of GE, rate curves for GE were generated and analyzed following the same procedures outlined previously. The parameters for the linear regression analysis of the data are listed in Table 6, p. 67.

There were relatively small differences in  $R_{max}$  among hybrids.  $R_{max}$  for 3995 was now larger than that of 1108 followed by 403, the reverse of the order in the two previous stages, PG and PE. The base temperatures were approximately equal to  $11.5^{\circ}\text{C}$  (Table 6), slightly greater than  $T_{base}$  for emergence. Since  $T_{base}$  for PE would be a weighted average of  $T_{base}$  for PG and GE, it was expected that  $T_{base}$  for GE should be larger than that for PE.

The differences in base temperatures for germination and emergence are not easily explained. As stated previously both seeding depth and the defined criteria of emergence can alter the base temperature for emergence. Cell division may not be needed for germination (Haber, 1962; Miedema, 1982). Seeds exposed to lethal doses of gamma radiation to prevent cell division may still, under proper conditions, show signs of germination (Haber, 1962). Presumably the uptake of water by the embryo results in cell enlargement causing the protrusion of the coleorhiza through the seed coat (germination). However, cell division and cell enlargement are both required processes for emergence. These

factors may combine in some way to alter the base temperatures needed for germination and emergence.

#### 7.4 ROOT ELONGATION

In early seedling growth, both root length and direction can be very important in obtaining water for subsequent growth. As the surface soil layers dry, the roots need to grow to deeper soil depths where water may be more plentiful. The direction and length of root growth depend on a number of factors, e.g. soil temperature, soil aeration, soil strength and soil moisture.

Root lengths of the individual hybrids were measured at harvest and are listed in Table 11. For each hybrid and temperature, as moisture content decreased, the root lengths generally decrease. The response of the roots to moisture content was hybrid dependent. All hybrids were responsive to decreasing moisture contents but 3995 was less affected than was 403. The hybrid most affected was 1108. Similar observations occurred for the GE stage of emergence. As temperatures decreased, progressively longer times were needed to attain a given root length. At 10°C root growth was minimal but all the hybrids had germinated and had some degree of root growth.

Figure 11 is a plot of root elongation rate versus relative available water for Pioneer 3995 grown in the Carroll clay loam soil at four different temperatures. Elongation rates were determined by first subtracting the calculated time to germination from the time to harvest. The mean root length was then divided by the time from germination to

TABLE 11

Mean root lengths (cm) at harvest as a function of volumetric water content and temperature.

Temperature	Hybrid	Volumetric water content (cc water/cc soil)					
Carroll clay loam							
30.5		.297(93)†	.258(93)	.200(141)	.150(285)		
	Pioneer 3995	19.1(2.0)*	16.8(2.8)	19.3(3.9)	18.2(5.9)		
	Northrup King 403	19.3(2.2)	19.2(1.9)	15.4(5.4)	11.1(4.4)		
	Pride 1108	16.6(2.1)	13.6(3.0)	12.6(3.6)	7.0(2.9)		
25		.366(145)	.294(145)	.225(167)	.176(240)	.156(380)	.129(646)
	Pioneer 3995	20.9(3.0)	18.9(3.1)	20.1(3.3)	18.9(4.4)	18.2(3.5)	4.5(3.0)
	Northrup King	20.2(2.8)	18.3(2.5)	17.9(3.7)	14.6(4.3)	11.1(3.9)	2.6(1.8)
	Pride 1108	20.7(3.5)	16.9(3.5)	14.3(2.9)	9.6(2.5)	7.6(2.8)	0.6(1.0)
19		.337(216)	.270(216)	.215(264)	.167(520)	.159(600)	.129(1050)
	Pioneer 3995	22.2(5.4)	19.4(3.3)	18.0(2.0)	14.6(3.7)	9.8(2.1)	5.6(2.7)
	Northrup King	23.3(4.9)	19.3(3.1)	16.8(2.8)	11.6(2.8)	8.1(2.3)	3.9(1.7)
	Pride 1108	20.9(1.9)	16.0(2.8)	10.8(3.7)	5.5(1.4)	6.6(1.8)	2.1(0.9)
15		.335(280)	.316(410)	.233(410)	.186(507)	.156(720)	
	Pioneer 3995	17.7(9.6)	14.7(3.7)	14.2(3.4)	14.6(4.2)	12.7(4.2)	
	Northrup King 403	13.8(7.8)	12.3(3.2)	14.6(3.9)	11.6(3.4)	8.4(1.5)	
	Pride 1108	12.2(3.7)	11.2(2.8)	11.1(2.8)	6.6(2.8)	5.4(1.5)	
Almasippi loamy sand							
30.5		.331( 95)	.228( 95)	.153(143)	.108(263)	.095(263)	
	Pioneer 3995	15.4(3.3)	16.4(3.0)	19.9(4.5)	21.8(5.9)	15.7(6.3)	
	Northrup King 403	16.1(2.7)	17.2(3.8)	14.0(2.9)	9.9(2.7)	9.4(2.5)	
	Pride 1108	15.6(2.2)	14.4(3.2)	7.4(1.6)	8.8(2.5)	7.7(1.7)	
25		.346(118)	.225(118)	.152(168)	.120(196)	.091(527)	.086(623)
	Pioneer 3995	18.6(3.8)	18.2(3.9)	19.6(5.9)	20.6(6.9)	21.3(6.9)	12.8(2.6)
	Northrup King	16.5(2.7)	17.1(3.2)	16.6(5.0)	16.2(5.0)	11.5(3.2)	7.5(2.9)
	Pride 1108	16.7(3.5)	16.9(2.6)	15.7(2.1)	10.9(3.8)	10.4(3.2)	6.4(1.6)
19		.348(263)	.222(263)	.155(263)	.123(308)	.097(570)	.079(838)
	Pioneer 3995	22.6(5.3)	20.9(3.7)	19.5(4.1)	18.9(4.5)	18.6(6.1)	9.7(3.0)
	Northrup King	22.4(3.6)	18.8(2.6)	19.3(3.2)	13.7(6.1)	7.8(2.3)	8.7(3.5)
	Pride 1108	19.0(2.1)	18.3(4.0)	13.4(3.1)	11.9(4.4)	7.5(2.7)	5.1(2.3)
15		.327(380)	.237(418)	.166(476)	.135(683)	.111(786)	
	Pioneer 3995	11.5(3.7)	11.8(3.4)	10.3(3.1)	10.8(5.1)	9.1(2.5)	
	Northrup King 403	9.0(3.4)	8.2(2.0)	6.5(1.4)	5.5(2.7)	4.3(1.1)	
	Pride 1108	7.5(2.4)	7.3(1.8)	5.9(1.3)	4.7(1.5)	4.3(1.0)	

† Numbers in brackets are the number of hours after planting when harvest occurred.  
 \* Numbers in brackets are standard deviations.

harvest. This calculation assumed constant elongation rates similar to findings of Blacklow (1972b) and Miedema (1982). The shapes and relative positions of the curves were similar to those plotted for germination and emergence. Maximum elongation rate of the primary root occurred at lower water contents as temperature decreased. As was observed for emergence, the plateau regions extended to lower water contents as temperatures decreased.

Morphologically, roots were noticeably thinner as temperature increased. Roots grown at 15°C were thicker, less branched with much fewer root hairs than those grown at the 3 higher temperatures. The effect of bulk density on the growth of these roots at low temperatures, was striking. Compared to the clay loam (bulk density=1050 Kg m<sup>-3</sup>) roots grown at 15°C in the loamy sand (bulk density=1380 Kg m<sup>-3</sup>) were very thick, short, with no branches and no root hairs.

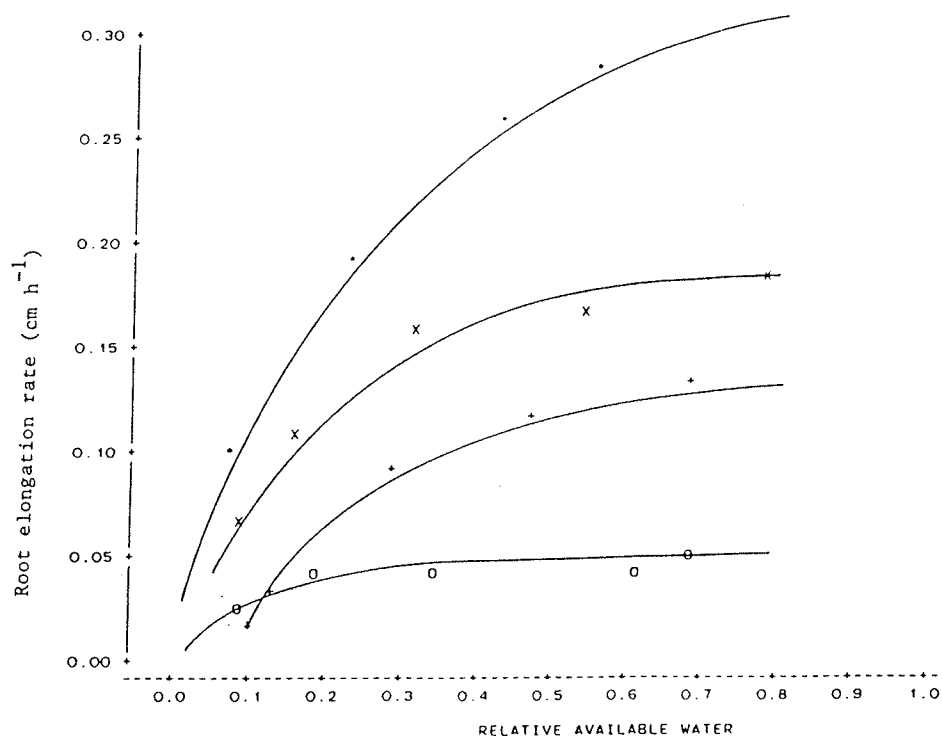


Figure 11: Root elongation rate for Pioneer 3995 grown in Carroll clay loam as a function of relative available water and temperature (\* - 30.5°C, X - 25°C, + - 19°C, O - 15°C).

PART IV  
FIELD STUDY



## Chapter 8

### MATERIALS AND METHODS

To study the effects of environment on corn phenology, field experiments were carried out during the growing seasons of 1980 to 1983. Site location and soil type are given in Table 12. At each site, except Vita 1981, 3 corn hybrids were grown - two early maturity hybrids, Pioneer 3995 and Northrup King 403, and one medium maturity hybrid, Pride 1108. Because of flooding and soil type differences at Vita 1981, NK 403 and Pride 1108 were monitored from planting to emergence and only Pride 1108 was monitored thereafter. The plots were fertilized to meet or exceed soil test recommendations.

#### 8.1 SITE DESCRIPTION

Six sites - Poplarfield, Treherne, Arborg, Vita 1981 and 1982, Fisher Branch - were established in cooperation with the Manitoba Corn Committee and the Agro - Man Corn Project. The Portage sites were established at the Department of Plant Science field station, Portage la Prairie. The Glenlea sites were established at the Glenlea Research Station.

TABLE 12

Site location, station number and soil types.

Station, Year and Legal Description	Abbreviation	Station number	Latitude (degrees)	Soil Type
Poplarfield 1980 NW 8-22-3W	Pop80	1	50.9	Inwood Sand
Portage 1980 NE 30-11-6W	Port80	2	50.0	Gnadenenthal Clay Loam
Glenlea 1980 Lot 6-8-3E	Glen80	3	49.6	Red River Clay
Treherne 1980 NW 9-8-10W	Tre80	4	49.6	Holland Loam
Arborg 1981 NW 20-22-2E	Arborg	5	50.9	Tarno Clay
Portage 1981 NE 30-11-6W	Port81	6	50.0	Gnadenenthal Clay Loam
Glenlea 1981 Lot 6-8-3E	Glen81	7	49.6	Red River Clay
Vita 1981 SW 21-3-7E	Vita81	8	49.2	Pine Ridge Sand (poorly drained)
Glenlea 1982 Lot 6-8-3E	Glen82	9	49.6	Red River Clay
Vita 1982 SW 19-1-8E	Vita82	10	49.1	Pine Ridge Sand
Fisher Branch 1983 NW 15-23-1W	Fish83	11	51.0	Balmoral Clay Loam (till substrate)
Glenlea 1983 Lot 6-8-3E	Glen83	12	49.6	Red River Clay

## 8.2 MEASUREMENTS

### 8.2.1 Soil Characteristics, Soil Moisture and Soil Temperature

Soil characteristics are shown in Table 13. Bulk densities were determined using the method described by Zwarich and Shaykewich (1969). Field capacity and permanent wilting points were determined using equations 2.1 and 2.2 from Shaykewich (1965). The 33 and 1500 kPa water contents were determined using the standard pressure membrane technique. Particle size analysis and particle densities were determined using standard soil analysis procedures.

Within row soil moisture contents were determined on a weekly basis from planting to silking. Soil moisture contents were determined gravimetrically in 5 cm intervals to a depth of 20 cm. Four to six replicates were taken per plot. Soil moisture below 20 cm was determined using the neutron scattering method. Because of equipment malfunction this data was discontinuous and of questionable accuracy.

Soil temperatures (ST) were measured from planting to silking except at Portage 1981 where soil temperatures were measured from planting to the start of stem elongation. Soil temperatures were not measured at Treherne 1980 or Vita 1982. Readings were taken at least once every 3 hours by using automatic recording potentiometers.<sup>1</sup> Thermocouples were positioned on wooden stakes placed in the soil within the corn rows so that temperatures were measured at 2.5, 5, 10 and 20 cm depths. Six replicates for each depth were recorded except with the Grant recorder

<sup>1</sup> a) Honeywell multipoint recorder from Honeywell Industrial Products Group, Phila., Pa. b) Campbell CR-5 digital recorder from Campbell Scientific Inc., Logan, Utah. c) Grant temperature recorder from Grant Instruments Ltd., Toft, Cambridge.

TABLE 13

Soil characteristics†, PROP and seed depth for each station.

Station	Station Number	Seed Depth (cm)	PROP	Particle Density	Bulk Density		Volumetric Water Contents				Particle Size (%)			Texture
				(g/cc)	(g/cc)	(g/cc)	(cc water/cc soil)				Sand	Silt	Clay	
				0-15	0-15	>15	Field Capacity	>15	Permanent Wilting	>15				
Pop80	1	6.0	.7	2.62	1.22	1.50	.25	.15	.07	.02	81.3	15.4	3.3	LS
Port80	2	6.0	.25	2.56	0.87	1.23	.40	.45	.20	.19	10.9	53.0	36.1	SICL
Glen80	3	5.0	.2	2.60	0.94	1.21	.42	.52	.24	.24	5.4	26.7	67.9	C
Tre80	4	5.0	.25	2.60	1.11	1.49	.30	.30	.07	.07	59.4	32.4	8.2	SL
Arborg	5	7.0	.7	2.61	1.0	1.32	.42	.48	.19	.22	3.5	48.5	48.0	SIC
Port81	6	5.0	.5	2.56	1.04	1.23	.44	.45	.20	.19	10.9	53.0	36.1	SICL
Glen81	7	5.0	.5	2.60	1.06	1.21	.45	.52	.24	.24	5.4	26.7	67.9	C
Vita81	8	7.0	.2	2.61	1.09	1.51	.32	.24	.10	.03	82.7	12.9	4.5	LS
Glen82	9	-	.8	2.60	1.06	1.21	.46	.52	.24	.24	5.4	26.7	67.9	C
Vita82	10	-	.4	2.57	1.29	1.56	.22	.22	.04	.04	83.0	15.0	2.0	LS
Fish83	11	7.0	.65	2.62	1.03	1.48	.29	.36	.12	.17	34.9	35.7	29.4	CL
Glen83	12	6.0	.7	2.60	1.02	1.21	.46	.52	.24	.24	5.4	26.7	67.9	C

† Particle density, particle size and texture apply to 0-15 cm layer only.

\* PROP - partitioning factor for water withdrawal from the soil profile.

where only 2 replicates were recorded.

### 8.2.2 Crop Measurements and Observations

The phenological development of corn was divided into various stages - planting to emergence, emergence to stem elongation, stem elongation to silking. The phenological events marking the beginning and/or end of the stages were defined as: 1. emergence - coleoptile just emerging from soil surface 2. stem elongation - that time when the growing point of the corn plant first extended above the soil surface. This phenological event was considered to have occurred when approximately 2.5 cm of hard stem could be measured above the soil surface. 3. silking - silks just beginning to emerge from the ear sheath.

Dates when 50% of the corn plants reached the respective phenological events were determined from weekly visits to each of the sites. Because the plots were observed once a week, linear interpolation was used to estimate the dates when 50% of the plants completed the respective stage. An example of the interpolative procedure follows:

DAY 1	DAY 8
10 emerged seedlings	40 emerged seedlings

If the total number of seedlings which finally emerged was 50 then 50% emergence (25 emerged seedlings) occurred someday between DAY's 1 and 8. To find this day the following formula was used:

$$\begin{aligned}
 \text{DATE} &= \text{DAY 1} + [(\text{DAY 8} - \text{DAY 1}) \{(25-10)/(40-10)\}] \\
 &= \text{DAY 1} + [7 \{15/30\}] \\
 &= \text{DAY 1} + 3.5 \\
 &= \text{DAY 5.}
 \end{aligned}$$

50% emergence occurred on approximately the fifth day.

The number of emerged leaves were also determined on a weekly basis. A leaf was counted as emerged when the tip was visible above the leaf whorl. Dates on which the phenological events occurred and appropriate leaf number are given in Appendix D.

All crop measurements and observations were made at 4 randomly placed 3 to 4 meter strips for each hybrid at each site. A total of at least 40 plants per hybrid from each site were used for observation and measurement purposes.

Seed depth (Table 13) was measured by physical removal of young seedlings from the soil and measuring from the position of the soil surface on the seedling to the attached seed. Accurate measurements of seed depth and date of emergence were not obtained for Glenlea 1982 and Vita 1982. Seed depths were assumed to be 6 cm and the emergence model was used to estimate the date of emergence at these two sites. For the emergence model actual soil temperatures were used for Glenlea 1982 while estimated soil temperatures were used for Vita 1982.

#### 8.2.3 Weather Data

Daily measurements of rainfall, maximum - minimum air temperature and solar radiation were taken from planting day until final harvest. All weather data was collected at the experiment sites. A standard climatological station is located at the Glenlea Research Station. At all sites pyrliographs<sup>2</sup> were used to measure solar radiation. Rainfall

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<sup>2</sup> Pyrliograph. Belfort Instruments, Baltimore, Md. Mechanical Pyranograph. Weather Measure, Sacramento, Calif.

and temperatures were measured using recording rain gauges<sup>3</sup> and hygrothermographs<sup>4</sup> at all sites except Glenlea.

### 8.3 MODELS AND ANALYSIS

#### 8.3.1 Model Description

##### 8.3.1.1 Soil Moisture Model

Soil moisture contents were measured once a week. To use an emergence model based on the controlled environment study, daily soil moisture contents for the surface 0 - 20 cm would be required. A soil moisture model was developed to estimate daily moisture contents. This model was iteratively fitted to the field measured soil moisture contents.

The soil moisture model is given in Appendix A. The model is a modified version of the 'mimic' procedure developed by van Keulen (1975). The daily soil moisture content is obtained from the summation of calculated daily infiltration and loss by evaporation. Rainfall is assumed to infiltrate and redistribute throughout the profile instantaneously. Actual evaporation is calculated as a function of the potential evapotranspiration and the water content, 'dryness', of the soil surface layer - the thickness of which was set equal to 2 cm. Ritchie and Burnett (1971) found evaporation decreased rapidly as the surface 3 cm dried.

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<sup>3</sup> Weighing Rain Gauge. Belfort Instruments, Baltimore, Md.

<sup>4</sup> Hygrothermograph. Belfort Instruments, Baltimore, Md.  
Hygrothermograph. Weather Measure, Sacramento, Calif.

In the model the soil profile was divided into 8 layers, the thickness of which increased with depth - 2, 3, 5, 5, 5, 20, 30 and 50 cm. All rainfall was assumed to enter the soil profile, i.e., no runoff. Infiltration and distribution of rain water was assumed instantaneous with each layer filling to field capacity before water drained to the next lower layer. Actual daily evaporation was obtained by multiplying the potential daily evaporation by a reduction factor due to the dryness of the surface layer. The potential daily evaporation was calculated using the regression equation of Baier and Robertson (1965):

$$PE = .0085 [.928 T_{max} + .933 (T_{max} - T_{min}) + .0486 Q - 87.03] \quad (4.1)$$

where PE = potential evaporation (cm/day)  
 $T_{max}$ ,  $T_{min}$  = daily maximum, minimum temperatures ( $^{\circ}F$ )  
 $Q$  = daily total solar radiation at the top of  
the atmosphere ( $cal/(cm^2-day)$ ).

Solar radiation was measured at each site and therefore could have been used, along with air temperature, to estimate daily PE with the appropriate equation (such as the Priestly-Taylor (1972) equation). However, solar radiation is measured at only very few weather stations in Manitoba. It was therefore thought more applicable and practical to use the Baier and Robertson (1965) equation to estimate PE. Actual daily evaporation was calculated using the following equation:

$$AE = PE (REDUCT) \quad (4.2)$$

where  $REDUCT = 0.9 + 0.1 Fsl$  for  $Fsl > 0.5$   
 $= 0.075 - 0.067 Fsl + 3.568 Fsl^2$  for  $Fsl \leq 0.5$   
 $AE$ ,  $PE$  = actual, potential evaporation (cm/day).

Actual evaporation was expressed as a function of the wetness of the surface layer,  $Fsl$ .  $Fsl$  is the ratio of the actual water in the surface layer available for evaporation to the potential amount of water in the



surface layer that would be available for evaporation if the layer was at field capacity. Fsl can be calculated using:

$$Fsl = (\theta - \theta_{ad}) / (\theta_{fc} - \theta_{ad}) \quad (4.3)$$

where Fsl = fraction of water in surface layer (0-2 cm)  
available for evaporation

$\theta$  = volumetric water content of the surface layer  
(cm H<sub>2</sub>O/cm soil)

$\theta_{ad}$  and  $\theta_{fc}$  = air dry and field capacity water contents,  
respectively, of surface layer (cm H<sub>2</sub>O/cm soil).

While equation 4.2 calculates the amount of water lost from the soil profile (to 120 cm) due to evaporation, an exponential function was used to partition this loss over the 8 soil layers. The ease of water withdrawal from a given layer was assumed to be directly proportional to the water content of the layer and inversely proportional to an exponential function of the depth of each layer and an extinction coefficient, PROP.

$$\begin{aligned} \text{VAR}(L) &= (\theta(L) - \theta_{ad}(L)) \text{EXP}((-PROP) \text{DEPTH}(L)) && \text{for } \theta(L) > \theta_{ad}(L) \\ &= 0.0 && \text{for } \theta(L) \leq \theta_{ad}(L) \end{aligned} \quad (4.4)$$

where VAR(L) = relative ease of water withdrawal from layer L  
 $\theta(L)$  = volumetric water content of layer L (cm<sup>3</sup> H<sub>2</sub>O/cm<sup>3</sup> soil)  
 $\theta_{ad}(L)$  = air dry volumetric water content of layer L  
(cm<sup>3</sup> H<sub>2</sub>O/cm<sup>3</sup> soil)  
DEPTH(L) = depth to centre of layer L (cm)  
L = layers in soil profile (1 to 8)  
PROP = extinction coefficient.

The partitioning factor was calculated using the following relationship:

$$PF(L) = \frac{\text{VAR}(L)}{\sum_{i=1}^8 \text{VAR}(L)} \quad (4.4A)$$

where PF(L) = partitioning factor, fraction of evaporative  
water loss from layer L.

Decreasing PROP increases the proportion of water extracted from the lower layers. The water content of each layer was obtained by adding water gained through infiltration to, and subtracting that lost through evaporation from, the previous day's water content for the respective soil layer.

### 8.3.1.2 Emergence Model

The equations developed from the controlled environment emergence study were incorporated into a computer program (Appendix B) to simulate emergence under field conditions. To adapt the controlled study equations to field conditions, several assumptions were incorporated into the model.

Because temperature gradients exist under field conditions roots may be developing under a different soil temperature regime than shoots. However, for the model it was assumed that the temperature at seed depth influenced the seedling (both roots and shoots) throughout the emergence stage. Seed depth temperatures were obtained by linear interpolation between the measured (or estimated) soil temperatures above and below seed depth using the equation:

$$T = T_1 - \{[(T_1 - T_2)/Z] (\text{DEPTH} - X)\} \quad (4.5)$$

where  $T$  = seed depth temperature ( $^{\circ}\text{C}$ )  
 $T_1, T_2$  = measured soil temperatures above and below seed depth ( $^{\circ}\text{C}$ ), respectively  
 $Z$  = difference between the depths at which  $T_1$  and  $T_2$  were measured (cm)  
 $X$  = depth at which  $T_1$  was measured (cm)  
 $\text{DEPTH}$  = seed depth (cm).

Many simplifying assumptions were used in determining the moisture content to be used in the emergence equation. Moisture contents were calculated using the soil moisture model. Since the seed was planted deeper than 5 cm, it was assumed that only the moisture in the third (5 - 10 cm) and fourth (10 - 15 cm) layers was available for germination and emergence. In an attempt to include the influence of moisture gradients and moisture movement within the soil profile on the rate of emergence, the moisture content used in the emergence equations was determined in the following manner:

$$\begin{aligned}\theta &= 0.75 \theta(3) + 0.25 \theta(4) && (4.6) \\ &\quad \text{(when planting to emergence stage less than half completed)} \\ &= 0.25 \theta(3) + 0.75 \theta(4) \\ &\quad \text{(when planting to emergence stage more than half completed)}\end{aligned}$$

where  $\theta$  = volumetric moisture content influencing emergence rate  
( $\text{cm}^3 \text{H}_2\text{O}/\text{cm}^3 \text{soil}$ )

$\theta(3)$ ,  $\theta(4)$  = volumetric moisture contents of layers 3 and 4,  
respectively ( $\text{cm}^3 \text{H}_2\text{O}/\text{cm}^3 \text{soil}$ ).

It was reasoned that when the planting to emergence stage was half completed the roots would be growing into the fourth layer. This layer would then become the major source of moisture to the emerging seedling.

The directional growth of roots has also been shown to be influenced by temperature gradients (Sheppard and Miller, 1977). Roots do not grow vertically down from the seed but grow at an angle determined by the temperature regime in the vicinity of the seed. Although root growth rates were observed to increase with temperature, the controlled study also showed that the germination phase occupied a larger portion of the emergence period as temperatures increased. For a given temperature increase, root growth rates would increase, thus decreasing the time from germination for roots to reach a specified depth. However, the

germination process would occupy a higher percentage of the duration from planting required by the roots to reach a specified depth. The time from planting for the roots to reach a specified depth would therefore be influenced by temperature through the two separate events; with the change in one tending to offset the change in the other. Based on these observations and assumptions, the accumulated development of 0.5 was assumed to be the time at which the roots entered the fourth layer which was independent of the temperature regime.

The daily emergence rate was calculated using the equations developed from the controlled environment study. The moisture content calculated using equation 4.6 was converted to relative available water (RAW) by:

$$\begin{aligned} \text{RAW} &= [\theta - \theta(\text{pwp})] / [\theta(\text{FC}) - \theta(\text{pwp})] && \text{for } \theta > \theta(\text{pwp}) \\ &= 0.0 && \text{for } \theta \leq \theta(\text{pwp}) \end{aligned} \quad (4.7)$$

where RAW = relative available water  
 $\theta$  = volumetric moisture content from equation 4.6  
 $\theta(\text{pwp})$ ,  $\theta(\text{FC})$  = volumetric permanent wilting point and field capacity, respectively.

The emergence rate was calculated by the exponential equation:

$$R = R_{\text{max}} [1 - \text{EXP}(-S \text{ RAW})] \quad (4.8)$$

where R = emergence rate ( $\text{hr}^{-1}$ )  
 $R_{\text{max}}$  = emergence rate at optimum moisture ( $\text{hr}^{-1}$ )  
 $S$  = rate constant  
RAW = relative available water.

$R_{\text{max}}$  was found to be a function of temperature only and described by the linear equation:

$$R_{\text{max}} = 0.00089 (T - 10.8) \quad (4.9)$$

where T = temperature ( $^{\circ}\text{C}$ ).

When  $T \leq 10.8$ ,  $R_{\max}$  was set equal to zero. The moisture sensitivity coefficient had been found to be temperature dependent and was calculated by the equation:

$$S = 8.1965 - 0.3229 T + 0.0055 T^2 \quad (4.10).$$

For a given day, the above equations were used to calculate hourly emergence rates for the appropriate maximum and minimum soil temperatures.  $\theta$  was assumed to be constant throughout the day and therefore RAW would also be a daily constant. When minimum soil temperature ( $ST_{\min}$ ) was above the base temperature,  $T_{\text{base}} = 10.8^\circ\text{C}$ , the hourly rates at both daily maximum and minimum temperatures were multiplied by 12 hours and added to give the daily emergence rate. If  $ST_{\min}$  was below  $T_{\text{base}}$ , only  $ST_{\max}$  multiplied by 12 hours equaled the daily rate. When  $ST_{\max}$  was less than  $T_{\text{base}}$ , daily emergence was zero. Mathematically, the above could be expressed as:

$$\begin{aligned} DR &= 12 R(ST_{\max}) + 12 R(ST_{\min}) && \text{for } ST_{\min} > 10.8 && (4.11) \\ &= 12 R(ST_{\max}) && \text{for } ST_{\min} \leq 10.8, ST_{\max} > 10.8 \\ &= 0 && \text{for } ST_{\max} \leq 10.8 \end{aligned}$$

where  $DR$  = daily rate of emergence  
 $R(ST_{\max})$  = hourly development rate for  $ST_{\max}$   
 $R(ST_{\min})$  = hourly development rate for  $ST_{\min}$ .

Thus, the method used to calculate the daily rate assumes a square wave daily temperature function. This was considered to be an improvement over using the average daily soil temperature. In that instance, if the average fell below  $T_{\text{base}}$ , the daily development rate would be calculated as zero even if  $ST_{\max}$  were above  $T_{\text{base}}$ . Thus the time during which development could have occurred would not have been taken into account.

Another alternative would have been to use a sine function to calculate hourly temperature from STmax and STmin. However, many of the heat unit equations used for practical purposes and by researchers use daily maximum-minimum temperatures which would be equivalent to a square wave temperature function. It was therefore decided to continue to use daily maximum-minimum instead of calculated hourly temperatures in estimating daily development units.

It was assumed that emergence occurred when:

$$\Sigma DR = .98 \quad (4.12).$$

Normally, emergence would occur when the sum of the daily rates equals or exceeds 1.0 but it was found that a value of .98 resulted in more accurate estimates.

#### 8.3.1.3 Iteration Model (IF Model)

This model (Appendix C) used an iterative procedure to obtain the best fit of the development rate (IF) equation to the field data. The criterion for best fit was determined by the lowest coefficient of variation (CV). The IF equation was expressed as:

$$IF = (IF_{max}/C) \{ (T - LCT)^B (UCT - T)^B \} \quad (4.13)$$

$$\text{where } C = (T_{opt} - LCT) (UCT - T_{opt})^B \quad (4.13A)$$

$$B = (UCT - T_{opt}) / (T_{opt} - LCT) \quad (4.13B)$$

IF = development rate

IFmax = maximum development rate, assumed equal to 1.0

T<sub>opt</sub> = optimum temperature for the function (curve)

LCT, UCT = lower, upper critical temperatures  
for the function, respectively.

For a given function, LCT would be the cardinal temperature below which development would not occur, and UCT would be the cardinal temperature above which development would not occur. With IFmax assumed equal to one, IF becomes, in essence, a relative development rate. By assuming IFmax = 1.0 the iterative procedure was simplified tremendously. If IFmax were not assumed to equal 1.0 it would have to be solved for in the iterative procedure. This would necessitate 2187 separate runs of the model on a daily basis for each location. With IFmax = 1.0, 729 runs would be needed resulting in a tremendous decrease in computer time.

To iteratively fit the IF equation to the field data, it was assumed that the corn plants had two T response functions; one for Tmin and one for Tmax. For the two equation approach, there were 6 cardinal temperatures; 3 of each equation. Each cardinal temperature was assigned an initial value. Each of these initial temperatures was increased by a given value, x, and then increased again by twice that value so that the following temperature matrices resulted:

Equation 1 (T=Tmin)			Equation 2 (T=Tmax)		
LCT	Topt	UCT	LCT	Topt	UCT
LCT+x	Topt+x	UCT+x	LCT+x	Topt+x	UCT+x
LCT+2x	Topt+2x	UCT+2x	LCT+2x	Topt+2x	UCT+2x

Initially x was given a value of 5°C. The values above were substituted into equation 4.13. Using daily temperature data from the beginning to end of a given stage, a contribution to daily development from both Tmin and Tmax was calculated.

$$R = IF(Tmin) + IF(Tmax) \quad (4.14)$$

where R = relative daily development rate

IF(Tmin) = equation representing response function to Tmin

IF(Tmax) = equation representing response function to Tmax.

The daily development rates,  $R$ , were summed over the duration of the stage.

$$\text{Sum} = \sum_{i=1}^n R \quad (4.15)$$

where Sum = accumulated daily rates from beginning to completion of stage (for a given location)

$i$  = day number

$n$  = last day of stage (duration of stage and was therefore location dependent)

$R$  = relative daily development rate.

For these sums over all station-years, the mean and standard deviation were calculated. The combination of LCT, UCT and  $T_{opt}$  for  $T_{max}$  and  $T_{min}$  giving the lowest coefficient of variation was selected for further study. A value of  $2^{\circ}\text{C}$  was now assigned to  $x$  and the process repeated. Finally,  $x$  was assigned a value of  $1^{\circ}\text{C}$  in order to 'zero in' on the values of LCT, UCT and  $T_{opt}$ . Thus, the equations were evaluated at all possible temperature combinations and the criterion for selection of the cardinal temperatures was the lowest coefficient of variation.

### 8.3.2 Planting to Emergence Stage

#### 8.3.2.1 Empirical Estimation of Soil Temperature

Linear regression analysis was used to develop empirical equations relating soil temperatures at 2.5 and 5.0 cm to aerial weather variables; and soil temperatures at 10 and 20 cm to the 2.5 and 5.0 cm soil temperatures. Maximum soil temperatures at each depth were regressed against the current and previous days air temperatures, solar radiation and calculated daily soil moisture content of the surface soil layer. The same procedure was used when regressing the minimum soil temperatures against the aerial weather variables. Only those variables that



added significantly at the  $P=0.05$  level to the regression were included in the resulting equations.

To empirically relate soil temperatures to aerial weather variables, the soils were divided into two groups, coarse and fine, as defined by their textural class. Fisher Branch 1983 was included with the coarse soils because of a high coarse sand content, a light surface color and a low water holding capacity (Table 13, p. 88) relative to the other soils in the fine group. The resultant regression equations are listed in Tables 14 and 15.

#### 8.3.2.2 Soil Moisture Model

Soil moisture contents were measured on a weekly basis. To model corn emergence using the equations developed from the controlled environment study, a daily estimation of the water content of the surface soil layers was needed. The infiltration - evaporation model was iteratively run adjusting PROP until the best fit between actual and estimated field values was obtained. PROP is the partitioning coefficient. Decreasing PROP increases the proportion of water extracted from the lower soil layers. The model was run for a minimum of 3 weeks for each site starting with the planting day when the first moisture samples were taken. For each location, 3 to 4 field observations were compared to the estimated values. The PROP values giving the best fit for each location (Table 13, p. 88) were used in estimating evaporation and hence daily moisture status.

TABLE 14

Regression equations developed to estimate daily maximum and minimum soil temperature for coarse textured soils during planting to 50% emergence + 7 days.

Depth (cm)	Equation	R <sup>2</sup> *
2.5		
	STmax = 6.56 + .8 Tmax†	.85
	STmax = 1.35 + .82 Tmax + .0092 RAD	.90
	STmin = 2.49 + .8 Tmin	.93
5.0		
	STmax = 5.86 + .7 Tmax	.85
	STmax = 2.92 + .53 Tmax + .22 Tmin + .0094 RAD	.87
	STmin = 3.87 + .69 Tmin	.89
	STmin = 3.84 + .64 Tmin + .01(PTmin) <sup>2</sup>	.93
10		
	STmax = .07 + .77 STmax <sub>5</sub>	.90
	STmax = .5 + .65 STmax <sub>5</sub> + .29 STmin <sub>5</sub>	.95
	STmin = 1.98 + .9 STmin <sub>5</sub>	.96
20		
	STmax = 3.99 + 0.87 STmin <sub>10</sub>	.86
	STmax = 0.83 + 0.4 STmax <sub>10</sub> + 0.53 STmin <sub>10</sub>	.94
	STmin = 1.03 + 0.89 STmin <sub>10</sub>	.97

\*All equations significant at P=.001

†PTmin = previous days minimum air T, °C

RAD = daily solar radiation received at site, cal/(cm<sup>2</sup>-day)

STmax, STmin = maximum and minimum soil temperatures for the specified depth, respectively, °C

STmax<sub>5</sub>, STmin<sub>5</sub> = maximum and minimum soil temperatures, respectively, at 5 cm depth, °C

STmax<sub>10</sub>, STmin<sub>10</sub> = maximum and minimum soil temperatures, respectively, at 10 cm depth, °C

Tmax, Tmin = maximum, minimum air temperatures, respectively, °C.

TABLE 15

Regression equations developed to estimate daily maximum and minimum soil temperature for fine textured soils during planting to 50% emergence + 7 days.

Depth (cm)	Equation	R <sup>2</sup> *
2.5		
	STmax = 3.57 + 0.84 Tmax†	.80
	STmax = 0.85 + 0.72 Tmax + .0093 RAD	.85
	STmin = 2.84 + 0.72 Tmin	.78
	STmin = 2.16 + 0.54 Tmin + .1 PPTmin + .0029(PTmax) <sup>2</sup>	.83
5.0		
	STmax = 5.0 + .63 Tmax	.79
	STmax = 3.25 + .55 Tmax + .006 RAD	.84
	STmin = 5.22 + .6 Tmin	.75
	STmin = 1.66 + 0.2 PTmax + .38 Tmin + .14 PPTmin	.84
10		
	STmax = 2.69 + .66 STmax <sub>5</sub>	.82
	STmax = 2.19 + .52 STmax <sub>5</sub> + .32 STmin <sub>5</sub>	.92
	STmin = 2.56 + .82 STmin <sub>5</sub>	.95
20		
	STmax = 3.16 + .82 STmin <sub>10</sub>	.84
	STmax = 0.29 + 1.13 STmax <sub>10</sub> + .25 STmin <sub>10</sub> - .43 STmax <sub>5</sub>	.95
	STmin = 0.94 + 0.87 STmin <sub>10</sub>	.93

\*All equations significant at P=.001

†PPTmin = the two day previous minimum air temperature, °C

PTmax = previous days maximum air temperature, °C

RAD = daily solar radiation, cal/(cm<sup>2</sup>-day)

STmax, STmin = maximum and minimum soil temperatures for the specified depth, respectively, °C

STmax<sub>5</sub>, STmin<sub>5</sub> = maximum and minimum soil temperatures, respectively, at 5 cm depth, °C

STmax<sub>10</sub>, STmin<sub>10</sub> = maximum and minimum soil temperatures, respectively, at 10 cm depth, °C

Tmax, Tmin = maximum, minimum air temperatures, respectively, °C.

### 8.3.2.3 Emergence Model

The emergence model was run using actual and estimated conditions. Both actual and estimated daily soil temperatures were used in the model in conjunction with estimated soil moisture contents. The model was also run assuming moisture was nonlimiting to determine the magnitude of the contribution of moisture to the emergence rate. As well, the model was run using the measured average seed depth for each location and an assumed seed depth of 6 cm. If an emergence model was to be adapted to estimate emergence at a number of locations, measuring seed depths would be impractical and an estimated seed depth would probably have to be used. The average seed depth for this study was approximately 6 cm.

### 8.3.3 Development Models

#### 8.3.3.1 Standard Thermal Models

A number of development models were tested for their ability to estimate the duration of the growth stages (1) emergence to stem elongation (ESE), (2) stem elongation to silking (SESI) and (3) emergence to silking (ESI). The literature reports a large number of thermal models used for predicting silking dates. Four of these models, or slight modifications of these models, were used in this study.

#### 1. Growing degree day

$$GDD = (T_{max} + T_{min})/2 - 10 \quad (5.1)$$

where  $T_{max} = 30$  for  $T_{max} > 30^{\circ}\text{C}$   
 $T_{min} = 10$  for  $T_{min} < 10^{\circ}\text{C}$ .

#### 2. Modified growing degree day

$$MGDD = (T_{max} + T_{min})/2 - 10 \quad (5.2)$$

where  $T_{max} = 30 - (T_{max} - 30)$  for  $T_{max} > 30^{\circ}\text{C}$

$$T_{min} = 10$$

$$\text{for } T_{min} < 10^{\circ}\text{C}.$$

### 3. Corn heat unit

$$CHU = (X + Y)/2 \quad (5.3)$$

$$\text{where } X = 1.8 (T_{min} - 4.4) \text{ for } T_{min} > 4.4^{\circ}\text{C} \quad (5.3A)$$

$$X = 0 \text{ for } T_{min} \leq 4.4^{\circ}\text{C}$$

$$Y = 3.3 (T_{max} - 10) - 0.083 (T_{max} - 10)^2 \text{ for } T_{max} > 10^{\circ}\text{C} \quad (5.3B)$$

$$Y = 0 \text{ for } T_{max} \leq 10^{\circ}\text{C}.$$

The maximum temperature response function,  $Y$ , reaches an optimum,  $Y_{max}$ , at  $30^{\circ}\text{C}$ . Dividing  $Y$  by  $Y_{max}$  results in a relative rate. This relative rate plotted as a function of temperature is represented by curve 1 in Figure 12. Curve 1 indicates that the maximum temperature for development would be  $50^{\circ}\text{C}$ . The literature suggests that development does not occur at temperatures above approximately  $40^{\circ}\text{C}$ . Therefore, the quadratic portion of the CHU equation overestimates development at temperatures greater than  $30 - 35^{\circ}\text{C}$ .

### 4. Optimum day

The optimum day concept was developed from the data of Lehenbauer (1914) by Gilmore and Rogers (1958). They plotted relative elongation rate of corn seedlings against temperature to obtain a temperature response function. This function was then used to estimate the daily contribution to development. Coelho and Dale (1980) fitted a series of linear equations to the data of Lehenbauer (1914). Using these equations, called the FT model, they obtained a better estimation of the time from planting to 75% silking than with GDD, MGDD or CHU. However, Daughtry et al. (1984) did not find any significant differences among the 4 models in estimating either silking or maturity dates. Our approach was to fit two polynomial equations to the response curve obtained from the Lehenbauer (1914) data by Gilmore and Rogers (1958).

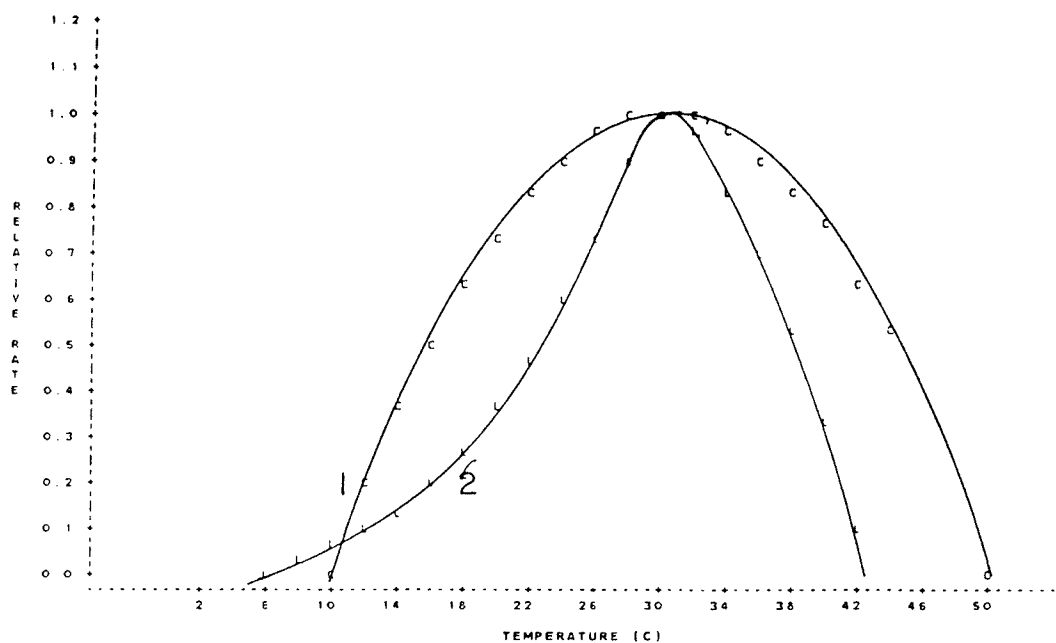


Figure 12: Curves representing temperature response functions determined from equations 5.3B (curve 1) and 5.4 (curve 2).

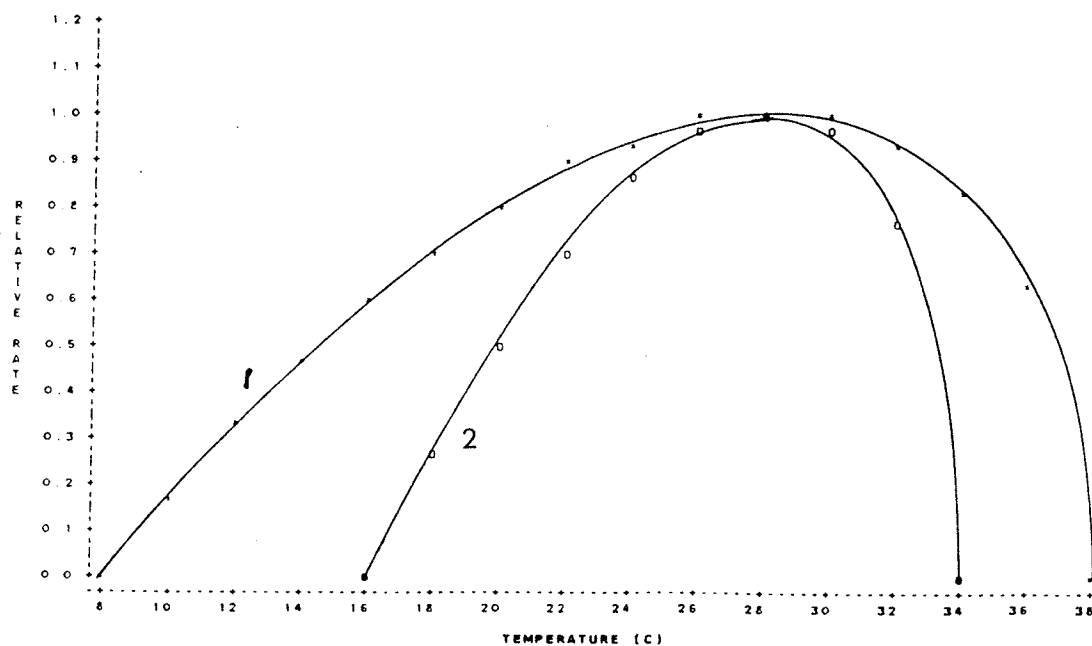


Figure 13: Curves representing temperature response functions determined by equation 5.7.

The best fit was obtained by plotting the polynomial equations and comparing the plotted curves to the original curve. The response function obtained using the polynomial equations can be described as:

$$\begin{aligned} \text{LEH} &= \text{LEH1} && \text{for } 4.4 \leq T < 27.5^\circ\text{C} \\ &= \text{LEH2} && \text{for } 27.5 \leq T \leq 43^\circ\text{C} \\ &= 0 && \text{for } T < 4.4^\circ\text{C} \text{ and } T > 43^\circ\text{C} \end{aligned} \quad (5.4)$$

$$\begin{aligned} \text{where } \text{LEH1} &= -.0678 + .0174T - .00092T^2 + .0000555T^3 \\ \text{LEH2} &= -20.99 + 1.476T - .01946T^2 - .0001529T^3 \\ &\quad - 6.642 \times 10^{-6}T^4 + 1.115 \times 10^{-8}T^5 \\ &\quad + 1.042 \times 10^{-8}T^6 - 1.441 \times 10^{-10}T^7. \end{aligned}$$

Curve 2 (Figure 12) is a graphical representation of equation 5.4. There is an initial curvilinear increase in relative rate with  $T$  from  $4.4^\circ\text{C}$  to an optimum at  $31^\circ\text{C}$  followed by an abrupt and rapid decrease in rate from 31 to  $43^\circ\text{C}$ . The temperature response function represented by equation 5.4 (curve 2) is a vastly different response function from that represented by equation 5.3B (curve 1).

LEH was evaluated separately using both  $T_{\text{max}}$  and  $T_{\text{min}}$  - LEHX and LEHN. The daily development was estimated by:

$$\text{LEHEN} = (\text{LEHX} + \text{LEHN})/2.$$

The above thermal models were used to calculate the daily contribution of temperature to development. The summation, from the beginning to the end of a stage, of the calculated daily contributions gave the total thermal units needed to complete the stage. The theory behind thermal models is that development should depend on temperature, i.e., thermal time, and not on chronological time, i.e., days. For a given stage, the duration of that stage in days may not be constant but accumulated heat units (thermal time) should be constant. With 12 station

years of data there were 12 estimates of the thermal units needed to complete the given stage. The coefficient of variation (CV) for these estimates was used to compare the thermal models for accuracy and reliability in estimating the duration of the stage.

#### 8.3.3.2 Iterative Models

Three iterative procedures were used to estimate the duration of the growth stages ESE, SESI, ESI.

##### 1. Modified corn heat unit equation

The corn heat unit equation was iteratively fitted to the field data in a manner very similar to that described in the model description section. The CHU equation is the sum of two other equations, one a linear equation and the other a quadratic equation representing response functions for  $T_{min}$  and  $T_{max}$ , respectively. Both of these response functions have their own base temperature. The CHU equation was modified by changing the base temperatures of the linear and quadratic equations. This had the effect of moving the linear and the quadratic equations along the horizontal (temperature) axis without changing their shape. For each site, daily heat units were summed to give the total corn heat units needed to complete a given stage. The iterative procedure searched for the base temperature combination (for the linear and quadratic equations) that resulted in the lowest coefficient of variation (CV) for the total corn heat units needed to complete the given stage.



## 2. Robertson's (1968) iterative procedure

Robertson's (1968) iterative procedure (RIP) was fitted to the field data to simulate development. The fitting procedure was developed by Robertson (1968). The model assumes that a) rate of growth is a function of temperature and daylength, and b) the response functions for temperature and daylength are quadratic. The overall response function is represented by the equation:

$$1 = \sum_S^E V_1(V_2+V_3) \quad (5.5)$$

where  $V_1 = a_1(L-a_0)+a_2(L-a_0)^2$   
 $V_2 = b_1(T_{\max}-b_0)+b_2(T_{\max}-b_0)^2$   
 $V_3 = b_3(T_{\min}-b_0)+b_4(T_{\min}-b_0)^2$   
 $S, E$  = start, end of a given stage  
 $L$  = daylength  
 $T_{\max}, T_{\min}$  = daily maximum, minimum temperature  
 $a_1, a_2, b_1, b_2, b_3, b_4$  = rate coefficients  
 $a_0, b_0$  = critical values of the function.

The stage is assumed completed when the sum of the daily rates equals 1. If photoperiod (daylength) does not influence the development rate, as with emergence or for photoperiod insensitive hybrids,  $V_1$  is set equal to 1. Then the rate equation is a function of the two temperature response functions:

$$1 = \sum_S^E \{b_1(T_{\max}-b_0)+b_2(T_{\max}-b_0)^2+b_3(T_{\min}-b_0)+b_4(T_{\min}-b_0)^2\} \quad (5.6)$$

This equation is very similar to the corn heat unit equation.

The RIP was iteratively fitted to the field data assuming that photoperiod did not influence the duration of the stages. Rood and Major



LCT and UCT define the base temperatures for the equation below and above which rate,  $R$ , equals zero. If  $R_{\max} = 1$  then the rate,  $R$ , would be a measure of the relative rate of the process being studied; in our case, development. Two possible temperature response functions represented by equation 5.7 are shown in Figure 13 (p. 106). Curve 1 has the cardinal temperatures  $LCT = 8^{\circ}\text{C}$ ,  $T_{\text{opt}} = 28^{\circ}\text{C}$ ,  $UCT = 38^{\circ}\text{C}$  while for curve 2 the cardinal temperatures are  $LCT = 16^{\circ}\text{C}$ ,  $T_{\text{opt}} = 28^{\circ}\text{C}$ ,  $UCT = 34^{\circ}\text{C}$ . The shape and position of the curves are determined solely by the 3 cardinal temperatures. Many temperature response functions can be represented by equation 5.7 simply by changing the cardinal temperatures. For curve 1, there is a gradual increase in the relative rate with increase in  $T$  to  $T_{\text{opt}}$  with further increases in  $T$  above  $T_{\text{opt}}$  resulting in rapid decreases in the relative rate. The same pattern is evident in curve 2.

Data from the literature indicated temperature response functions similar to those represented in Figure 13. Coligado and Brown (1975a) studied the effect of various temperature ranges ( $0, 8.6, 17.2^{\circ}\text{C}$ ) about given mean temperatures ( $15, 20, 25^{\circ}\text{C}$ ) on the number of days from emergence to tassel initiation. Reworking their data gathered under a 10 hour photoperiod (Figures 2 and 5, Coligado and Brown, 1975a) resulted in the data plotted in Figures 14a and b. Regression analysis of the data gave the equations:

$$\text{Rate} = -0.0618 + 0.00971T - 1.6 \times 10^{-7}T^4 \quad (R^2=.98) \quad (5.8)$$

$$\text{Rate} = -0.0543 + 0.00751T - 8.79 \times 10^{-11}T^6 \quad (R^2=.99) \quad (5.9)$$

for Figure 14a (hybrid United 108) and Figure 14b (hybrid Guelph GX122), respectively. The cardinal temperatures -  $LCT$ ,  $T_{\text{opt}}$  - and  $R_{\max}$  at  $T_{\text{opt}}$

for equations 5.8 and 5.9 were approximately 6.5°C, 25°C, 0.1185 days<sup>-1</sup>, and 7.5°C, 27°C, 0.1145 days<sup>-1</sup>, respectively. These equations and the data indicate a relationship between rate and temperature similar to that shown by the two curves in Figure 13 (p. 106); a gradual increase in development rate with increase in T to T<sub>opt</sub>. Further increases in temperature result in rapid decreases in development rate. Assuming UCT = 36°C and using the cardinal temperatures for equations 5.8 and 5.9, equation 5.7 provides a very good representation (Figures 15a and b) of the temperature response function for the two hybrids of Coligado and Brown's (1975a) study. Although R<sup>2</sup> values were not determined, the fit of the equations to the data was very acceptable. Equations 5.8 and 5.9 also show that the temperature response functions were hybrid dependent.

The data plotted in Figure 14 was obtained from the original data of Coligado and Brown (1975a) by solving linear equations relating development rate under a given day/night temperature regime to the sum of the development rates for constant temperature conditions in the following manner:

$$R(\text{day} + \text{night}) = a R_{\text{day}} + b R_{\text{night}} \quad (5.10)$$

where R(day + night) = development rate (1/days) for a given temperature regime

a, b = coefficients

R<sub>day</sub>, R<sub>night</sub> = individual development rates for the day and night temperatures.

The photoperiod was 10 hours (10 hrs daylight, 14 hrs darkness), therefore, coefficients a and b were assumed to be;  $a = 10/24 = .42$  and  $b = 14/24 = .58$ . The basis of the above equation was the assumption that the day and night temperatures contributed equally to the development rate. By progressively solving all the formulated linear equations, a development rate for a given temperature could be determined. For

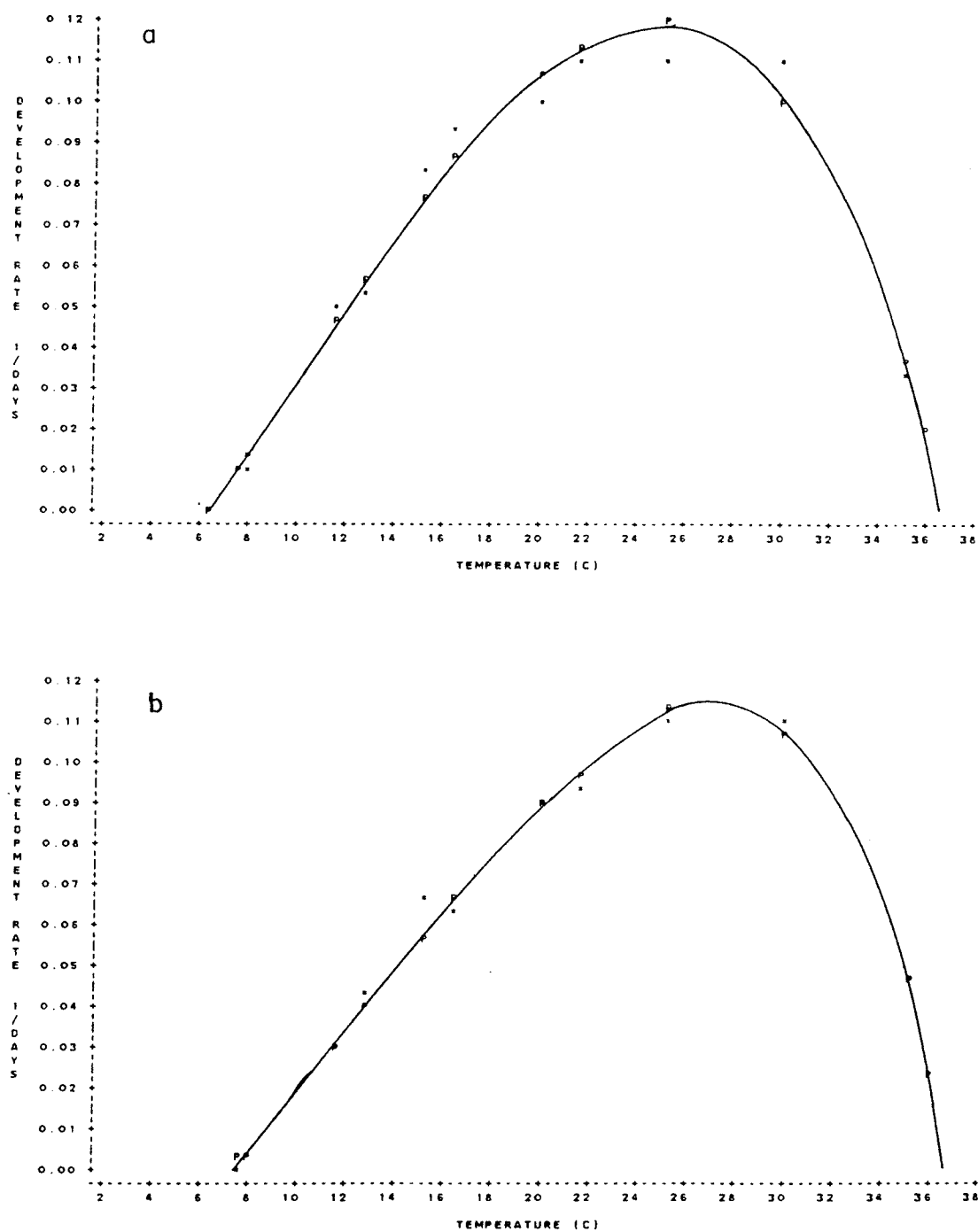
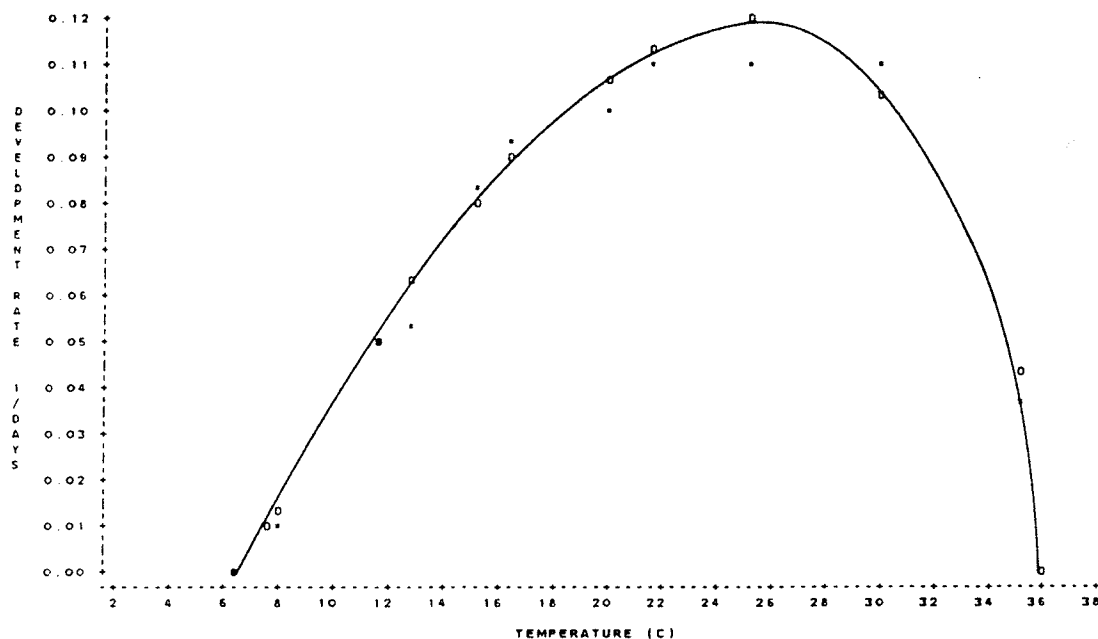


Figure 14: Development rate (ETI) as a function of temperature for hybrids United 108 (a) and Guelph GX122 (b) (P = line of best fit, \* = experimental data).

(a) (LCT=6.5,  $T_{opt}$ =25, UCT=36,  $R_{max}$ =.1185) (Hybrid United 108)



(b) (LCT=7.5,  $T_{opt}$ =27, UCT=36,  $R_{max}$ =.1145) (Hybrid GX122)

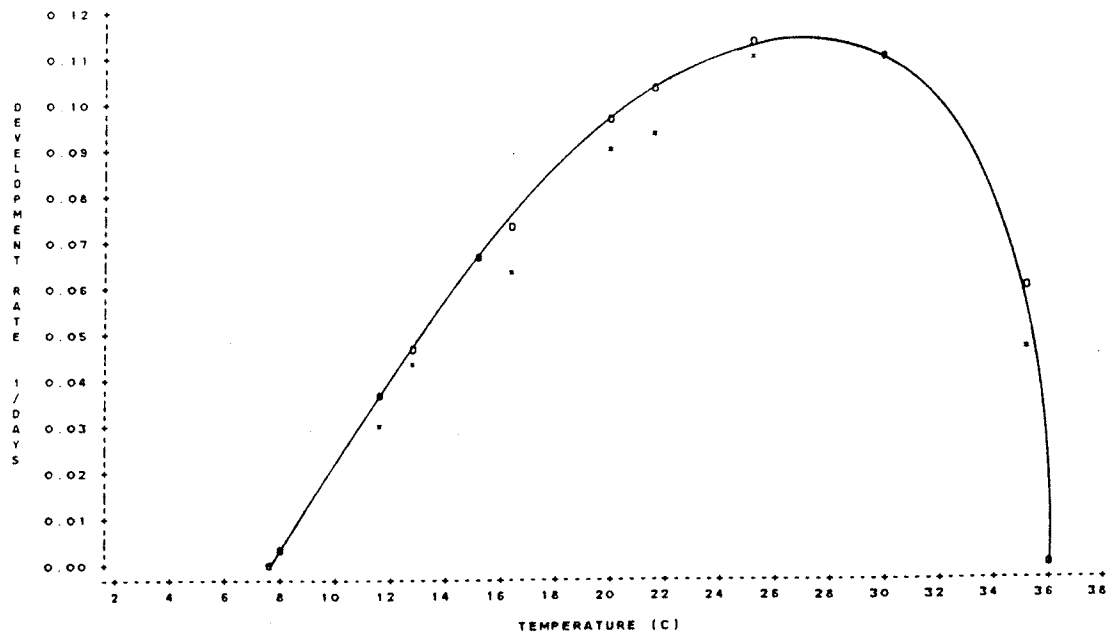


Figure 15: Development rate (ETI) as a function of temperature and the temperature response function determined from equation 5.7. (\* = experimental data, O = line of best fit).

example, at a constant day/night temperature of  $T = 20^{\circ}\text{C}$ , the duration from emergence to tassel initiation (ETI) was 10 days. Therefore the development rate at  $T = 20^{\circ}\text{C}$  was  $R(20) = 1/10 = .1 \text{ days}^{-1}$ . For a day/night temperature regime of  $20/11.4^{\circ}\text{C}$ , the duration of ETI was 14 days. Therefore the development rate for the  $20/11.4^{\circ}\text{C}$  T regime was  $R(20/11.4) = 1/14 = 0.071 \text{ days}^{-1}$ . From this information the development rate at  $11.4^{\circ}\text{C}$  can be calculated by:

$$\begin{aligned} R(20/11.4) &= a R(20) + b R(11.4) \\ 0.071 &= .42(.1) + .58 R(11.4) \\ R(11.4) &= (.071 - .042)/.58 = 0.05 \text{ days}^{-1} \end{aligned}$$

The data of Warrington and Kanemasu (1983a) reaffirm the conclusion that equation 5.7 would be a good representation of development rate as a function of temperature. Reworking their data slightly by subtracting days from planting to emergence from days from planting to tassel initiation gives the duration between emergence and tassel initiation in days. Plotting the resultant data gave Figure 16. The regression equation describing the data was:

$$\text{Rate} = -0.0727 + 0.00782T - 7.91 \times 10^{-20}T^{12} \quad (R^2=0.96) \quad (5.11)$$

where Rate = development rate ( $\text{days}^{-1}$ )  
 $T$  = temperature ( $^{\circ}\text{C}$ ).

The data and equation suggest the skewed nature of development rate as a function of temperature: the gradual increase in rate with  $T$  increase to  $T_{opt}$  ( $= 28^{\circ}\text{C}$ ) with the rapid decrease in rate as  $T$  increases above  $T_{opt}$ . Both Coligado and Brown (1975a) and Warrington and Kanemasu (1983a) carried out their experiments in controlled environment chambers.

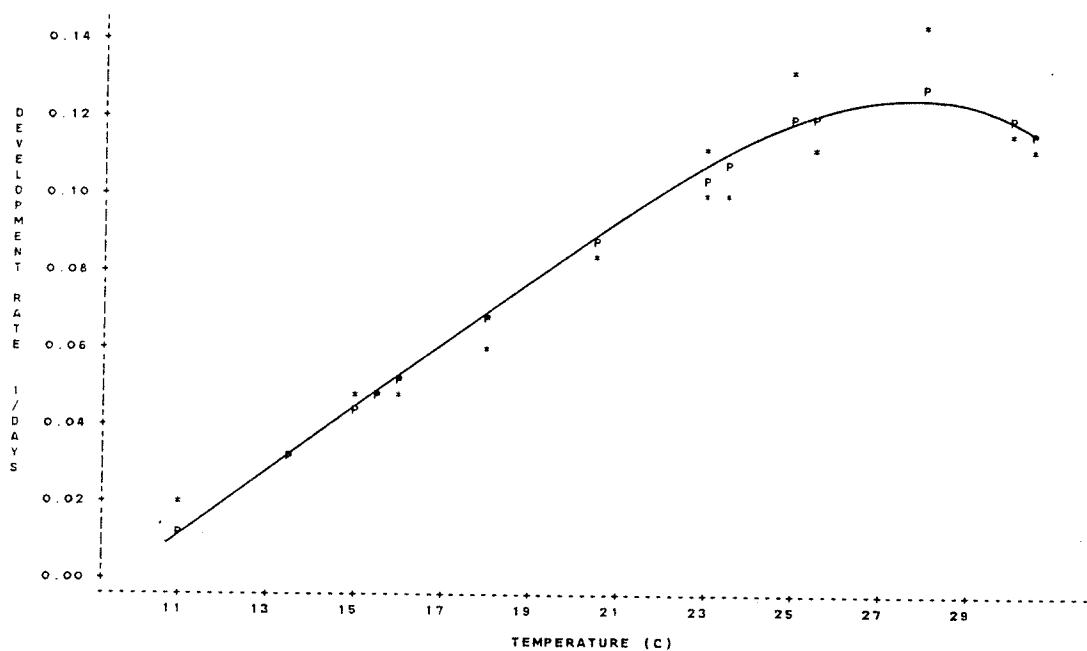


Figure 16: Development rate (emergence to tassel initiation) plotted as a function of temperature for hybrid W346 (original data from Warrington and Kanemasu, 1983a).



Because of the equations derived from the reworked data of Coligado and Brown (1975a) and Warrington and Kanemasu (1983a) produce T response curves very similar to those produced by equation 5.7, an iterative procedure (IF model - described previously in model description section) was employed to fit combinations of equation 5.7 to the field data. The iterative fitting (IF) procedure was carried out using air temperatures and/or 5.0 cm soil temperatures. Equation 5.7 is a very versatile equation - the shape (response function) and position (along the T axis) of the curve derived from the equation depends on the relative positioning of the 3 cardinal temperatures. The iterative procedure used also allows two completely separate T response functions, representing response to  $T_{min}$  and  $T_{max}$  separately to be fitted to the field data. Equation 5.7 may represent a more accurate T response - gradual increase in development rate with T to  $T_{opt}$  with a rapid decrease in rate as T increases beyond  $T_{opt}$  - than is obtained with a quadratic equation.

The accuracy of the above thermal and iterative models was further tested by using the mean units of each model needed for stage completion to predict the duration (in days) of emergence to stem elongation. Using this approach, all the models could be compared to one another for accuracy and reliability. The predicted duration minus the actual duration (in days) of a stage was called the error of prediction,  $e$ . The mean error,  $\bar{e}$ , is a measure of the bias of a model's predictions while mean absolute error,  $|\bar{e}|$ , measures its accuracy. The standard deviation of the absolute error,  $SD(|e|)$ , provides a measure of the precision or variability of a model's errors in predicting the duration of a stage (Daughtry et al., 1984). To minimize the positive bias (a longer predicted duration of stage than actual - overestimation) inherent in

all the models, the mean units of each model, except for Robertson's (1968) iterative procedure (RIP), were multiplied by 0.975. The modified means were then used to estimate the duration of the given stage. To improve the prediction ability of the RIP the base temperature was adjusted until the lowest mean error was obtained. Burnett et al. (1985) used a similar procedure to improve the accuracy of the RIP in estimating soybean development. Similar methods were used to improve the estimation of the duration of planting to emergence (PE). The mean units needed to reach emergence in the emergence model were multiplied by 0.98. The RIP used to estimate the duration of PE was modified in a manner similar to that described above.

## Chapter 9

### RESULTS AND DISCUSSION

#### 9.1 GERMINATION AND EMERGENCE

Unless otherwise stated germination and emergence refer to 50% germination and 50% emergence, respectively.

##### 9.1.1 Field Data

In theory, although the duration in days of a particular growth stage may vary substantially with location and year, the calculated corn heat units (CHU) and growing degree days (GDD) should remain relatively constant. Our field data (Table 16), and the data of the researchers (Major et al., 1983), does not support this concept for the planting to 50% emergence (PE) stage of corn development.

Table 16 shows the duration in days and the calculated CHU using maximum and minimum air and 5.0 cm soil temperatures. The duration of PE ranged from 10 to 32 days. There was also a large variation in the calculated CHU, for both air or soil temperatures.

Other soil parameters may be involved in the germination and emergence processes. It is usually assumed that soil moisture does not limit the emergence process. In the majority of cases this may be true. However, during the field study there was a large reduction in CHU's for

TABLE 16

Corn heat units (CHU) calculated using air temperatures and 5.0 cm soil temperature, duration and total rainfall for planting to 50% emergence. The rainfall for the 3 days prior to planting was included in the total.

Location	CHU		Rainfall (mm)	Duration (days)
	Air Temp	5.0 cm Soil Temp		
Treherne 1980	150	-	147	10
Glenlea 1980	241	242	0	12
Poplarfield 1980	205	222	0	14
Portage 1980	260	254	0	14
Portage 1981	226	204	29	16
Vita 1981	208	221	45	16
Glenlea 1981	283	236	66	18
Glenlea 1983	303	283	14	22
Arborg 1981	354	329	25	26
Fisher Branch 1983	298	334	23	32
MEAN	253	258		18
S.D.	59	47		6.8
C.V.	23%	18%		38%

emergence at Treherne where a major rainstorm occurred just prior to planting (Table 16). The site at Portage during 1980 was very dry during the early part of the growing season. Because of malfunction of the planter, depth control was poor. Seed planted 5 cm deep did not emerge until after the first rain whereas the deeper sown seed (7 - 9 cm) emerged before the rain. The deeper sown seed was placed in soil at higher moisture content.

Early in the growing season, gradients in soil temperature and moisture near the soil surface can be very large. Temperatures usually decrease while moisture levels increase with increasing soil depth. Increasing seeding depth may therefore improve moisture conditions at the expense of decreased soil temperature. Depending on which is most limiting, the duration of PE may be increased or decreased.

#### 9.1.2 Modeling Emergence in the Field

In their attempt to estimate the time to emergence for corn, Major et al. (1983) found calendar days to be the best estimator of the length of this stage. They concluded that corn heat units calculated using air temperatures failed to improve the estimates because of the variation in moisture and temperature conditions at seed depth caused by soil type, seeding depth and crop residue. Wall and Stobbe (1983, 1984) found conventional tillage practices provided the best soil environment for early corn growth and development. Under conventional tillage, crop residues were not present in sufficient quantity to decrease soil temperatures and delay emergence. Crop residue was not a concern during our field studies. However, soil type and seed depth did vary with location. An attempt was made to estimate on a daily basis both soil mois-

ture and soil temperature from aerial weather measurements and relate these estimates, as well as their measured values to corn emergence.

#### 9.1.2.1 Soil Moisture Model

The coefficient determining the relative water withdrawal rate at different depths, PROP (Table 13, p. 88) varied substantially among locations. It was anticipated that as soils dried, the change in water transmission properties (such as hydraulic conductivity) in fine as compared to coarse soils would result in lower PROP values for finer soil textures, i.e., relatively more water be removed from the lower depths in fine as compared to coarse soils. The PROP values obtained from this study did not seem to support this concept. In general, the PROP values for the fine soils were larger than those for the coarse soils. Other factors, such as tillage practices before, during and just after seeding and evaporative demand may also influence the magnitude of PROP.

The condition of the surface 3 to 5 cm (spring tillage depth) may have a strong influence on the value of PROP. For the heavy clays at Glenlea, shallow tillage prior to seeding followed by harrowing after seeding created a surface layer of small pebble sized soil fragments that resist wetting from below. They would thus provide an effective barrier to evaporation. In 1980, when the only spring tillage operation at Glenlea was planting, the 'pebbly' layer was not present. However, this layer was present the following 3 years. During 1980, the PROP value at Glenlea was much lower (reflecting relatively more removal from the lower depths) than for the other years.

TABLE 17

Duration in days and the average daily rainfall, available soil water, potential evaporation for the planting to 50% emergence stage.

Station	Station Number	Duration, N (Days)	Mean Daily Rainfall (cm)	Mean Available Water		Mean Relative Available Water		Mean Daily Potential Evaporation (cm/day)
				Layer 3 (5-10cm)	Layer 4 (10-15cm)	Layer 3 (5-10cm)	Layer 4 (10-15cm)	
Treherne 80	4	10	0.10	.68	1.00	.59	.87	.60
Glenlea 80	3	12	0.01	.24	.81	.27	.90	.74
Poplarfield 80	1	14	0.01	.80	1.00	.80	1.00	.60
Portage 80	2	14	0.00	.08	.58	.08	.58	.66
Glenlea 82	9	14	0.10	1.03	1.10	.94	1.00	.58
Portage 81	6	16	0.18	.76	1.04	.63	.87	.56
Vita 81	8	16	0.28	.63	.87	.57	.79	.58
Vita 82	10	16	0.14	.49	.58	.54	.64	.56
Glenlea 81	7	18	0.37	.89	1.04	.85	1.00	.57
Glenlea 83	12	22	0.09	.79	1.05	.72	.95	.60
Arborg 81	5	26	0.10	.69	1.05	.60	.91	.60
Fisher Branch 83	11	32	0.08	.31	.79	.36	.93	.53

For coarse soils, the compaction of the soil in the seed row can be substantial compared to the soil outside the seed row. This compacted soil may have hydraulic properties contributing to lower than expected PROP values.

Another factor influencing PROP would be the temperature of the evaporating surface. The temperature of the evaporating surface may vary with air temperature, soil type, solar radiation levels and water content. In coarse textured soils, the 2.5 cm maximum soil temperature (STmax) was usually higher than maximum air temperatures (Tmax) but in fine textured soils the differences were very small (Table 18). Examination of the regression equations of Tables 14 and 15 (p. 102 and 103), for Tmax = 25°C, indicates there may be a 2°C difference in the 2.5 cm STmax between coarse and fine soil types. Because potential evaporation was calculated using air temperatures only, the differences between actual and assumed temperature of the evaporating surface would not be taken into account. These differences may have influenced the estimation of PROP to give the best fit between observed and calculated water contents.

Under the conditions of this experiment no specific relationship between PROP and measurable soil or weather variables could be determined. To make general use of a model of this type, other than for research purposes (where best fit to field data can be obtained), a relationship between PROP and other relatively easily measurable variables would have to be determined.



TABLE 18

Duration in days and the average daily values of soil and air temperature, daylength and incoming solar radiation for the planting to 50% emergence stage.

Station	Station Number	Duration (Days)	Mean Daily Air Temp(°C)		Mean Daylength (h)	Mean Daily Solar Radiation Rad(MJ/m <sup>2</sup> -day)	Mean Daily Soil Temperature (C)							
			ATmin†	ATmax			2.5 cm		5.0 cm		10.0 cm		20.0 cm	
							ASTmin	ASTmax	ASTmin	ASTmax	ASTmin	ASTmax	ASTmin	ASTmax
Treherne 80	4	10	8.5	21.6	16.0	26.8	--	--	--	--	--	--	--	--
Glenlea 80	3	12	10.4	28.7	15.6	27.7	--	--	--	--	--	--	--	--
Poplarfield 80	1	14	7.4	22.1	15.6	--	10.2	29.9	11.1	24.5	11.7	17.8	10.9	13.4
Portage 80	2	14	9.9	25.7	15.6	--	8.5	22.8	9.4	20.7	10.5	16.3	10.4	13.4
Glenlea 82	9	14	8.5	21.1	16.0	23.4	10.7	24.8	11.5	20.5	11.8	16.2	11.2	12.8
Portage 81	6	16	7.1	20.4	15.6	21.7	9.2	21.2	10.7	17.9	11.2	15.1	10.5	12.2
Vita 81	8	16	6.0	20.2	15.4	24.2	6.9	21.3	8.4	17.8	9.5	14.3	8.9	10.8
Vita 82	10	16	7.8	19.9	15.8	22.2	6.3	23.7	7.0	20.1	8.3	15.4	8.0	11.4
Glenlea 81	7	18	9.2	21.4	15.8	22.2	--	--	--	--	--	--	--	--
Glenlea 83	12	22	4.6	20.2	15.8	24.5	8.5	19.2	9.6	17.2	10.3	14.2	10.1	12.1
Arborg 81	5	26	4.6	20.2	15.9	23.7	5.9	20.8	7.4	17.2	8.4	13.7	8.3	10.4
Fisher Branch 83	11	32	2.2	16.2	15.9	23.1	5.3	20.8	6.8	17.6	8.3	12.8	7.4	8.8
							4.2	19.2	5.7	16.8	6.8	12.8	7.2	9.4

† ATmin, ATmax - average minimum, maximum air temperatures, respectively, for the planting to emergence (PE) stage  
 ASTmin, ASTmax - average minimum, maximum soil temperature, respectively, at the depth specified for the PE stage.

### 9.1.2.2 Empirical Estimation of Soil Temperature

The temperature of the seed and emerging seedling are more closely approximated by the temperature of their immediate environment, i.e., soil temperature rather than air temperature. Soil temperatures are rarely measured, other than for research purposes, whereas air temperature is the next most commonly measured weather parameter to precipitation. Soil temperatures at seed depth (approximately 5.0 cm) can be substantially different than air temperatures (Table 18). For coarse soils, the average maximum soil temperature (ASTmax) at 5.0 cm was approximately equal to the average maximum air temperature (ATmax). For fine soils, the 5.0 cm ASTmax was lower than ATmax. For all soils the 5.0 cm ASTmin were slightly higher than ATmin. Therefore, for a given air temperature regime, the soil temperatures at seed depth may differ with texture and this difference would probably influence the time to 50% emergence. Air temperatures may be fairly constant over a wide area which may include very different soil types. Because of the dependence of soil temperature on texture, it may be beneficial to estimate soil temperatures from air temperatures and use the predicted soil temperatures to estimate time to 50% emergence.

The coefficient of determination ( $R^2$ ) of the equations relating maximum-minimum air temperatures to the maximum-minimum soil temperatures at 2.5 and 5.0 cm depths were greater than 0.85 for the coarse soils (Table 14, p. 102) but were less than 0.80 for the fine soils (Table 15, p. 103). The inclusion of daily incoming solar radiation in the regression equations for STmax at the 2.5 and 5.0 cm depth significantly increased the  $R^2$  for STmax estimation to between 0.85 and 0.90 for both soil groups. The regression of 2.5 and 5.0 cm minimum soil

temperature ( $ST_{min}$ ) on minimum air temperature ( $T_{min}$ ) was highly significant and  $R^2$  were greater than 0.90 for the coarse soils but less than 0.80 for the fine soils. For the fine soils, when the previous day  $T_{max}$  and the two day previous  $T_{min}$  were included in the regression, the  $R^2$  were improved from less than 0.8 to approximately 0.84. For coarse soils, including the previous days  $T_{min}$  significantly improved the empirical relationship for the 5.0 cm, but not the 2.5 cm,  $ST_{min}$ . This would indicate that for fine soils, and to a lesser degree for coarse soils, the weather conditions of the previous one or two days may significantly influence the present day soil temperature regime. These differences in the regression equations between the two soil groups may be related to the differences in the water holding capacities.

Thermal diffusivity,  $D$ , is a proportionality coefficient between the temperature gradient and the rate of change in temperature that can occur in a given volume. It is proportional to the thermal conductivity,  $k$ , and inversely proportional to the volumetric heat capacity ( $C_v$ ), both of which change with moisture content (Hillel, 1980).  $D$  is usually larger for coarser soils than finer soils at most volumetric moisture contents ( $\theta$ ). However, as  $\theta$  approaches 0.0,  $D$  for all soils become approximately equal (Hillel, 1980). Therefore, under most moisture conditions, coarser soils warm up and cool down faster than finer soils.

Water has a heat capacity approximately 5 times that of the solid matrix in soils (Taylor and Ashcroft, 1972). To produce a  $1^\circ\text{C}$  rise in temperature 5 times as much heat would have to be applied to water than to the solid matrix. Since fine soils usually hold more water on a unit

volume basis than coarse soils, sometimes 2 to 3 times as much water, their heat capacities are usually much higher. This high heat capacity of water may act as a buffer (resistance) to changes in soil temperature. Because of this buffering ability of water, soil temperature in soils with high moisture contents (fine vs coarse soils) may be influenced by heat storage from previous days.

Within each soil group, calculated daily moisture contents did not add significantly to the regression analysis. Under prairie conditions and over long periods of time (greater than one week) other researchers have found precipitation did not significantly affect soil temperature (Reimer and Shaykewich, 1980). However, over short periods of time (less than one or two days) the soil temperature regime may be significantly affected by precipitation. The temperature of the rain itself, evaporative cooling and increased cloud cover (decreasing incoming solar radiation) may combine to affect the soil temperature regime.

The regression equations of Tables 14 and 15 (p. 102 and 103) indicate that for a  $T_{max}/T_{min}$  regime of  $25/10^{\circ}\text{C}$  and incoming solar radiation of  $25.1 \text{ MJ/m}^2\text{-day}$  ( $600 \text{ cal/cm}^2\text{-day}$ ), the 2.5 and 5.0 cm  $ST_{max}$  for coarse soils were 3 and  $3.5^{\circ}\text{C}$  higher, respectively, than those for fine soils.  $ST_{min}$  for each soil group were approximately equal and only slightly higher than  $T_{min}$ . Therefore under the same aerial environment, corn may develop and emerge faster in coarse than in fine textured soils.

Soil temperatures in the top 20 cm were adequately estimated using air temperatures and incoming solar radiation. The regression equations here should be tested further using independent data and should be

revised using the larger data base. It may be beneficial to divide the two soil textural groups into three; coarse, medium and fine. The equations of Tables 14 and 15 should be restricted to conventional tillage conditions where trash cover is minimal.

#### 9.1.2.3 Estimating Corn Emergence

Differences between observed dates of emergence and those calculated from the emergence model are shown in Table 19. The inclusion of a moisture term in the emergence equation noticeably decreased the difference between calculated and observed days to emergence, the improvement in the sum of the differences ranging from 7 to 10 days, depending upon whether actual or estimated soil temperature data was used. The use of either the actual seeding depth or an assumed constant seed depth of 6.0 cm did not noticeably change the sum of the differences but the standard deviation was larger when a constant seed depth was assumed. At those locations with seed depths deeper than 6.0 cm, time to emergence was underestimated (more negative differences between calculated and observed days to emergence). For locations with seed depths shallower than 6.0 cm, times would be overestimated (more positive difference when compared to the calculations for actual seed depth). This resulted in increased deviation about the average difference.

When estimated soil temperatures were used, the model did not predict emergence as well as when measured soil temperatures were used. The empirical equations used to estimate soil temperatures were derived from the measured soil temperature data. The equations accounted for only a portion of the variability of the dependent (soil temperature) variable

in relation to the independent variables (air temperatures and/or solar radiation). Therefore, the error associated with the empirical equations would be transferred to the emergence model. However, the use of estimated soil temperatures does have merit when considering that only air temperatures (and if available, incoming solar radiation) need be measured and used in the emergence model. The empirical equations should be further tested on independent data and revised before extensive use to estimate soil temperatures. Soil temperatures were not measured at location 4 (Treherne 1980). Therefore the soil temperatures for this location were estimated and used in the emergence model (Table 19). The calculated and observed days to emergence were very close, lending support to the use of estimated soil temperatures to estimate emergence.

The calculated days to emergence were less than the observed days by an average of at least 3 days, resulting in an overall error of 15 to 20%, i.e., calculated emergence rates were too high. The difference between calculated and observed days to emergence increased as observed days increased. Observed days increased as soil temperatures at seed depth decreased.

When moisture is not limiting, daily phenological development of the emerging seedling would be proportional to the area under the actual temperature curve bounded by a base temperature,  $T_0$ . The actual temperature curve resembles a modified sine curve. Figure 17 shows the assumed square temperature curve superimposed on the actual temperature curve bounded by three base temperatures;  $T_0 = 0, 10, 20^\circ\text{C}$ . When  $T_0$  is lower than or equal to  $T_{\min}$ , the area under both temperature curves are

TABLE 19

Differences (days) between calculated and observed days to 50% emergence for each location with emergence rate a function of temperature only (moisture assumed nonlimiting), and then a function of temperature and moisture.

Station											Sum of Differences†	Average Difference†	Standard Deviation†
1	2	3	4*	5	6	7	8	11	12				
Remerg = Rmax: function of T only													
Measured soil temperature													
a) measured seed depth													
-1	-2	-3		-5	-3	-1	-4	-7	-5	-31	-3.4	2.0	
b) seed depth assumed to be 6.0 cm													
-1	-2	-3		-9	1	0	-5	-9	-5	-33	-3.7	3.6	
Estimated soil temperature													
a) measured seed depth													
1	-2	-3	-1	-8	-4	-4	-5	-9	-6	-40	-4.4	3.0	
b) seed depth assumed to be 6.0 cm													
1	-2	-2	0	-10	-3	-3	-6	-10	-6	-41	-4.6	3.7	
Remerg = Rmax (1-EXP[-S RAW]): function of T and moisture													
Measured soil temperature													
a) measured seed depth													
-1	1	-3		-4	-2	-1	-4	-6	-5	-25	-2.8	2.2	
b) seed depth assumed to be 6.0 cm													
-1	1	-2		-8	2	0	-5	-8	-5	-26	-2.9	3.8	
Estimated soil temperature													
a) measured seed depth													
1	1	-2	0	-7	-3	-4	-4	-8	-6	-32	-3.6	3.2	
b) seed depth assumed to be 6.0 cm													
1	1	-1	1	-9	1	-2	-5	-10	-6	-30	-3.3	4.3	

\* soil temperatures were not recorded at station 4 (Treherne-1980).

† the differences for station 4 were not included in the calculation of these variables. Negative numbers indicate that calculated date of emergence was earlier than observed.

approximately equal. When  $T_0$  increases above  $T_{min}$  to approach  $T_{max}$  the area under the actual curve decreases faster than the area under the square curve. Therefore, as  $T_0$  approaches  $T_{max}$ , the ratio of the area under the actual curve to the area under the square curve decreases from approximately 1.0 to approximately 0.0. When the ratio of areas,  $A(\text{ratio})$ , was plotted against the temperature ratio,

$$T(\text{ratio}) = (T_{max} - T_0) / (T_{max} - T_{min}) \quad (6.1)$$

the relationship shown in Figure 18 resulted. The areas and temperatures used to obtain Figure 18 were from daily air temperature curves. Regression analysis of the curve gave the following equation ( $R^2=.82$ ):

$$A(\text{ratio}) = 0.015 + 1.589 T(\text{ratio}) - 0.657 T(\text{ratio})^2 + 0.027 T(\text{ratio})^4 \quad (6.2).$$

$A(\text{ratio})$  represents the fraction of the area of the square wave occupied by the area of the actual temperature curve. Because the area under the actual temperature curve dictates development, the temperature portion of the rate equation from the controlled studies was multiplied by  $A(\text{ratio})$  (called REDUCT in the computer model). Without the reduction factor,  $A(\text{ratio})$ , daily development when  $ST_0$  was close to  $ST_{max}$  would be overestimated. Calculated emergence would then occur earlier than observed emergence, as illustrated by the data of Table 19.

The results from the use of this modified model are shown in Table 20. Multiplying the temperature portion of the rate equation by the reduction factor substantially improved the accuracy of the model. Comparing Tables 19 and 20 the improvement in sum of the differences between calculated and observed days to emergence was 15 to 20 days. The improvement was most striking when measured soil temperatures at



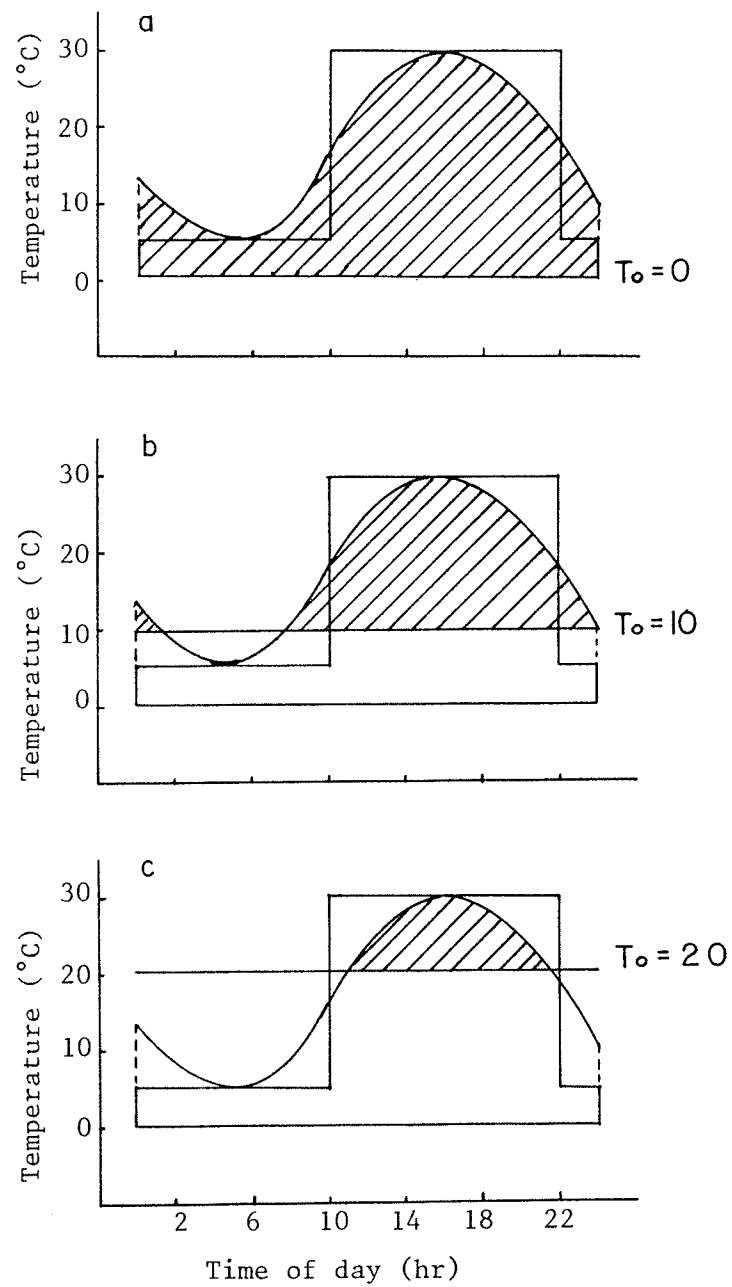


Figure 17: Graphs comparing area under the air temperature curve to that under a square wave temperature curve with varying base temperatures.

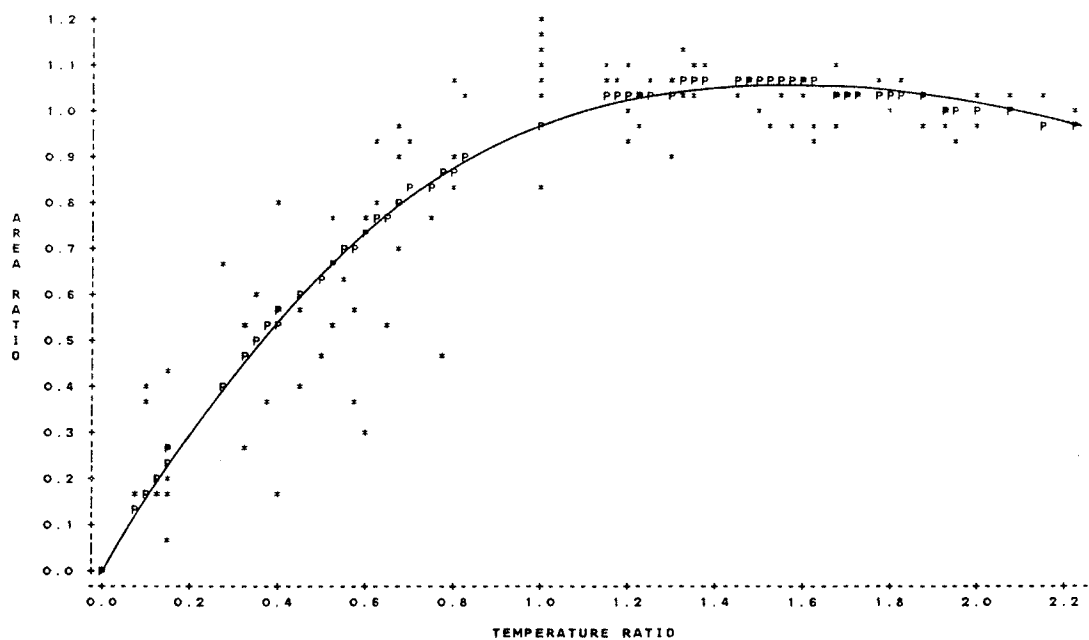


Figure 18: Graph of data and regression equation 6.2 used to calculate the contribution of daily temperatures above  $T_{base}$  to emergence rate.

measured seed depths were used in the model; the greatest improvement occurring for those stations where low soil temperatures were most prevalent. For these cooler conditions, emergence rates would be overestimated with greater frequency and magnitude than for warmer temperature regimes. In this regard seed depth becomes important. With introduction of the reduction factor, there was a separation in accuracy between measured and constant seed depth, the measured seed depth being more accurate mainly because of the increased accuracy for the 'cooler' locations. Three of the 'cooler' locations had seed depths greater than 7.0 cm. Using a constant seed depth of 6.0 cm assumed these seeds were in a warmer temperature environment. This assumed environment would not be as sensitive to the reduction factor as the cooler conditions for the actual seed depths. This would result in overestimation of emergence rates, increasing error.

If hourly temperatures estimated from  $ST_{max}$  and  $ST_{min}$  using a sine function had been used in the model to estimate development rate the reduction term  $A(\text{ratio})$  - called REDUCT in the model - would probably not have been needed. In effect, when the minimum temperature is below the base temperature  $A(\text{ratio})$  approximates, from a square wave function, the area under a sine wave function, where development could occur. When only daily maximum-minimum temperatures are used to estimate development, the equation could be multiplied by  $A(\text{ratio})$  to better estimate daily development when  $T_{min}$  may regularly fall below the base temperature, i.e., early in the growing season.

Although temperature was the major factor influencing development, moisture was shown to have a lesser but important environmental influence on development and emergence (Tables 19 and 20). The emergence

TABLE 20

Difference (days) between calculated and observed days to 50% emergence for each location with the temperature portion being multiplied by a reduction factor (REDUCT) to approximate the area under the actual temperature curve.

Station											Sum of Differences†	Average Difference†	Standard Deviation†
1	2	3	4*	5	6	7	8	11	12				
Remerg = Rmax (REDUCT): function of T only													
Measured soil temperature													
a) measured seed depth													
-1	-2	-3		-2	1	0	-3	-2	-1		-13	-1.4	1.3
b) seed depth assumed to be 6.0 cm													
-1	-2	-2		-4	2	0	-4	-5	-1		-17	-1.9	2.2
Estimated soil temperature													
a) measured seed depth													
1	-2	-2	0	-4	-3	-4	-4	-3	-4		-25	-2.8	1.6
b) seed depth assumed to be 6.0 cm													
1	-2	-2	1	-6	1	-2	-4	-7	-4		-25	-2.8	2.8
Remerg = Rmax (REDUCT) (1-EXP[-S RAW]): function of T and moisture													
Measured soil temperature													
a) measured seed depth													
-1	1	-2		-1	2	0	1	-1	0		-1	-0.1	1.3
b) seed depth assumed to be 6.0 cm													
-1	1	-2		-3	3	1	-3	-3	0		-7	-0.8	2.2
Estimated soil temperature													
a) measured seed depth													
1	1	-2	0	-4	1	-3	0	-3	-4		-13	-1.4	2.2
b) seed depth assumed to be 6.0 cm													
1	1	-1	1	-5	2	-2	-4	-5	-4		-17	-1.9	2.8

\* soil temperatures were not recorded at station 4 (Treherne-1980).

† the differences for station 4 were not included in the calculation of these variables. Negative numbers indicate that calculated date of emergence was earlier than observed.

rate equations developed from the controlled studies, with the inclusion of the reduction factor and using actual seed depth and soil temperatures, provided an accurate estimate of emergence. The temperatures at seed depth would be a good approximation of the average temperature the emerging seedling would experience as the roots grow deeper into cooler soil and the shoot grows upwards into warmer soil. Comparing the controlled study with the field study, root volume and the shoot-root temperature differences would not be as large a problem during the emergence stage as it would for later stages. At these later stages, temperature differences between the above ground shoots and below soil surface roots could be very large. The interaction of these two greatly different temperature regimes and the effects of restricted root volumes during controlled studies may affect phenological development and make it difficult to apply phenological measurements from controlled studies to those from field studies. However, for emergence, conditions during controlled environment studies may closely approximate those in the field and equations and observations from these studies should closely describe those in the field.

### 9.1.3 Regression Analysis of Field Data

#### 9.1.3.1 Analysis of Mean Environmental Variables and Days to 50% Emergence

The influence of the mean environment at each location (Tables 17, p. 123 and 18, p. 125) on emergence rate (inverse days to 50% emergence) was analyzed using linear regression analysis. The resulting equations are listed in Table 21.

TABLE 21

Regression equations relating the average daily environmental data (Tables 17 and 18) at each location to the emergence rate (inverse of observed time to 50% emergence).

Equation	R <sup>2</sup>
Air temperature†	
$1/D = .0053 (AVT - 2.43)$	0.54 *
$1/D = .0039 (AT_{max} - 5.16)$	0.40 *
$1/D = .0062 (AT_{min} + 3.06)$	0.62 *
6.0 cm soil temperatures†	
$1/D = .0082 (AVT6 - 6.34)$	0.86 ***
$1/D = .0092 AVT6 + .0094 MAVW - .081$	0.93 ***
$1/D = .0434 AVT6 - .001252 (AVT6)^2 - .2951$	0.94 ***
$1/D = .0033 AST_{max} + .005 AST_{min} - .0462$	
$= .0033 (AST_{max} - 5.57) + .005 (AST_{min} - 5.57)$	0.87 ***
$1/D = .00456 AST_{max} + .00463 AST_{min} + .0093 MAVW - .08$	0.93 ***

† AVT is average air temperature (°C)

AT<sub>max</sub> is average daily maximum temperature (°C)

AT<sub>min</sub> is average daily minimum temperature (°C)

† AVT6 is average 6.0 cm soil temperature (°C)

AST<sub>max</sub> is average daily 6 cm maximum soil temperature (°C)

AST<sub>min</sub> is average daily 6 cm minimum soil temperature (°C)

MAVW is mean available water (cm) from the 3 to 15 cm soil layer

D is duration from planting to 50% emergence in days.

\* significant at P=.05

\*\* significant at P=.01

\*\*\* significant at P=.001

The relationships between air temperatures ( $AT_{max}$ ,  $AT_{min}$  and average temperature,  $AVT = [AT_{max} + AT_{min}]/2$ ) and emergence rates were significant ( $P=.05$ ) but the  $R^2$  values for the regression equations were low ( $\leq 0.62$ ). When the 6.0 cm soil temperatures ( $AST_{max}$ ,  $AST_{min}$  and average soil temperature,  $AVT_6 = [AST_{max} + AST_{min}]/2$ ) were used the relationships were highly significant ( $P=.001$ ) and the  $R^2$  values improved to greater than 0.85. Emergence rate (inverse of duration,  $1/D$ ) and the average 6.0 cm soil temperature ( $AVT_6$ ) calculated from the data of Tables 17 (p. 123) and 18 (p. 125) are plotted in Figure 19. Also plotted are the linear and quadratic regression equations (Table 21) describing the relationship between  $1/D$  and  $AVT_6$ . The regression equations listed in Table 21 have no real biological significance. They merely represent the best fit to the data. The base temperatures,  $T_0$ , obtained from the data through regression analysis were all much lower than the accepted  $T_0$  of approximately  $10^\circ\text{C}$ .

When the analysis was carried out using air temperatures, moisture content did not contribute significantly (at  $P=0.05$ ) to the regression. Only those variables that contribute significantly ( $P=0.05$ ) to the regression were included in the equations. Therefore, equations relating  $1/D$  to air  $T$  and soil moisture were not added to Table 21. When using  $AVT$ ,  $R^2$  for the regression was equal to 0.54. However, when  $AT_{max}$  and  $AT_{min}$  were used in separate analysis the  $R^2$  were 0.40 and 0.62, respectively. These results seem to indicate that emergence rate may be more dependent upon  $AT_{min}$  than  $AT_{max}$ .

In equations predicting emergence as a linear function of soil temperature, the addition of moisture content added significantly to the

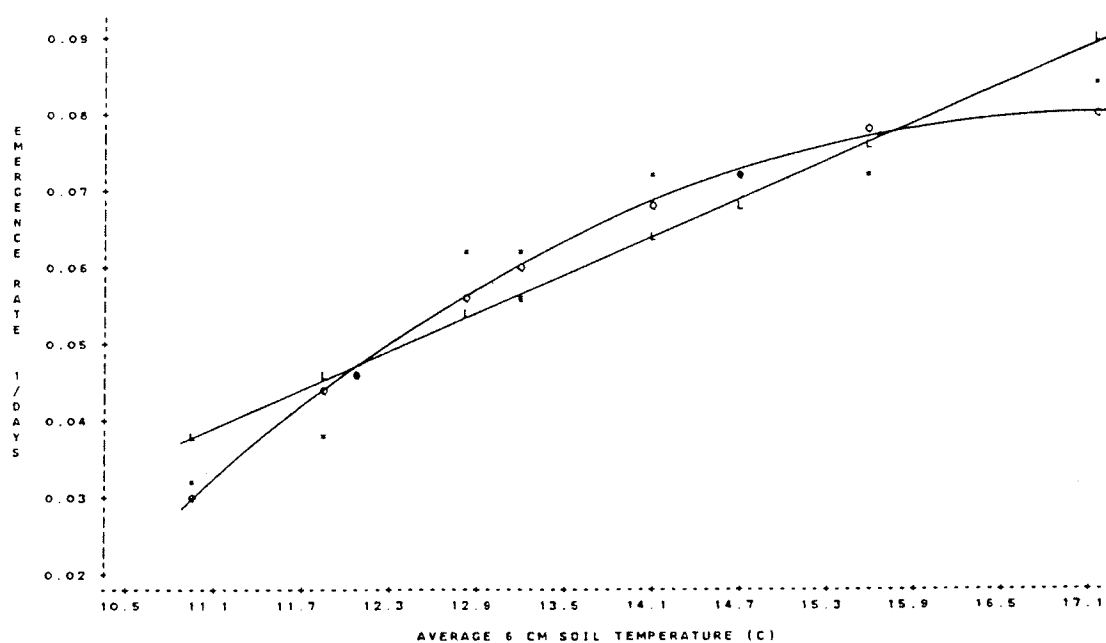


Figure 19: Emergence rate as a function of the average 6 cm soil temperature. The linear (L) and quadratic (Q) equations describing the relationship are also plotted.



regression and increased the  $R^2$  from 0.86 to 0.93 (when using either AVT6 or ASTmax and ASTmin). On the other hand, when the regression analysis was carried out using both the linear and quadratic terms for AVT6 (Figure 19), moisture content did not contribute significantly to the regression. However, the  $R^2$  for the quadratic was approximately equal to the  $R^2$  of the equation involving AVT6 and moisture content. Higher temperatures and solar radiation levels may be associated with lower rainfall and therefore drier soil moisture conditions. The lower soil moisture may result in lower than expected emergence rates for the higher temperatures.

The regression equations obtained when AVT6 was partitioned into the two components, ASTmax and ASTmin, did not differ from those involving AVT6. The  $R^2$ , intercepts and coefficients were very similar. Without moisture, the coefficients were weighted towards ASTmin. However, with the addition of moisture, the coefficients for ASTmax and ASTmin were approximately equal indicating maximum-minimum temperatures made the same contribution to rate. The change in the coefficients with the addition of the moisture term may indicate that rate limitations caused by moisture stress may be more severe at the higher temperatures, as was concluded from the controlled study. The regression equations confirmed the previous conclusion that under field conditions soil temperatures were usually the dominating influence on emergence rate. Moisture stress can also significantly affect emergence rates but would usually be of only minor importance.

### 9.1.3.2 Robertson's (1968) Iterative Procedure (RIP)

A sophisticated statistical procedure involving iteration was employed by Robertson (1968) to fit a combination of quadratic equations to phenological field data. The nature of the method is such that a number of best fit equations can be determined from a given set of data, especially if the data base is relatively small. Robertson's method provides the statistical best fit to the data and it may therefore be difficult to attach any biological meaning to the calculated coefficients and base temperatures. In addition, the best fit to the available data may have little accuracy when applied to new data. Comparing the statistically derived solutions with biologically obtained parameters and concepts may not yield the best fit for the available data but may help choose the solution that may be best applied to other data.

Robertson's procedure was used to fit the temperature quadratic equations to the data assuming daylength did not influence planting to emergence. Three groups of temperatures (air, measured and estimated soil temperatures) were used in the analysis with the resulting coefficients listed in Table 22. Measured soil temperatures gave the best results, air temperatures the worst (Table 23). The coefficients and  $T_0$  for the measured and estimated soil temperatures were very similar with only the linear terms contributing significantly to the relationship. The coefficients were also very similar to those obtained from linear regression analysis of the mean data (Table 18, p. 125) illustrating the statistical basis of the Robertson method. Actual temperatures at seed depth rarely exceed 30°C. Below these optimum temperatures the results from fitting the RIP to field data indicate that the relationship of rate to

temperature was linear. When using air temperatures, the equation of best fit resulted from the use of  $T_{max}$  only with a base temperature of  $15.7^{\circ}\text{C}$ .

The field data were used to determine the coefficients providing the best fit, for the RIP (Table 22). There was no independent data with which to test the models. Therefore the best measure of the goodness of fit of the model (derived coefficients) was to predict emergence dates and compare them to the observed dates (Table 23). The original coefficients showed strong bias to earliness. The coefficients listed (Table 22) were modified by adjusting the base temperature,  $T_0$ , to obtain minimal bias. The differences between calculated (using the modified  $T_{base}$ ) and observed days to emergence with standard deviations are listed in Table 23. The model using actual soil temperatures resulted in the lowest SD followed by the models using estimated soil temperatures and, lastly, air temperatures.

TABLE 22

Parameters obtained from fitting Robertson's (1968) Iterative Procedure to the field data for planting to 50% emergence.

Tbase (°C) b <sub>0</sub>	b <sub>1</sub>	Tmax	Coefficients		Tmin	b <sub>4</sub>
			b <sub>2</sub>	b <sub>3</sub>		
Air T 15.7	.01602		-.0005644	--		--
Estimated 6 cm soil T 6.65	.00375		--	.0055		--
Actual 6 cm soil T 5.278	.0035		--	.0045		--

TABLE 23

Difference (days) between those calculated with the Robertson's (1968) Iterative Procedure and observed days from planting to 50% emergence.

Station												Sum of Differences (days)	Standard Deviation (days)
1	2	3	4	5	6	7	8	9	10	11	12		
Air T													
-1	0	1	-3	8	-2	2	-3	-4	-4	1	5†	0	3.7
Estimated 6 cm soil T													
-3	0	0	-4	5	-2	2	-2	-4	1	5	2	0	3.1
Actual 6 cm soil T													
-1	0	0	-	4	-3	0	-2	-3	-	4	1	0	2.5

† positive days - predicted greater than actual length of stage  
negative days - predicted less than actual length of stage

## 9.2 EMERGENCE TO STEM ELONGATION (ESE)

### 9.2.1 Relationship of Average Mean Temperatures to the Duration of ESE.

Average daily weather variables for the emergence to stem elongation stage for hybrids Pioneer 3995, Northrup King 403 and Pride 1108 are given in Appendices E, F and G, respectively. The relationship between development rate for the emergence to stem elongation (ESE) period and the average daily air temperature (AVT) for ESE was linear and very highly significant ( $P=0.001$ ) for all three hybrids ( $R^2 \geq 0.75$ ). Curvilinear regression did not improve the relationships. Using the two components of AVT, ATmax and ATmin, in the regression analysis did not substantially improve the  $R^2$  except for Pioneer 3995 (Table 24). From this type of analysis the coefficients for ATmax and ATmin suggested that the minimum and maximum temperatures contributed equally to development of NK 403 and Pride 1108. However, for 3995 the influence of the maximum temperature on development, as indicated by the size of the regression coefficient, was approximately twice that of the minimum temperature. The base temperatures for the equations involving AVT were between 8-10°C, similar to that reported by Warrington and Kanemasu (1983a).

Because of problems with the neutron probes used to measure soil moisture at depths >20cm, soil moisture readings were discontinuous and unreliable. Therefore soil moisture was not included as one of the independent variables in the regression analysis for the ESE stage. Under Manitoba conditions the soil profile at the beginning of the growing season is usually near field capacity. During ESE root exten-

TABLE 24

Regression equations describing the relationship between development rate ( $1/D$  - inverse of the duration in days of the stage) and the average daily temperature (AVT) for the emergence to stem elongation stage.

Hybrid	Development rate equation†	R <sup>2</sup>
3995	$1/D = .003729 (AVT - 8.3)$	.76
	$1/D = .002612 AT_{max} + .001182 AT_{min} - .04126$	.81
403	$1/D = .003472 (AVT - 8.0)$	.80
	$1/D = .001877 AT_{max} + .001592 AT_{min} - .02955$	.81
1108	$1/D = .004271 (AVT - 9.8)$	.76
	$1/D = .002120 AT_{max} + .002157 AT_{min} - .04165$	.76

† All equations significant at  $P=.001$

TABLE 25

Regression equations for the relationships between leaf number at stem elongation (SELN) and the final leaf number (FLN) and the average 5 cm soil temperature (AVTS) for the emergence to stem elongation stage.

Hybrid	Regression equation	R <sup>2</sup>
3995	$SELN = .5435 AVTS + 1.2283$	.44
	$FLN = .4068 AVTS + 7.4493$	.36
1108	$SELN = 95.410 - 9.615 AVTS + .279 AVTS^2$	.58
	$FLN = 149.826 - 15.25 AVTS + .438 AVTS^2$	.48

sion into this deeper wetter soil would be occurring and moisture availability therefore was assumed to be nonlimiting.

For all 3 hybrids, the relationship between the development rate and the average 5 cm soil temperature ( $AVTS = [ASTmin + ASTmax]/2$ ) for ESE was not significant at  $P=.05$ ; neither linear nor curvilinear regression analysis was significant. The overall regression analysis indicated that air temperatures were better estimators of the development rate during ESE than soil temperatures. Preliminary examination indicated that these results were contrary to those implied from growth room experiments (Beauchamp and Lathwell, 1967; Brouwer et al., 1973) and field experiments using mulch treatments to control soil temperatures (Cooper and Law, 1978; Watts, 1973). The above researchers used leaf number and/or leaf extension rates as a measure of development rates. By contrast, the criterion for development in the present study was stem elongation, defined as that time when the apical meristem just emerged above the soil surface. Thus, the difference in results obtained may be due entirely to the difference in the definition of development rate.

Although the development rate for ESE was significantly influenced by air temperatures and not soil temperatures, there were indications that the opposite may be true for both leaf number at stem elongation (SELN) and final leaf number (FLN). Regression analysis indicated that at  $P=.10$ , for Pioneer 3995, both SELN and FLN were related linearly to AVTS and, for Pride 1108, quadratically to AVTS (Table 25). For both hybrids SELN and FLN showed little relationship to air temperatures. At  $P=.10$ , SELN and FLN for NK 403 were not significantly related to either AVTS or

AVT. The relationship of leaf number to soil or air temperature would require further research before further conclusions could be reached. Warrington and Kanemasu (1983b) also found a curvilinear relationship for FLN to temperature. They found leaf numbers first decreased and then increased with increase in mean temperature from 11 to 35.5°C. The lowest leaf number occurred at 18°C. Beauchamp and Lathwell (1967) found leaf numbers increased slightly with increase in soil temperature independent of air temperature.

Depending on how development rate is measured, and during what stage, there may be a significant relationship between development and either air or soil temperatures. Leaf number and leaf appearance rates have been found to be influenced by soil temperatures. The data of Iremiren and Milbourn (1979) showed that the time from planting to emergence was significantly influenced by soil temperature but the time from emergence to tassel initiation (ETI) or from emergence to silking (ESI) was not influenced by the soil temperature. The duration of ETI was equal for the two mulch treatments of their study despite an average 4°C difference in soil temperature between the two treatments. Carr (1977) presented data which showed an approximate 15 day delay in silking with a decrease of approximately 3°C in the average 5 cm soil temperature during the first 6 weeks after planting. This compared very well with the data of Iremiren and Milbourn (1979) which showed a 15 day delay in emergence with an average 4°C decrease in soil temperature. Therefore for Carr's (1977) experiments the delay in silking caused by decreased soil temperatures may have occurred during the planting to emergence stage with soil temperatures having little influence on development rates after emergence.



The data of our experiments suggested that, with the analysis used, air temperatures were more significantly related to development rate during ESE than were soil temperatures.

### 9.2.2 Thermal Models

For each hybrid the accumulated daily development calculated using air temperatures with the LEHEN, CHU and GDD thermal models are listed in order of increasing duration in days from emergence to stem elongation (ESE) in Table 26. The means, standard deviations (SD) and coefficient of variations (CV) are also shown. The results obtained from the models MGDD and GDD were almost identical and therefore only GDD was compared to the other models.

For the ESE stage there was very little difference in the mean duration (days) between the 3 hybrids. The hybrids can be arranged in order of increasing mean duration (DAYS) - 3995 > 403 > 1108 - with a difference in mean duration between 3995 and 1108 of only 2 days. However, for a given hybrid the difference among the locations with the shortest and longest duration of ESE was approximately 15 days. Among hybrids there was little difference in the means for each of the thermal models. The order of increasing mean was the same as for increasing duration - 3995 > 403 > 1108. Of the thermal models, the LEHEN model had the lowest CV; only slightly lower than the CV for GDD. The CV for the CHU model was substantially larger than for the other two models. Since the CV for duration in days of ESE were approximately twice the CV's for the thermal models, the results indicate that all of the 3 thermal models were better estimators of the duration of ESE than calendar days.

TABLE 26

The sum of the calculated daily units for each of the thermal models and two of the iterative models (IF and modified CHU) for the emergence to stem elongation stage (ESE).

Hybrid	Station Number	Duration (DAYS)	Accumulated development units				Iterative models	
			Thermal models			GDD	IF	MCHU (7, 15°C)
			LEHEN	CHU (4.4, 10°C)				
Pioneer 3995	12	25	9.48	551	218		11.63	416
	4	27	10.03	561	220		11.75	415
	3	28	9.36	526	212		11.00	386
	2	30	11.01	607	244		12.85	453
	5	31	10.24	625	238		12.35	445
	7	31	10.47	634	245		12.81	456
	11	31	10.16	628	238		12.35	443
	1	32	11.16	620	254		12.80	452
	6	36	9.88	671	233		12.00	430
	9	37	10.83	654	249		12.54	442
	10	40	10.70	695	255		12.55	449
	MEAN	31.64	10.30	616	240		12.24	439
	SD	4.48	0.59	52	14		0.59	22
	CV(%)	14.12	5.77	8.39	5.83		4.79	5.01
Northrup King 403	4	27	10.03	561	220		16.13	415
	12	27	9.82	582	226		16.62	430
	2	30	11.01	607	244		17.04	453
	3	30	10.57	583	238		15.59	438
	11	31	10.16	628	238		17.12	443
	7	32	11.14	665	259		18.26	485
	1	33	11.37	637	260		17.19	462
	5	33	11.11	674	258		17.55	484
	6	35	9.67	654	228		16.96	421
	9	38	11.39	682	261		17.43	465
	10	39	10.44	674	248		16.66	435
	MEAN	32.27	10.61	632	247		16.96	448
	SD	3.93	0.63	43	15		0.72	24
	CV(%)	12.17	5.92	6.8	6.07		4.22	5.36
Pride 1108	4	27	10.03	561	220		14.75	415
	12	28	9.99	594	231		15.80	436
	11	29	9.31	578	219		14.25	402
	2	30	11.01	607	244		15.70	453
	3	30	10.57	583	238		14.43	438
	7	31	10.83	647	252		16.50	472
	1	33	11.37	637	260		16.16	462
	5	34	11.57	695	267		16.84	501
	6	37	10.13	691	239		15.33	443
	9	40	12.42	735	284		16.90	510
	10	40	10.70	695	255		15.48	449
	8	45	12.39	806	292		16.71	515
	MEAN	33.67	10.86	653	253		15.74	458
	SD	5.66	0.96	74	23		0.93	36
	CV(%)	16.82	8.80	11.33	9.09		5.90	7.86

Another way of evaluating the models was to use the mean development units from Table 26 for the respective models to estimate the duration in days of ESE. To correct for bias toward earliness, the means of each model were multiplied by 0.975. The results are shown in Table 27. Four statistical measures were used to compare the models for estimation ability. Mean error,  $\bar{e}$ , is a measure of bias of a model's predictions while mean absolute error,  $|\bar{e}|$ , measures its accuracy. The standard deviation of absolute error,  $SD(|e|)$ , provides a measure of the precision or variability of a model's errors in predicting the duration of a stage (Daughtry et al., 1984). The standard error of estimate provides a measure of the precision of the model when the bias is assumed to be zero. The data in Table 27 suggest the same conclusions as those provided in Table 26, viz. the thermal models were much more accurate than calendar days. The LEHEN and GDD models were of approximately equal accuracy with LEHEN being slightly more accurate than the GDD for Pioneer 3995 and Pride 1108. The CHU model was the least accurate thermal model. The CHU model had a larger mean absolute error,  $|\bar{e}|$ , than the other two models.

The theory behind the heat unit or thermal models suggests that the accumulated thermal units should be independent of the duration of the stage under study. The data of Table 26 suggested that for the ESE stage this was not the case, especially for the CHU model. Plotting (Figure 20) and analyzing the data with linear regression analysis (Table 28) provides statistical evidence for a highly significant relationship ( $P=.001$ ) between CHU and duration of ESE (days) for all 3 hybrids. Cooler locations required more CHU to complete the ESE stage than did warmer locations. The relationship between GDD and days was

TABLE 27

Difference in days for predicted minus actual days for the duration of the emergence to stem elongation stage (ESE) calculated using air temperatures with various models.

Station number	Calendar Days	Thermal models			Iterative models			RIP
		LEHEN	CHU	GDD	IF	MCHU	Modified RIP	
Pioneer 3995								
1	0*	-1	0	-1	-1	-1	-2	-6
2	2	-1	0	0	-1	-1	-3	-7
3	4	2	3	2	2	2	-1	-5
4	5	1	2	2	1	1	-3	-10
5	1	0	0	0	0	0	-1	-3
6	-4	1	-2	0	0	0	3	-2
7	1	0	-1	-1	-1	-1	-1	-4
9	-5	-2	-2	-2	-1	-1	-1	-6
10	-8	-1	-4	-2	-1	-1	3	-3
11	1	0	-1	0	0	-1	1	-4
12	7	3	4	3	2	2	3	-5
$\bar{e}$	0.36	0.18	-0.09	0.09	0.0	-0.09	-0.18	-5.0
SE=SD( $e$ )	4.48	1.47	2.34	1.64	1.18	1.22	2.32	SD=2.24, SE=5.7
$ \bar{e} $	3.45	1.09	1.73	1.18	0.91	1.0	2.0	5.0
SD( $ e $ )	2.66	0.94	1.49	1.08	0.70	0.63	1.0	2.24
Northrup King 403								
1	-1	-2	-1	-2	-1	-1	-2	-3
2	2	0	1	0	0	0	-1	-2
3	2	0	2	1	2	0	-1	-2
4	5	1	3	2	1	2	1	0
5	-1	-1	-2	-1	-1	-2	-2	-2
6	-3	-2	-1	1	0	1	1	0
7	0	-1	-1	-1	-1	-1	-1	-2
9	-6	-2	-2	-2	-1	-1	-4	-4
10	-7	0	-2	0	0	1	-1	-2
11	1	1	0	0	0	0	1	0
12	5	2	3	2	0	2	3	2
$\bar{e}$	-0.27	0.0	0.0	0.0	-0.09	0.09	-0.55	-1.36
SE=SD( $e$ )	3.93	1.41	1.95	1.41	0.94	1.3	1.92	SD=1.69, SE=2.21
$ \bar{e} $	3.0	1.09	1.64	1.09	0.64	1.0	1.64	1.73
SD( $ e $ )	2.37	0.83	0.92	0.83	0.67	0.77	1.03	1.27
Pride 1108								
1	1	-1	0	-1	-1	-1	-2	-9
2	4	0	2	0	0	0	-3	-8
3	4	1	3	1	2	1	-3	-8
4	7	2	4	3	2	2	-3	-11
5	0	-2	-2	-2	-2	-2	-3	-6
6	-3	1	-2	1	1	1	4	-2
7	3	0	0	0	-1	0	-1	-5
8	-11	-3	-6	-4	-2	-3	1	-5
9	-6	-3	-3	-3	-1	-2	-2	-9
10	-6	0	-2	-1	0	0	6	-3
11	5	3	3	3	2	3	4	-2
12	6	2	2	2	-1	1	1	-9
$\bar{e}$	0.33	0.0	-0.08	-0.08	-0.08	0.0	-0.08	-6.42
SE=SD( $e$ )	5.66	1.95	3.0	2.23	1.51	1.76	3.23	SD=3.03, SE=7.35
$ \bar{e} $	4.67	1.5	2.42	1.75	1.25	1.33	2.75	6.42
SE( $ e $ )	2.9	1.17	1.62	1.29	0.75	1.07	1.48	3.03

\* negative - actual greater than predicted days

positive - predicted greater than actual days

†  $\bar{e}$  = mean error, SE = standard error of estimate,

SD(e) = standard deviation of mean error,  $|\bar{e}|$  = mean absolute error,

SD(|e|) = standard deviation of mean absolute error.

significant ( $P=.05$ ) for two of the hybrids, 3995 and 1108. However, only one hybrid, 1108, had a significant relationship ( $P=.05$ ) between LEHEN and days. The analysis suggested that there may be a relationship between thermal units calculated using LEHEN or GDD and days but that this relationship was hybrid dependent, i.e., the temperature response was hybrid specific. The analysis indicated there was a definite relationship between CHU and days that was hybrid independent with cooler locations requiring more CHU to complete ESE than warmer locations. The level of significance for the relationship, and the coefficient of determination are also shown.

The CHU model is essentially a quadratic equation describing soybean development under growth chamber conditions that has been iteratively fitted to field data through the use of a linear equation representing the developmental response of corn to minimum temperatures. The stage used to obtain this fit was planting to silking. The results of this study indicated that for the ESE stage, the CHU model does not represent the temperature response functions for the phenological development of corn.

Although the CHU model may be an accurate estimator of development at higher temperatures ( $T \geq 20^{\circ}\text{C}$ ), it may overestimate development at the lower temperatures ( $T \leq 20^{\circ}\text{C}$ ). Instead of a quadratic or linear response to temperatures, the shape of the response function for the lower temperatures may be S-shaped (Figure 21) similar to the LEHEN model. Curve 1 (Figure 21) is representative of the quadratic response function of the CHU model. Curve 2 represents the S-shaped response function that would result in decreased development at the lower temperatures in relation to the quadratic function (curve 1). Based on the CV's of Table 26

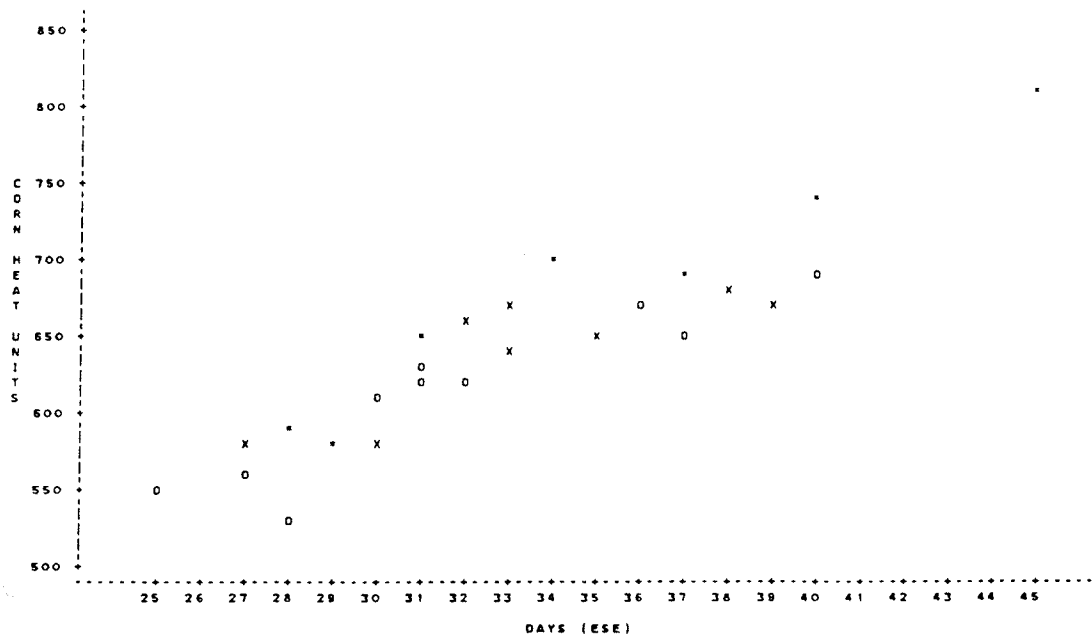


Figure 20: Corn heat units plotted as a function of the duration in days of the emergence to stem elongation stage (ESE).  
(O - 3995, X - 403, \* - 1108).

Linear regression equations describing the relationship between the accumulated units for the thermal models and the duration of the stage (N).

Stage	Hybrid	Equation	R <sup>2</sup>
ESE†			
	3995	CHU = 283 + 10.52 N GDD = 161 + 2.39 N	.83 *** .52 *
	403	CHU = 324 + 9.50 N	.76 ***
	1108	CHU = 232 + 12.5 N LEHEN = 6.85 + 0.119 N GDD = 147 + 3.15 N	.92 *** .50 * .61 **
SESI			
a) stations 11 and 12 (Fisher Branch 83 and Glenlea 83) included			
	3995	CHU = 52 + 21.27 N LEHEN = 0.533 + 0.411 N GDD = 25 + 8.69 N	.77 *** .48 * .50 *
	403	CHU = -137 + 28.11 N LEHEN = -6.13 + 0.646 N GDD = -117 + 13.75 N	.77 *** .55 ** .57 **
b) stations 11 and 12 not included			
	3995	CHU = 24 + 21.99 N LEHEN = -1.15 + 0.46 N GDD = -2 + 9.39 N	.89 *** .86 *** .81 ***
	403	CHU = -59 + 24.78 N LEHEN = -2.88 + 0.506 N GDD = -52 + 10.98 N	.92 *** .88 *** .87 ***
	1108	CHU = -3 + 22.52 N LEHEN = -2.62 + 0.481 N GDD = -19 + 9.58 N	.75 *** .52 * .52 *
ESI			
a) stations 11 and 12 included			
	3995	CHU = 652 + 9.56 N	.44 *
	1108	CHU = 758 + 9.15 N	.55 **
b) stations 11 and 12 are not included			
	3995	CHU = 356 + 14.56 N	.7 **
	403	CHU = 318 + 15.61 N GDD = 146 + 5.77 N	.71 ** .49 *
	1108	CHU = 555 + 12.15 N	.67 **

\* significant at P=.05

\*\* significant at P=.01

\*\*\* significant at P=.001

† ESE = emergence to stem elongation, SESI = stem elongation to silking,  
ESI = emergence to silking

(p. 150) and the error calculations of Table 27 (p. 152), the LEHEN model (similar to curve 2, Figure 21) would be the best of the thermal models used to estimate the development for this stage.



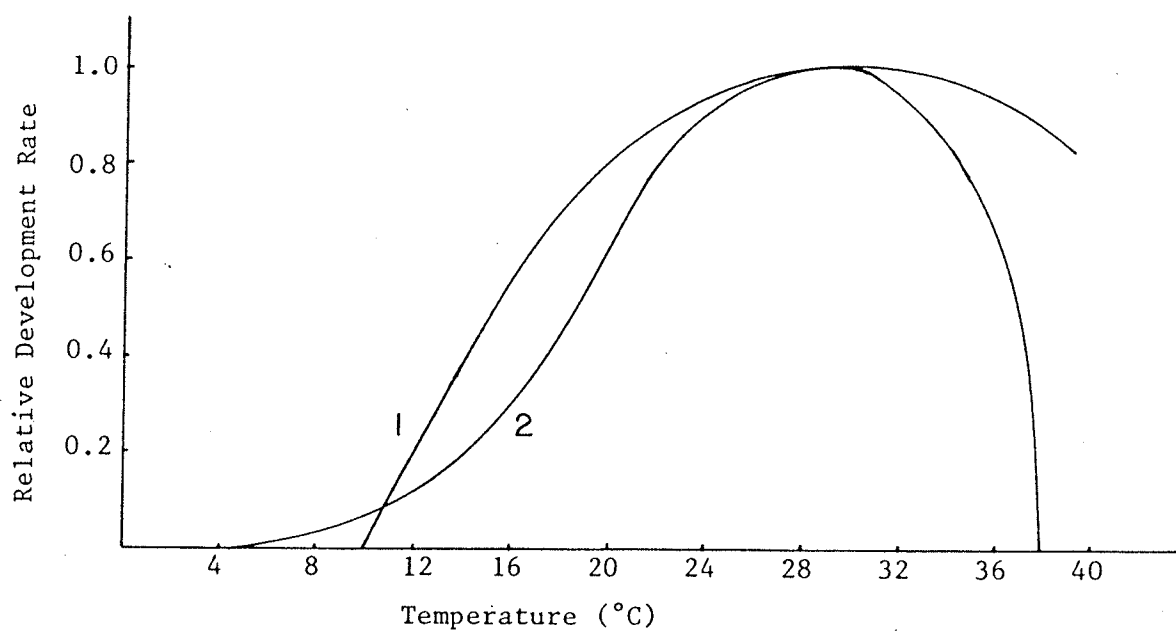


Figure 21: Temperature response functions. Curve 1 is representative of a quadratic response function similar to the CHU equation. Curve 2 is a curvilinear response function similar to the LEHEN equation.

### 9.2.3 Iterative Models

There were 3 iterative approaches used in fitting equations to the field data. Unless otherwise stated, all fitting procedures were performed using air temperatures and not soil temperatures. The first approach was to fit a modified form of the CHU model to the field data. The shapes of the two response equations, i.e., the slope coefficients, representing the CHU model were maintained but the position of the curves along the temperature axis was modified by adjusting the base temperatures until the best fit, lowest CV, was obtained. For the original CHU model, the base temperatures ( $T_{base}$ ) for the minimum and maximum temperature response functions were 4.4 and 10°C, respectively. For the modified CHU (MCHU) model the respective base temperatures were 7 and 15°C. These  $T_{base}$  provided the lowest CV for all 3 hybrids for the ESE stage. The MCHU model had a lower CV (Table 26, p. 150) and was more accurate (Table 27, p. 152) than any of the thermal models, including the original CHU. As a method of estimating the duration of ESE, the modified CHU would be adequate. However, if accuracy as well as a true representation of the temperature response functions were desired, neither the original nor the modified CHU would be acceptable. The quadratic response function indicates that for the original and modified CHU models the temperature above which development ceases would be 50 and 55°C, respectively. These temperatures are much too high when compared to the literature. The base temperature above which development does not occur has been shown to range from 35 to 45°C (Lehenbauer, 1914; Blacklow, 1972b; Singh and Dhaliwal, 1972). The study of Warrington and Kanemasu (1983a) and the reworked data of Coligado and

Brown (1975a) (Figures 14a and b, p. 113) showed that development decreased rapidly as temperatures increased above the optimum temperature. Their results indicated that the relationship between development and temperature is not quadratic, nor is the curve S-shaped below  $T_{opt}$  as indicated by the LEHEN model.

The second iterative procedure fitted to the field data using air temperatures was Robertson's (1968) iterative procedure (RIP). The model was fitted to the data assuming that photoperiod did not affect the development of the hybrids used in this study. Based on the small geographic area over which this study was done, and the small daily change in photoperiod during this stage (compare average photoperiods between stations - Appendices E, F, and G) this assumption was considered valid. The conclusions of Rood and Major (1981) also supported this conclusion. In this study, for all the models tested, analysis showed no relationship between accumulated development units needed for completion of ESE listed in Table 26 (p. 150) and the average photoperiods of the ESE stage (Appendices E, F, and G).

The results obtained from fitting the temperature only part of the RIP model to the data for the ESE stage are shown in Table 29. According to the fitting procedure (used for the RIP) only the maximum daily temperatures contributed to the development of each hybrid.  $T_{min}$  did not contribute to development, i.e., the corn plants were dormant at night. The minimum base temperatures obtained for the quadratic response function for 3995, 403 and 1108 were approximately 16, 11 and 17°C, respectively. Because in the fitting procedure the base temperatures for the quadratic equations relating  $T_{min}$  and  $T_{max}$  to development are assumed equal, the two response curves have a common point.

Therefore, if the base temperature for one of the curves was substantially different from that of the other curve, the influence of  $T_{min}$  or  $T_{max}$  on development may be overlooked and discarded in the fitting procedure, as was probably the case in this study. The base temperatures of 16 and 17°C were much larger than the 6 to 8°C reported in the literature (Warrington and Kanemasu, 1983a) and derived from the data of Coligado and Brown (1975a).

For each hybrid, the CV's for this fitting procedure (Table 29) were very similar to those of the original CHU model (Table 26, p. 150). When the base temperatures and the coefficients of Table 29 were used to estimate the duration of ESE in days for each location, there was a strong bias towards predicting earliness (Table 27, p. 152). The bias was especially large for hybrids 3995 and 1108. To decrease this bias the original RIP equations were modified by adjusting  $T_{base}$  until the bias,  $\bar{e}$ , and error  $|\bar{e}|$ , were minimized - the modified RIP in Table 27 (p. 152). The equations were evaluated on the same data from which they were derived. This gives an indication of the goodness of fit of the model to the original data. The goodness of fit of the derived coefficients for the RIP model was poor (Table 27, p. 152) and for this reason the  $T_{base}$  were modified to improve the fit. The original  $T_{base}$  derived by the model for 3995, 403 and 1108 were 15.80, 10.85 and 16.93°C, respectively while  $T_{base}$  for the modified RIP equations were 17.25, 11.25 and 18.5°C. Burnett et al. (1985) also found that the originally derived coefficients of the RIP had to be modified to obtain reasonable estimates of the duration in days of the stage used in their study of soybean development. Because the goodness of fit of the originally derived coefficients was poor, and the results obtained with the modi-

fied RIP model were only slightly better than with the original CHU model, the RIP was considered inadequate for estimation of stage duration. Also because temperature response functions have been found to be other than quadratic (Warrington and Kanemasu, 1983a), the RIP may not reflect the true temperature response function for development. The modified CHU model was a much more accurate estimator of the duration of the ESE stage than was the modified RIP model.

The third iterative approach to fit equation 5.7 to the field data was the iteration (IF) model. The equation is a very versatile equation that was found to describe the temperature response curves obtained from the growth chamber studies of Warrington and Kanemasu (1983a) and Coligado and Brown (1975a). The model developed was used to fit to field data two completely separate equations describing the temperature response functions of  $T_{min}$  and  $T_{max}$ , respectively. The cardinal temperatures for each hybrid resulting from the fitting procedure (using air temperatures) are shown in Table 30 with the accumulated development units needed to complete the ESE stage, as well as CV's, shown in Table 26 (p. 150). This procedure provided the lowest CV (Table 26, p. 150), especially for Pride 1108, and the best accuracy ( $|\bar{e}|$  - Table 27, p. 152) and best precision ( $SD(|e|)$  - Table 27, p. 152) of any of the models tested. The lowest standard error of estimate was also obtained with this method (Table 27, p. 152). Figure 22 is a graph of the development units calculated using the IF model plotted as a function of duration of ESE in days. Analysis of the data showed no relationship between accumulated units and duration of the stage in days. The cardinal temperatures that resulted from the fitting procedure using air

TABLE 29

Robertson's (1968) iterative procedure (RIP) coefficients derived using air temperature (photoperiod assumed to have no effect on development).

Stage & Hybrid	Tbase b <sub>0</sub>	b <sub>1</sub>	Tmax b <sub>2</sub>	Tmin b <sub>3</sub>	b <sub>4</sub>	CV(%)
<u>Emergence to Stem Elongation</u>						
3995	15.89	.005646	-.0001348	0.0	0.0	6.6
403	10.85	.002726	-.00001479	0.0	0.0	7.4
1108	16.93	.006920	-.0002345	0.0	0.0	10.2
<u>Emergence to Silking</u>						
3995	5.66	.0009539	0.0	0.0	0.0	4.7
403	1.281	.0005741	-.000001771	.0008577	-.00003657	5.4
1108	7.853	.0009627	0.0	0.0	0.0	5.1

temperatures (Table 30) showed that the temperature response functions were hybrid dependent. Although the individual hybrids responded differently to the  $T_{min}$  and  $T_{max}$  temperatures, the general patterns of the responses were similar. The  $T_{max}$  response functions among the hybrids were very similar with a lower base (critical) temperature (LCT),  $T_{opt}$  and upper base (critical) temperature (UCT) of approximately 15, 33 and 35-40°C, respectively. The UCT was more representative of those in the literature than the 50-55°C temperatures for the CHU equations. The  $T_{opt}$  (33°C) is slightly higher than the 25-30°C optimum reported in the literature (Coligado and Brown, 1975a; Warrington and Kanemasu, 1983a).

The  $T_{min}$  response functions for 403 and 1108 were similar to one another with the cardinal temperatures being approximately equal. However, the  $T_{min}$  response function for 3995 was substantially different with the  $T_{opt}$  and UCT approximately 10°C higher than for the other two hybrids. The LCT for the  $T_{min}$  response functions are similar to those reported by Warrington and Kanemasu (1983a) and those found upon reworking the data of Coligado and Brown (1975a). The base temperatures of these two studies were found to range between 6 and 9°C.

Replacing air temperature with the 5 cm soil temperature and obtaining the best fit did not improve CV (Table 30) for the ESE stage. The general patterns between hybrids of the response functions for the 5 cm soil temperatures (ST) were very similar to those for the air temperatures (AT) except that all the cardinal temperatures were lower for the soil compared to air temperature response functions.

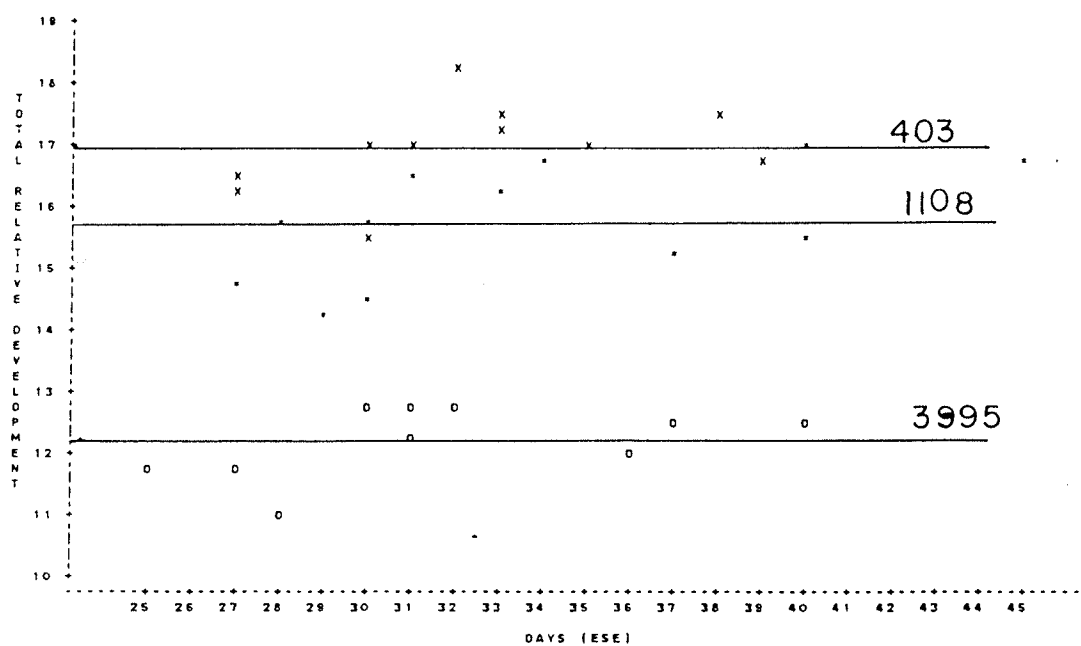


Figure 22: Development units for ESE calculated with the IF model plotted as a function of the duration of the stage in days. The mean development units for each hybrid are also shown.



When iterative procedures are used, the resulting response functions are a sum of at least two separate response functions: 1. the relationship of plant temperature (PT) to either soil or air temperature, and 2. the temperature response function for development. The relationship between plant temperatures and soil temperatures will be different than the relationship between PT and AT. These different relationships will be reflected in the cardinal temperatures determined with the IF model using air or soil temperatures. Although not shown, the same results were obtained when the other iterative and thermal models were run using soil temperatures instead of air temperatures. As stated earlier, using the analysis of this study, air temperatures provided a better estimate of the duration of the emergence to stem elongation (ESE) stage than did 5 cm soil temperatures.

The IF model provided the most accurate estimation of the duration of the ESE stage and may also be a better approximation of the temperature response functions both under growth chamber and field conditions. For growth chamber studies, the IF equation represented very well the rate of development (inverse time) from emergence to tassel initiation as a function of temperature. A plot of the Lehenbauer (1914) data is a representation of the elongation rate of corn seedlings as a function of temperature. For this study, tassel initiation was coarsely approximated by the beginning of stem elongation. It was expected, therefore, that the IF equation evaluated at  $T_{max}$  and  $T_{min}$  would better estimate the duration ESE than would equations developed from the Lehenbauer data. This was not the case. Two separate IF equations, one representing the  $T_{min}$  response function, and one for the  $T_{max}$  response func-

TABLE 30

Cardinal temperatures obtained from iteratively fitting the IF model to the field data for each location.

Stage	Hybrid	LCT†	Cardinal Temperatures (°C)						CV %
			Tmin Topt	UCT	LCT	Tmax Topt	UCT		
ESE*									
Air temperatures									
	3995	7	32	33	15	33	39	4.8	
	403	5	19	23	15	33	35	4.2	
	1108	8	18	22	15	33	35	5.9	
5 cm Soil temperatures									
	3995	4	24	26	9	26	30	9.4	
	403	4	17	25	12	26	30	7.4	
	1108	9	17	18	11	26	30	8.4	
SESI									
Air temperatures									
	3995	7	17	30	6	26	40	10.7	
	403	7	12	20	16	26	35	9.9	
	1108	7	22	30	6	26	35	5.8	
5 cm Soil temperatures									
	3995	9	20	23	10	26	39	8.9	
	403	7	15	25	18	26	33	4.5	
	1108	9	24	25	8	24	39	4.2	
ESI									
Air temperatures									
	3995	10	15	23	10	32	37	4.7	
	403	10	13	23	10	30	39	4.7	
	1108	10	15	23	10	32	37	4.1	

† LCT, Topt, UCT - lower, optimum, upper cardinal temperatures, respectively.

\* ESE = emergence to stem elongation, SESI = stem elongation to silking, ESI = emergence to silking.

tion, rather than one equation containing both  $T_{max}$  and  $T_{min}$ , were needed to accurately estimate the duration of ESE. However, a good estimate of ESE duration was obtained when both  $T_{min}$  and  $T_{max}$  were evaluated using the elongation rate response equations developed from the Lehenbauer data. It is tempting to speculate as to: 1. why for the IF model there should be two response functions, one for each  $T_{max}$  and  $T_{min}$ , needed for a best fit rather one response function suitable for both  $T_{max}$  and  $T_{min}$ , as indicated by growth chamber studies; and 2. why the LEHEN model, one response function evaluated at  $T_{max}$  and  $T_{min}$ , was a good estimator of development (duration, not elongation) under field conditions.

There may indeed be two separate temperature response functions, one for  $T_{min}$  and one for  $T_{max}$ . Hardacre and Eagles (1980) found major differences among hybrids in the ability to grow autotrophically at  $13^{\circ}\text{C}$ . The United States hybrids of their study could not grow autotrophically at  $13^{\circ}\text{C}$ . The lower base temperature of the  $T_{max}$  response function using the IF model was  $15^{\circ}\text{C}$ . These results may indicate that under the high radiation load that may exist during daylight hours, the base temperature below which development does not occur may indeed be approximately  $15^{\circ}\text{C}$ . Photodegradation of the photosynthetic enzymes has been found to occur at temperatures below  $13-15^{\circ}\text{C}$ . At night, there would be no photodegradation of enzymes and development may proceed at temperatures lower than  $13-15^{\circ}\text{C}$ . Many of the growth chamber studies on development have been done under conditions where the radiation load on the corn plants was approximately half of that under field (full sunlight) conditions. The potential for photodegradation of the enzymes

may not be as severe for growth chamber conditions with the result that the temperature response functions for growth chamber studies may be different than those developed under field conditions. The  $T_{max}$  response function developed with the IF model may reflect the inability of corn plant to grow autotrophically at temperatures less than about  $13-15^{\circ}\text{C}$  during the daylight hours.

The difference between the response functions determined from growth chamber (Warrington and Kanemasu, 1983a; reworked data of Coligado and Brown, 1975a) and field studies may also occur because of the influence of transpirational cooling on plant temperature. Under growth chamber conditions the plant temperature and the chamber temperature may be approximately equal, especially if humidities are high and radiation load only half that of full sunlight (i.e., low transpirational demand). However, under field conditions plant temperature may be significantly lower or higher than air temperature, depending on transpirational demand and moisture supply (Jackson, 1982; Choudhury, 1983; Gardner et al., 1981a). If this is true and if equation 5.7 is a measure of the true temperature response function for development, the LEHEN model, which is essentially only one curve representing the response function for  $T_{min}$  and  $T_{max}$ , may work well because the curvilinear response from the LCT to  $T_{opt}$  may also reflect the difference between air and plant temperature brought about by transpirational cooling. For example, plotting the LEHEN curve and equation 5.7 with cardinal temperatures 8, 32, and  $36^{\circ}\text{C}$  on the same graph will help illustrate this point (Figure 23). If we assume that plant temperatures were known, equation 5.7 would represent the true temperature response function for development. With adequate moisture supply and high radiation load the plant tempera-

ture may be  $3^{\circ}\text{C}$  lower than air temperature, i.e., with a maximum air temperature of  $25^{\circ}\text{C}$ , plant temperature may be  $22^{\circ}\text{C}$ . Therefore, the development rate would correspond to the plant temperature ( $22^{\circ}\text{C}$ ) - point B and not to the air temperature ( $25^{\circ}\text{C}$ ) - point A (Figure 23). When air temperatures are used to estimate daily development rate, the shape of the LEHEN curve would help compensate for the decrease in plant temperature over that of the air temperature at temperatures lower than the optimum - point C (Figure 23).

Above  $T_{opt}$  the plant may suffer from temperature induced water stress, closing the stomates and restricting transpirational water loss. This may cause plant temperatures to be closer to air temperatures. Under Manitoba conditions, the soil profile during early summer is usually near field capacity and during ESE, root growth, both length and depth of roots, is probably continuing at its maximum rate. Therefore water supply may not be limiting; although this could not be determined from our study.

The fitting procedure of the IF model may also reflect the effect of transpirational cooling on the plant-air temperature relationship. Figure 24 is a plot of the  $T_{min}$  and  $T_{max}$  response functions for NK 403 determined with the IF model. Also plotted is the LEHEN model temperature response function. The  $T_{max}$  response function (curve 1b - Figure 24) is very similar in shape and position to the LEHEN curve for  $T > 16-18^{\circ}\text{C}$ . As previously suggested the shape of the LEHEN curve may help compensate for the decrease in plant temperature compared to air temperature because of transpirational cooling. This argument may explain why the IF model gave a better fit to the field data with two

separate temperature response functions (one for  $T_{min}$ , another for  $T_{max}$ ) instead of one temperature response function for both  $T_{min}$  and  $T_{max}$ . The separation may have been brought about by the effects of transpirational cooling during the daylight hours (when the maximum temperature occurs). If the effects of the availability of moisture on plant temperature could be incorporated into the IF model, the temperature response function may then best be represented by one equation instead of two separate equations. Similarly if the effects of moisture availability could be incorporated into the LEHEN model, the shape of the LEHEN curve representing the temperature response function may approach that represented by equation 5.7 (Figure 13, p. 106). From this study it could not be determined if one, or either, of the above 2 proposed hypotheses explained why two response curves were obtained from the IF model, or why the LEHEN model was an accurate estimator of ESE.

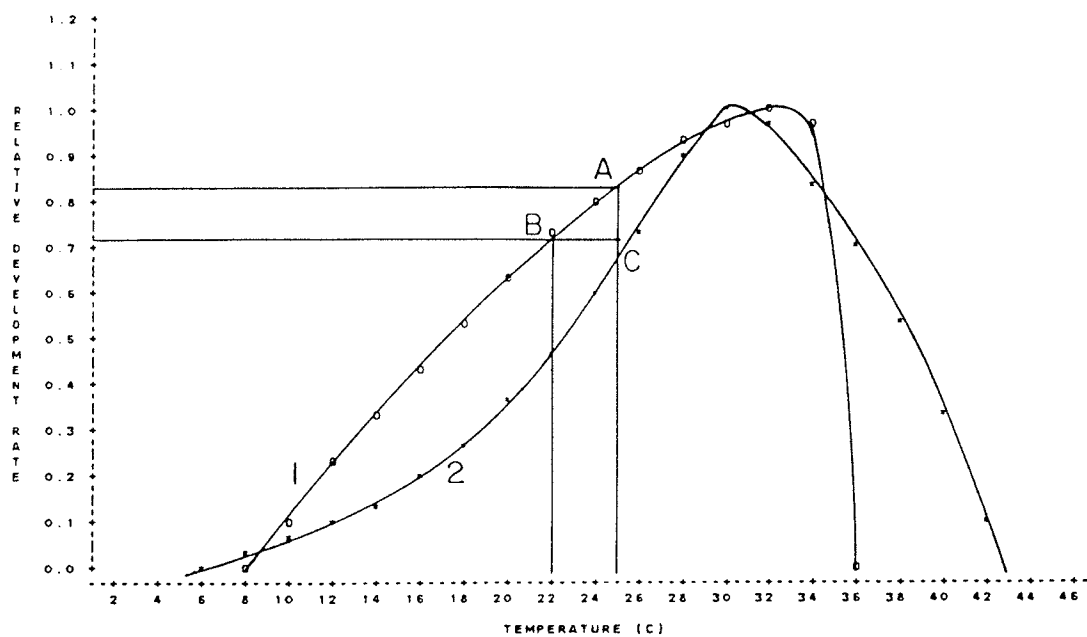


Figure 23: Temperature response functions represented by the LEHEN model (curve 2) and equation 5.7 with cardinal temperatures 8, 32 and 36°C (curve 1).

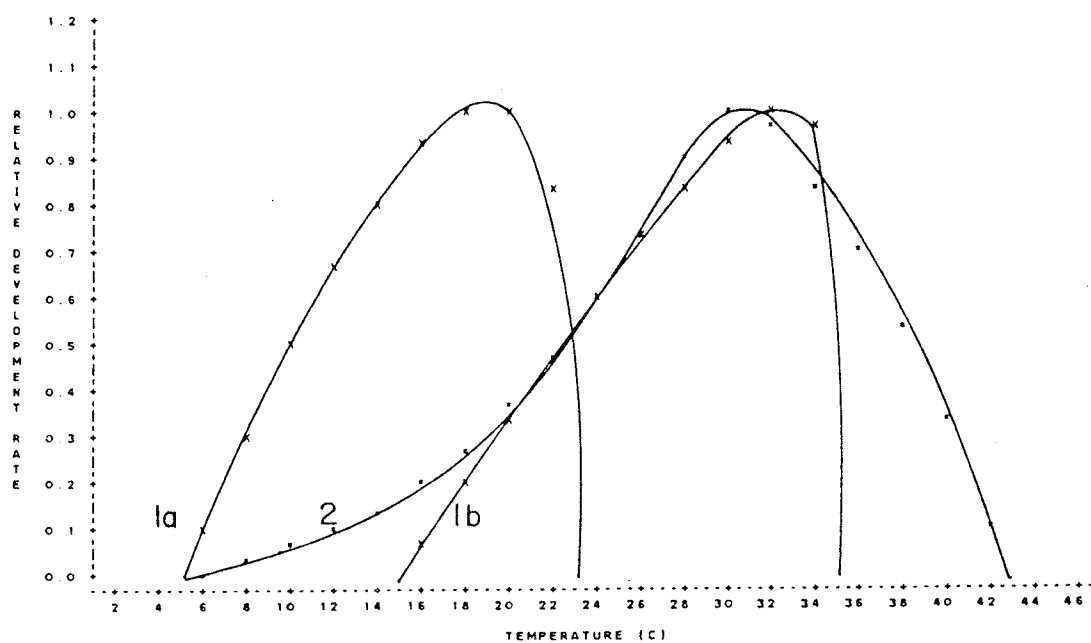


Figure 24: Temperature response functions for  $T_{min}$  (curve 1a) and  $T_{max}$  (curve 1b) for NK 403 determined with the IF model and the response function for the LEHEN model (curve 2).

### 9.3 STEM ELONGATION TO SILKING (SESI)

#### 9.3.1 Relationship of Average Daily Temperatures to the Duration of SESI.

Average daily weather variables for the SESI stage for hybrids 3995, 403 and 1108 are given in Appendices E, F and G, respectively. The previous two stages, planting to emergence (PE) and emergence to stem elongation (ESE) had highly significant relationships between average soil or air temperatures and development rate (inverse duration in days of the stage). For SESI, analyses found absolutely no relationship between air and/or soil temperatures and development rate obtained from Appendices E, F, and G. It has been suggested by other researchers (Robertson and Holmes, 1957) that, for a given stage of crop growth and for a number of observations, the relationship between development rate and temperature may be determined from the average temperature during the stage (development rate being determined by taking the inverse in duration of the stage). For the present study, this concept may be true for the PE and ESE stages but not for the SESI stage. Other methods have to be employed to determine the relationship that may exist between development rate, temperature and other climatic variables.

#### 9.3.2 Thermal Models

Accumulated daily development units calculated from air temperatures using the LEHEN, CHU and GDD thermal models are listed in Table 31. The locations are listed in order of increasing duration in days of the SESI stage. Also shown are the means, standard deviations (SD) and coefficients of variation (CV). The mean durations of this stage for hybrids 3995, 403 and 1108 were approximately 24, 28 and 30 days, respectively.



Of the 3 stages studied, planting to emergence (PE), emergence to stem elongation (ESE) and stem elongation to silking (SESI), the least variability among hybrids, with respect to stage duration, occurred during PE (0 days) with the greatest variability during SESI (6 days). For this stage, the CV for calendar days (duration of SESI in days) was much smaller than the CV for any of the thermal models. The thermal model with the lowest CV was the CHU model with the other two models, LEHEN and GDD, having CV's substantially larger than the CHU model. The opposite was true for the ESE stage where: 1. the thermal models were all more accurate estimators of stage duration than calendar days, and 2. the LEHEN and GDD models were more accurate estimators than the CHU model.

Figures 25 and 26 (p. 178) are graphs of the accumulated CHU and LEHEN units, respectively, listed in Table 31, plotted as a function of the duration in days of the SESI stage. A graph of GDD versus duration would be very similar to Figures 25 and 26 (p. 178). The data of Table 31 was analyzed in two ways, with and without locations 11 and 12 - Fisher Branch 1983 and Glenlea 1983, respectively. For these two locations there were visible signs of severe moisture stress, leaf rolling for much of the day, for at least the last half of the SESI stage. Visible signs of moisture stress were not evident at any of the other locations. Locations 11 and 12 are identified on Figures 25 and 26 (p. 178). The resulting equations from linear regression analysis of accumulated development units and duration of SESI are listed in Table 28 (p. 155). The relationship between CHU and duration (N) was highly significant ( $P=.001$ ) for 3995 and 403 with and without locations 11 and 12. The relationships between LEHEN and N and between GDD and N for

Accumulated daily units for the stem elongation to silking (SESI) stage calculated using the thermal models and two of the iterative models (IF and modified CHU).

for development from planting to silking							
Hybrid	Station Number	Duration (DAYS)	Accumulated Units for the Specified Model				
			Thermal Models		Iterative Models		
			LEHEN	CHU (4.4, 10°C)	GDD	IF	MCHU (7, 15°C)
Pioneer 3995	2	21	8.43	472	191	10.06	357
	10	21	8.08	485	186	10.24	366
	7	22	8.94	486	200	10.63	376
	11	22	11.26	549	242	13.13	459
	6	23	10.32	577	243	12.86	465
	1	25	9.48	563	219	11.60	415
	12	25	13.47	651	298	15.71	555
	9	26	11.60	619	256	13.77	487
	3	27	11.4	606	253	13.53	475
	5	28	11.31	617	249	13.36	471
	4	29	12.15	671	273	14.68	520
	MEAN	24.45	10.59	572	234	12.69	450
	SD	2.84	1.68	69	33	1.84	64
	CV(%)	11.62	15.92	12.06	14.1	14.53	14.22
Northrup King 403	10	23	8.5	521	197	15.29	386
	5	26	10.41	565	227	16.32	429
	7	26	10.36	576	232	16.55	441
	3	27	10.87	588	239	17.46	451
	6	27	11.68	655	273	19.03	521
	2	28	10.91	628	249	18.98	471
	12	29	16.16	770	356	23.72	665
	1	30	11.41	676	265	19.71	501
	11	30	15.27	751	334	23.83	634
	4	31	12.6	708	284	21.22	542
	9	32	13.94	742	307	22.21	581
	MEAN	28.09	12.01	653	266	19.48	511
	SD	2.63	2.29	84	45	2.97	88
	CV(%)	9.34	19.09	12.86	16.92	15.23	17.22
Pride 1108	10	27	9.47	583	221	15.74	425
	12	27	15.38	730	337	21.84	633
	2	29	11.52	657	263	19.12	496
	6	29	12.63	708	295	20.2	564
	7	29	11.49	639	258	17.28	489
	11	29	14.84	730	326	22.4	617
	8	30	10.06	635	236	16.37	454
	9	30	12.91	689	284	19.24	537
	3	31	12.68	679	279	18.69	526
	1	32	11.98	714	277	19.52	526
	4	32	12.85	728	291	20.57	554
	5	34	13.72	761	306	20.98	581
	MEAN	29.92	12.46	688	278	19.33	534
	SD	2.07	1.73	51	31	2.07	62
	CV(%)	6.90	13.89	7.41	11.15	10.71	11.61

hybrids 3995 and 403 were significant ( $P=.05$ ) when locations 11 and 12 were included in the analysis but were highly significant when locations 11 and 12 were excluded. For hybrid Pride 1108, there were no significant relationships between the accumulated development units and duration with locations 11 and 12 in the analysis. However, without locations 11 and 12 the relationships were significant, with the relationship between CHU and N being highly significant. These results indicated that a) the temperature response functions represented by the thermal models were incorrect for this stage, SESI, and/or b) other weather variables as well as temperature significantly influence development during this stage.

Warrington and Kanemasu (1983a) found the temperature response function for tassel initiation to anthesis (TIA) to be very similar in shape to the temperature response function for emergence to tassel initiation (ETI), i.e., equation 5.7 represents very well the temperature response functions determined from growth chamber studies. However, Brown (1977) suggested that the temperature response function changes throughout the life cycle of the corn plant. Whereas before tassel initiation (TI) there was a definite optimum temperature for development, the temperature response function after TI may have a temperature range over which development was optimum. Field studies (Herrero and Johnson, 1981; Shaw and Thom, 1951; Mallet, 1972) have shown that moisture stress may significantly increase the period from tassel emergence to silking. Herrero and Johnson (1981) found the interval between TI and silking could be doubled by moisture stress. The accumulated development units for LEHEN and CHU models (Table 31) were plotted as a function of the

mean daily rainfall during the SESI stage (Appendices E, F, and G) and analyzed. The linear regression equations,  $R^2$  and level of significance are shown in Table 32. Location 5 - Arborg 1981 - was not included in the analysis because during the latter half of SESI the rainfall was high enough to leave standing water (water logged conditions) for much of this period. There have been reports in the literature that if N levels were high, prolonged flooding during the latter half of SESI may not influence development rates (Wenkert et al., 1981; Ritter and Beer, 1969). Although N levels were high ( $>300$  kg/ha) at this location, the experiment was not designed for this occurrence and therefore it was thought best to exclude location 5 from the analysis.

Curvilinear (quadratic) regression analysis may have increased the  $R^2$  and shown an optimum average daily rainfall for this stage, above and below which the duration would increase. However, without the widely varying soil types, soil moisture holding capacities and, therefore, soil moisture supply included in the analysis, the curvilinear response function would have little meaning. With linear regression analysis a comparison of the effects of moisture stress (as measured by amount of rainfall) on each hybrid could be obtained, as well as whether or not there was a significant relationship between rainfall during SESI and development. The addition of stored soil moisture to the analysis would probably have improved the results. However, the soil moisture data was incomplete and of questionable accuracy. Figure 27 (p. 179) is a plot of LEHEN versus average daily rainfall during SESI. The regression equations of Table 32 show a significant relationship between LEHEN and rainfall for 3995 and a highly significant relationship for hybrids 403

and 1108. The only significant relationship between CHU and rain was for 403. However, this may have resulted from the iterative fitting procedure used to obtain the best fit of the CHU model to the field data. In using iterative procedures to obtain best fits, the influence of other weather variables on development may be masked or hidden in the analysis. The results indicated that the development during SESI for all 3 hybrids was affected by moisture stress. For the data of this study, the equations of Table 32 indicated that as rainfall during the SESI stage increased the calculated development units for the duration of SESI decreased. The  $R^2$ 's indicate that more of the variation in development units for hybrids 1108 and 403 was accounted for by rainfall than for 3995. These results may indicate that 3995 was less sensitive to moisture stress than were hybrids 1108 and 403.

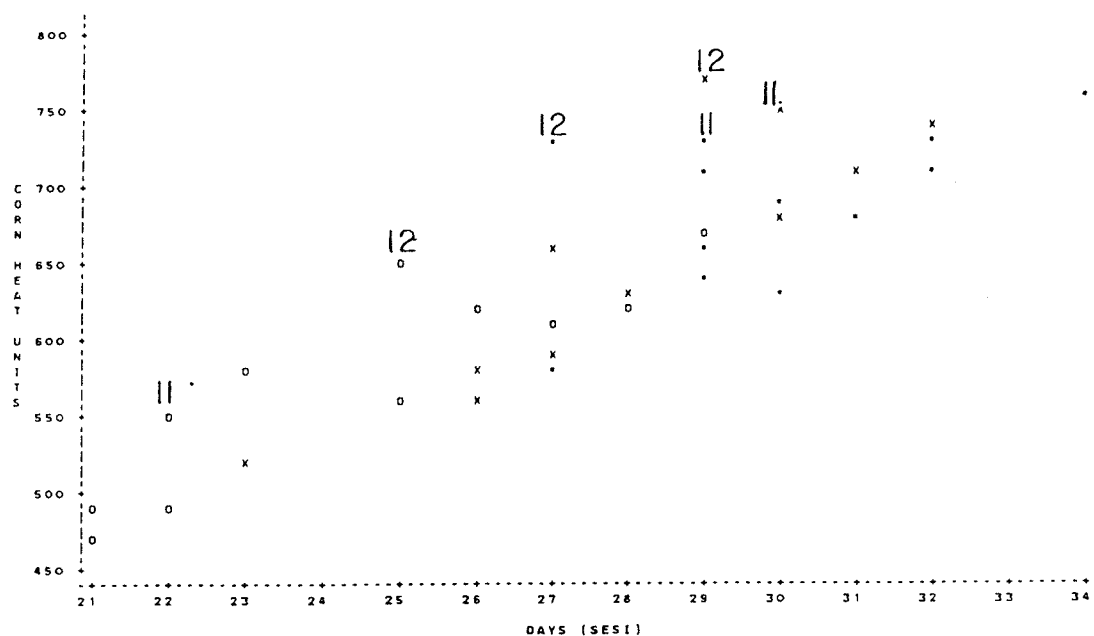


Figure 25: Corn heat units (Tbase of 4.4 and 10°C) plotted as a function of duration in days from stem elongation to silking (SESI). (0 - 3995, X - 403, \* - 1108).

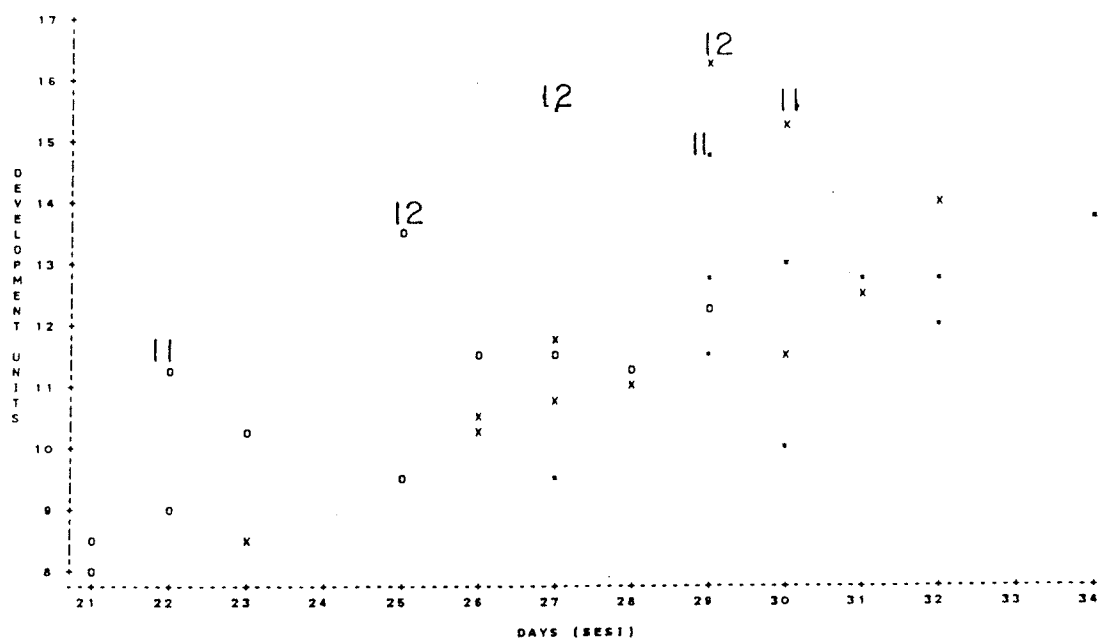


Figure 26: Development units calculated using the LEHEN model plotted as a function of duration in days of the SESI stage. (0 - 3995, X - 403, \* - 1108).

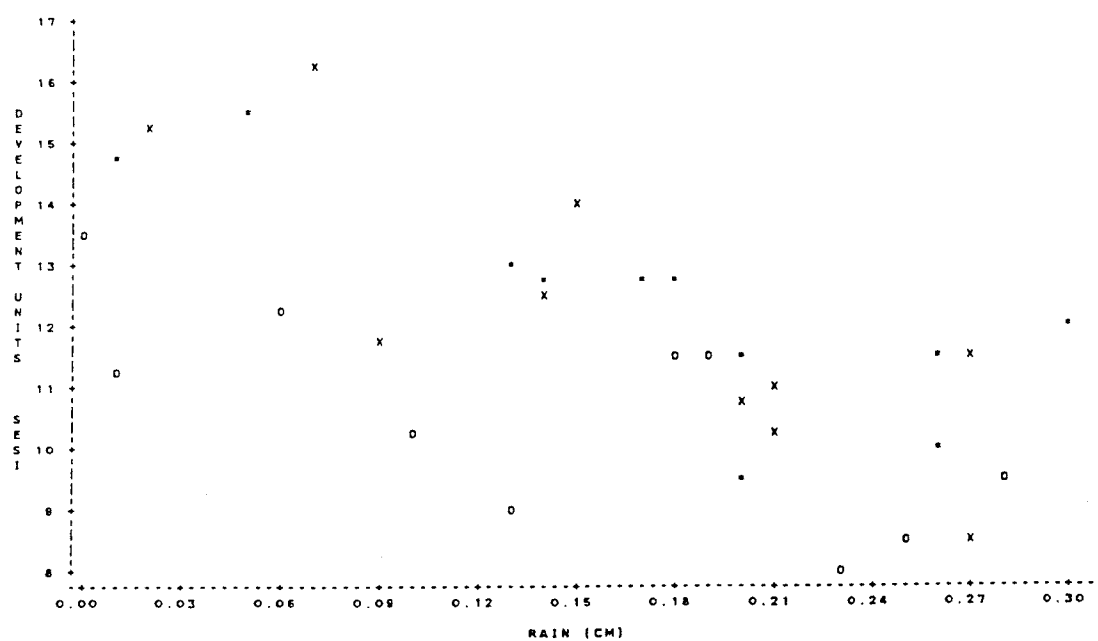


Figure 27: Accumulate development units for the LEHEN thermal model plotted as a function of average daily rainfall during SESI. (0 - 3995, X - 403, \* - 1108).

TABLE 32

Linear regression equations describing the relationship of the accumulated development units of the thermal models LEHEN and CHU and of the iterative models MCHU and IF to the average daily rainfall (PREC) to SESI.

Hybrid	Equation	R <sup>2</sup>
3995	LEHEN = 12.33 - 12.71 PREC	.51 *
	MCHU = 514.2 - 465.4 PREC	.47 *
	IF = 14.56 - 13.58 PREC	.49 *
403	LEHEN = 15.94 - 23.16 PREC	.69 **
	CHU = 780.3 - 728.4 PREC	.54 *
	MCHU = 662.4 - 878.4 PREC	.70 **
	IF = 24.91 - 26.93 PREC	.60 **
1108	LEHEN = 15.11 - 16.02 PREC	.64 **
	MCHU = 624.1 - 549.3 PREC	.59 **
	IF = 22.23 - 17.68 PREC	.55 **

\* significant at 5%

\*\* significant at 1%



### 9.3.3 Iterative Models

Listed in Table 31 (p. 174) are the accumulated development units calculated using the IF and MCHU models that were derived from the data for the previous stage, ESE. The assumption, based on the observations of Warrington and Kanemasu (1983a), was that the temperature response function for SESI was very similar to that for ESE. The CV's of the iterative models were much larger than the CV for calendar days, i.e., calendar days would be the better estimator for the duration of the SESI stage. Overall, the IF model was slightly superior to the MCHU model and was a better estimator of duration than the LEHEN and GDD models. The CHU model had the lowest CV of any of the models listed in Table 31 (p. 174). There was a significant and highly significant linear relationship between accumulated development units of the IF and MCHU models and duration (days) of SESI for hybrids 3995 and 403, respectively (Table 33). When locations 11 and 12 were excluded from the analysis (because of visible signs of moisture stress) the relationships were highly significant for 3995 and 403 and were now significant for hybrid 1108.

The relationship between the accumulated development units of the IF and MCHU models and average daily rainfall (PREC) during SESI was highly significant for hybrids 403 and 1108 and significant for 3995 (Table 32). The overall results of Table 32, as well as field observations and the root growth results of the emergence study, indicated that 3995 was more tolerant of moisture stress than were 403 and 1108; with 403 being slightly more sensitive to moisture stress than 1108. If the temperature response functions for ESE and SESI were similar, as the data of

Warrington and Kanemasu (1983a) indicated, then the results of Tables 31 (p. 174), 32 and 33 would suggest that moisture stress had a significant influence on the duration and accumulated thermal units needed for the completion of this stage, SESI. As mentioned previously other researchers have found moisture stress significantly delayed silking, as was indicated by the results of this study. If we assume that the temperature response function changes with age as suggested by Brown (1977), then the data and results of Tables 31 (p. 174), 32, and 33 indicated that the temperature response functions represented by the models tested may be influenced by other weather variables such as moisture during the SESI stage.

The iterative approaches to curve fitting, RIP, MCHU and IF models, that were relatively successful for the ESE stage, were not as successful for the SESI stage. The RIP was completely unsatisfactory. After repeated but unsuccessful attempts to stabilize the iterative procedure at coefficients that were reasonable, the fitting procedure was abandoned. Base temperatures ranging from  $-25$  to  $-150^{\circ}\text{C}$  were not acceptable and the CV's were approximately equal to the CV's for calendar days (Table 31, p. 174). The RIP model, therefore, provided no improvement over calendar days in estimating the duration of SESI.

The procedure used to fit the modified Corn Heat Unit (MCHU) model to the field data provided similar results to the RIP model. The CV's for 3995, 403 and 1108 were 11.2, 11.7 and 5.9%, respectively. Although the CV's for the MCHU model were superior to those of the CHU model, they were approximately equal to the CV's for calendar days and therefore did not improve on the ability to estimate the duration of the SESI stage.

TABLE 33

Linear regression analysis of the accumulated development units during SESI calculated using the iterative models IF and MCHU determined for the ESE stage to the duration in days (N) of SESI.

Hybrid	Equation	R <sup>2</sup>
a) stations 11 and 12 (Fisher Branch 83 and Glenlea 83) included		
3995	IF = 1.30 + 0.466 N	.51 *
	MCHU = 56.1 + 16.1 N	.51 *
403	IF = -7.08 + 0.945 N	.70 **
	MCHU = -195.3 + 25.1 N	.56 **
b) stations 11 and 12 not included		
3995	IF = -0.28 + 0.510 N	.83 ***
	MCHU = 7.1 + 17.4 N	.79 **
403	IF = -3.6 + 0.792 N	.92 ***
	MCHU = -75.5 + 20.0 N	.85 ***
1108	IF = -0.24 + 0.628 N	.50 *
	MCHU = -23.4 + 17.8 N	.52 *

\* significant at 5%

\*\* significant at 1%

\*\*\* significant at 0.1%

The base temperatures of the  $T_{min}$  and  $T_{max}$  response functions of the MCHU model were 8.4 and 2°C, respectively. The 2°C base temperature for the  $T_{max}$  response function (quadratic) was significantly lower than the 15°C base temperature of the MCHU model for ESE. The optimum temperature for the quadratic with  $T_{base} = 2^{\circ}\text{C}$  would be 22°C, much lower than the  $T_{opt} = 30^{\circ}\text{C}$  for the CHU model and  $T_{opt} = 35^{\circ}\text{C}$  for the MCHU model for the ESE stage.

Fitting the IF model to the field data for SESI provided some interesting results. Comparison of the CV's for the cardinal temperatures determined using air temperatures (Table 30, p. 166) to the CV's for calendar days (Table 31, p. 174), showed that the IF model provided little improvement in the ability to estimate the duration of the SESI stage. However, using 5 cm soil temperatures in the IF iterative procedure provided lower CV's than did air temperatures. It is difficult to explain why soil temperatures should provide a better estimate of stage duration than air temperatures. One reason may be that during the SESI stage the canopy becomes 'closed'. The leaves fill in the rows and provide an effective barrier to air exchange between the canopy and atmosphere above the canopy. Without this air exchange, the canopy may become a heat source during the day, i.e., the air temperature within the canopy may be significantly greater than air temperatures outside the canopy. If this were the case, soil temperatures may have provided better estimates of plant temperature than air temperatures outside the canopy and this would have been reflected in the ability to estimate the duration of SESI.

The thermal models and the iterative models did not prove to be better estimators than calendar days of the duration of the SESI stage. This study and other research has shown that moisture stress can significantly delay silking. With the addition of a moisture stress term to the IF iterative procedure, the IF model may have provided a more accurate estimate of the duration of SESI. However, with the use of temperature alone, none of the iterative procedures or thermal models were acceptable estimators of this stage.

#### 9.4 EMERGENCE TO SILKING (ESI)

The duration of ESE was much more accurately estimated by all the development models than it was by calendar days. However, the duration of SESI was not accurately estimated by the development models tested. Since this stage, ESI, is a sum of the previous two stages the estimation ability of the development models should be somewhere between reasonably accurate and inadequate.

##### 9.4.1 Thermal Models

The accumulated development units calculated using the thermal models LEHEN, CHU and GDD are shown in Table 34. For 3995 and 1108, the thermal models were better estimators of the duration of ESI than was calendar days - the CV's of the thermal models were less than the CV's for calendar days. For 403, only the CV for CHU was slightly less than the CV for calendar days, the CV for LEHEN and GDD were substantially larger than the CV for calendar days. For all 3 hybrids the model with the lowest CV was the CHU model. This was contrary to the results of Coelho and Dale (1980) who found their FT model (essentially the LEHEN

model) was a slightly superior estimator of the planting to 75% silking stage than were the CHU and GDD models. Hybrid NK 403 was found to be especially sensitive to moisture stress during the SESI stage and this would result in the higher calculated CV's for ESI.

Using linear regression analysis as a means of testing for a significant relationship between the accumulated units calculated with the thermal models and duration of ESI yielded the results shown in Table 28, (p. 155). With locations 11 and 12 included in the analysis there was a significant relationship between CHU and duration (calendar days) for hybrids 3995 and 1108 - the two hybrids least sensitive to moisture stress. Excluding locations 11 and 12 from the analysis, the relationship between CHU and calendar days became highly significant for all 3 hybrids. As stated for the previous stage, SESI, the relationship between CHU and calendar days indicate a) the CHU model does not represent the proper temperature response function, and/or b) other weather variables were involved in development. It is apparent from previous research, as well as from this study, that moisture stress can prolong development, especially the SESI stage.

Accumulated daily units for the emergence to silking (ESI) stage calculated using the thermal models. The development units were calculated using air temperatures.

Hybrid	Station number	Duration (DAYS)	Accumulated Units Thermal Models		
			LEHEN	CHU (4.4, 10°C)	GDD
Pioneer 3995	12	50	22.95	1202	578
	2	51	19.43	1079	443
	7	53	19.41	1119	446
	11	53	21.42	1176	482
	3	55	20.76	1133	468
	4	56	22.19	1232	498
	1	57	20.64	1182	475
	5	59	21.55	1242	494
	6	59	20.19	1248	476
	10	61	18.78	1180	441
	9	63	22.44	1274	504
	MEAN	56.09	20.89	1188	477
	SD	4.16	1.36	60	26
	CV(%)	7.41	6.49	5.05	5.45
Northrup King 403	12	56	25.98	1352	584
	3	57	21.44	1171	483
	2	58	21.91	1236	501
	4	58	22.63	1269	510
	7	58	21.50	1241	495
	5	59	21.53	1239	492
	11	61	25.42	1379	574
	6	62	21.35	1310	501
	10	62	18.94	1194	445
	1	63	22.77	1313	527
	9	70	25.33	1424	568
	MEAN	60.36	22.62	1284	516
	SD	3.93	2.14	79	43
	CV(%)	6.51	9.48	6.15	8.33
Pride 1108	12	55	25.37	1324	571
	11	58	24.15	1308	545
	2	59	22.53	1264	515
	4	59	22.89	1289	516
	7	60	22.32	1285	514
	3	61	23.25	1262	523
	1	65	23.34	1351	539
	6	66	22.77	1400	534
	10	67	20.18	1278	476
	5	68	25.29	1456	579
	9	70	25.33	1424	568
	8	75	22.45	1441	529
	MEAN	63.58	23.32	1340	532
	SD	5.85	1.52	72	29
	CV(%)	9.21	6.53	5.37	5.45

#### 9.4.2 Iterative Models

As with the ESE and SESI stages, the MCHU, RIP and IF models were iteratively fitted to the field data for the ESI stage. The application of these models incorporated the assumption that only temperature influences development. Excluding the effects of moisture limits both accuracy and interpretation of the resultant temperature response curves.

For hybrids 3995 and 1108, the base temperatures for the  $T_{min}$  and  $T_{max}$  response functions of the MCHU model, the one which provided the lowest CV's were 9 and 11°C, respectively. The CV's for 3995 and 1108 were 4.6 and 4.9%, respectively. The base temperatures for hybrid 403 were 2 and 8°C with a CV of 5.7%. These CV's are slightly smaller than the CV's of the CHU model. Therefore, MCHU provided only slight improvement over the CHU model in estimating the duration of ESI.

The derived coefficients for RIP are shown in Table 29 (p. 162). As before, the photoperiod effects on development were assumed negligible. According to the fitting procedure, hybrids 3995 and 1108 have very similar patterns of development throughout this stage, ESI.  $T_{min}$  did not contribute to the development for either hybrid and there was no quadratic term (i.e., no optimum) of  $T_{max}$  for development. These two results are difficult to comprehend. For 403, the base temperature was 1°C and the temperature response functions for  $T_{min}$  and  $T_{max}$  were determined to be quadratic in nature. The CV's were approximately equal to those of the MCHU model and offered only slight improvement in estimation of duration when compared to the CHU model. As stated previously RIP provides the best fit to the data of two quadratic functions with the same base temperature. Because of these limitations the ability of



the procedure to simulate actual temperature response functions would be severely limited. To assume, because of the results obtained from this procedure, that  $T_{min}$  does not contribute to development and that there was no  $T_{opt}$  for the  $T_{max}$  response function would not be justifiable. Research has indicated optimum temperature for corn development of between 25 - 35°C (Warrington and Kanemasu, 1983a; Coligado and Brown, 1975a; Miedema, 1982).

The cardinal temperatures and CV's obtained from fitting the IF model to the field data are listed in Table 30 (p. 166). Among hybrids, the  $T_{min}$  response functions are similar and the  $T_{max}$  response functions are also similar to one another. Comparing Table 30 (p. 166) with Table 34 (p. 187) there was an improvement in the ability to estimate the duration of ESI as indicated when comparing the CV's of the IF and CHU models. The improvement was most noticeable for 403, but also for 1108. Before the coefficients of Table 30 (p. 166) could be used to estimate duration of ESI, they should be thoroughly tested, and possibly refined, using one or more independent data bases.

#### 9.5 LIMITATIONS OF ITERATIVE PROCEDURES

When using any iterative procedure, only the variables included in the analysis are assumed to significantly influence the process (in this case development) under study. The influence of other variables would be "hidden" in the analysis. If one or more of the excluded variables did significantly influence the process under study, the derived coefficients would be dependent upon the external conditions described by the excluded variables.

As would be the case in regression analysis, the coefficients of the best fit derived using the iterative procedure would change with changes in the data base, i.e., changes in the size of the data base, or change to a new data base. The degree or significance of the change in the coefficients would also depend upon the range in the magnitude of the variables represented in the data base. Thus, both size and variability of the data base are important for iterative procedures. The size of the data base needed to derive the coefficients would change with the size of the climatic region over which the data was collected. The smaller the region, quite possibly the smaller would be the data base needed to represent the region. However, the coefficients derived would only apply to the climatic region from which the data base was collected.

Ideally, the derived coefficients should be tested on an independent data base. For this project, the data base used was relatively small (12 location years) although climatic variability was evident (hot to cool, wet to dry conditions, depending upon location and year). Because there was no independent data with which to test the coefficients, caution would be advised in applying this iterative technique to estimate growth stage duration without further testing and refining of the technique and coefficients. The equation itself is a better representation of the temperature response function for development (as defined) than the quadratic but the coefficients and base temperatures may change when derived from a larger or different data set.

For the conditions of this study, a number of assumptions were made when using the iterative (IF) procedure. It was assumed that tempera-

ture was the only weather variable influencing development. The availability of moisture was assumed to be nonlimiting. During ESE these assumptions may be valid. Under Manitoba conditions, the soil profile for the rooting depth (120-150 cm) is usually at or near field capacity at the beginning of the growing season. The depth of root extension in deep soils is a linear function of time until tasseling (Larson and Hanway, 1977). During ESE the roots are continually extending into new volumes of moist soil. With the onset of stem extension, leaf area may increase more than 5-fold (Arnon, 1975) greatly increasing the percentage of solar radiation intercepted resulting in increased evapotranspiration. Therefore, during ESE, moisture use may be considerably less than during SESI (Shaw, 1977). Because evapotranspiration rates (per unit land area) may be relatively low during ESE compared to SESI and roots are usually continually growing into moist soil, it was assumed that during ESE moisture was not limiting and only temperature affected development.

On the other hand, the assumption that the availability of moisture is nonlimiting during the SESI stage was probably not valid. Maximum rooting depth usually occurs during this stage (Larson and Hanway, 1977). Once maximum rooting depth has been reached, the roots no longer occupy new moist soil volume. Therefore, rainfall may become the principal water source with soil moisture probably becoming less important as the stage progresses. Also, the corn plant reaches its maximum leaf area during this stage almost doubling its water use compared to the previous stage, ESE (Shaw, 1977). It has been shown that the tasseling to silking (TSI) stage may be especially sensitive to moisture stress

(Herrero and Johnson, 1981; Moss and Downey, 1971). The duration of TSI may be doubled by even a mild stress. In Manitoba the TSI stage usually occurs during July-August when temperatures are relatively high and rainfall relatively low, i.e., period of high evapotranspirational demand and low rainfall. Therefore because of the sensitivity of the corn plant during TSI to moisture and because TSI usually occurs in that part of the summer associated with high evaporative demand and low rainfall, the assumption that moisture availability during SESI is nonlimiting was probably not valid.

When the availability of moisture is nonlimiting, moisture may still indirectly influence the development of the corn plant. Silk appearance may be directly influenced by moisture stress. Larson and Hanway (1977) stated that moisture stress may delay silk appearance for as much as 2 or more weeks. Indirectly, moisture may influence development by decreasing plant temperature through transpirational cooling (Gardner et al., 1981a; Jackson, 1982). Therefore moisture may indirectly influence development during both the ESE and SESI stages.

Because of the importance of moisture for development during the SESI stage, a large data base may be required with the use of an iterative procedure involving temperature only to ensure a full range of weather variability for this stage. However, there may be years when moisture may be the limiting factor for development (i.e., drought), and a temperature only equation to estimate development would fail. A more reliable estimate of development for climatic extremes may result with use of a procedure to estimate development using both temperature and moisture data.

PART V  
CONCLUSIONS

## Chapter 10

### CONTROLLED ENVIRONMENT STUDY

1. For a given temperature, increased moisture stress decreased germination and emergence rates.
2. For the 3 hybrids of this study, emergence rates were hybrid and soil type independent. Therefore, the rate curves could be mathematically described by a single equation involving soil temperature and soil moisture.
3. Germination rates were independent of soil type but were not hybrid independent. Therefore, the mathematical description of the rate curves was soil type independent but hybrid dependent.
4. Hybrids differed substantially in the response of root growth, both with morphology and development rate, to environmental stress. Visual and measured root growth differences suggested that for early seedling growth, Pioneer 3995 was more stress tolerant (low temperature and/or low moisture) than Northrup King 403 and Pride 1108.

## Chapter 11

### FIELD STUDY

#### 11.1 PLANTING TO EMERGENCE (PE)

1. Of all the stages studied, the duration of the PE stage was the most variable (CV = 38%). The corn heat unit equation estimated the duration of PE with greater accuracy than did calendar days but the CV's were still very high, approximately 20%.
2. Regression analysis indicated that the duration of PE was more significantly related to seed depth soil temperature than to air temperatures.
3. The emergence rate equations from the controlled environment study using seed depth soil temperature and estimated daily soil moisture levels provided a good estimate of time (days) to emergence under field conditions.

#### 11.2 EMERGENCE TO STEM ELONGATION (ESE)

1. For this study regression analysis indicated that the duration of this stage was more significantly related to air temperatures than to the 5 cm soil temperatures.
2. All heat unit equations provided much better estimates of the duration of ESE than did calendar days.

3. The relationship between accumulated corn heat units (CHU) and duration of ESE was found to be highly significant. This may indicate that for this stage, the CHU equation did not adequately represent the development temperature response function of corn.
4. Of all the development models tested, the IF model provided the best estimate of the duration of the ESE stage. This model uses two separate temperature response functions, one for  $T_{min}$  and one for  $T_{max}$ , to estimate daily development rates. However, this model should be further tested and evaluated before general use in estimating development units needed for stage completion.

#### 11.3 STEM ELONGATION TO SILKING (SESI)

1. Regression analysis found no relationship between average air and/or soil temperature and development rate (inverse duration) for SESI.
2. Using air temperatures, none of the thermal or iterative models were better estimators of the duration of SESI than calendar days. Of the thermal models, the CHU model was the best estimator.
3. When locations with visible signs of moisture stress during SESI were excluded from the analysis, there were highly significant relationships between accumulated development units and duration in days of SESI. This may indicate that either the models did not represent the proper response functions and/or other weather variables were affecting development.



4. During SESI, there was a significant relationship between accumulated heat units required for completion of this stage and average daily precipitation.

#### 11.4 EMERGENCE TO SILKING (ESI)

1. The CHU model was the thermal model that best estimated the duration of the ESI stage. When locations with visible signs of moisture stress were excluded from the analysis, the relationship between accumulated CHU and duration of ESI was highly significant.
2. For all the models tested, the IF model, using air temperature, was the best estimator of the ESI stage. However, as stated previously, the IF model is an iterative procedure requiring more testing and analysis before it can be used for purposes other than research.

## Chapter 12

### GENERAL CONCLUSIONS

From this study, a method other than the corn heat unit model in estimating the duration from emergence to silking could not be recommended. Although the IF model proved to be a better estimator of the duration of the ESE and ESI stages, further testing would be needed to determine its suitability for estimating development units needed for corn hybrids to reach a given stage.

The study suggested that development may be more accurately estimated with the use of stages of shorter duration, such as emergence to stem elongation and stem elongation to silking. The study also suggested that for further improvement in the estimation of development rates, a term involving moisture stress should be incorporated into the model, especially for the SESI stage. If further studies are undertaken it is suggested that the SESI stage be further divided into the stem elongation to tasseling and tasseling to silking stages. The effects of temperature and moisture stress on development during these stages could be studied further for the purpose of determining the stage during which moisture stress becomes the dominant environmental factor affecting development.

## REFERENCES

- Alessi, J. and Power, J. F. 1971. Corn emergence in relation to soil temperature and seeding depth. *Agron. J.* 63:717-719.
- Allison, J. C. S. and Daynard, T. B. 1979. Effect of change in time of flowering, induced by altering photoperiod or temperature, on attributes related to yield in maize. *Crop Sci.* 19:1-4.
- Arnon, I. 1975. Mineral Nutrition of Maize. International Potash Institute. Bern, Switzerland.
- Baier, W. and Robertson, G. W. 1965. Estimation of latent evaporation from simple weather observations. *Can. J. Plant Sci.* 45:276-284.
- Barlow, E. W. R., Boersma, L. and Young, J. L. 1977. Photosynthesis, transpiration, and leaf elongation in corn seedlings at suboptimal soil temperatures. *Agron. J.* 69:95-100.
- Beauchamp, E. G. and Lathwell, D. J. 1966. Effect of root zone temperatures on corn leaf morphology. *Can. J. Plant Sci.* 46:593-601.
- Beauchamp, E. G. and Lathwell, D. J. 1967. Root-zone temperature effects on the early development of maize. *Plant and Soil* 26:224-234.
- Bierhuizen, J. F. 1973. The effect of plant temperature on plant growth, development and yield. In: R. O. Slatyer (ed.) *Plant Response to Climatic Factors*. Unesco, Paris. p.89-98.
- Bilanski, W. K. and Varma, R. K. 1976. Effect of bulk density and moisture tension on corn shoot growth. *Tran. A.S.A.E.* 19:337-340.
- Blacklow, W. M. 1972a. Mathematical description of the influence of temperature and seed quality on imbibition by seeds of corn (*Zea mays* L.). *Crop Sci.* 12:643-646.
- Blacklow, W. M. 1972b. Influence of temperature on germination and elongation of the radicle and shoot of corn (*Zea mays* L.). *Crop Sci.* 12:647-650.
- Blacklow, W. M. 1973. Simulation model to predict germination and emergence of corn (*Zea mays* L.) in and environment of changing temperature. *Crop Sci.* 13:604-608.
- Bonaparte, E. E. N. A. 1975. The effects of temperature, daylength, soil fertility and soil moisture on leaf number and duration to tassel emergence in *Zea mays* L. *Ann. Bot.* 39:853-861.

- Boone, F. R. and Veen, B. W. 1982. The influence of mechanical resistance and phosphate supply on morphology and function of maize roots. *Neth. J. Agric. Sci.* 30:179-192.
- Breuer, C. M., Hunter, R. B. and Kannenberg, L. W. 1976. Effects of 10- and 20-hour photoperiod treatments at 20 and 30 C on rate of development of a single-cross maize (Zea mays) hybrid. *Can. J. Plant Sci.* 56:795-798.
- Brouwer, R. Kleinendorst, A. and Th. Locher, J. 1973. Growth responses of maize plants to temperature. In: R. O. Slatyer (ed.) *Plant Response to Climatic Factors*, Unesco, Paris. p. 169-174.
- Brown, D. M. 1960. Soybean ecology. I. Development - temperature relationship from controlled - environment studies. *Agron. J.* 52: 493-496.
- Brown, D. M. 1963. A "heat unit" system for corn hybrid recommendations. The 5th Nat. Conf. on Agric. Meteorol., Lakeland, Fla.
- Brown, D. M. 1969. Heat units for corn in southern Ontario. Factsheet, AGDEX 111/31. Ontario Ministry of Agriculture and Food, Toronto, Ont. 4 p.
- Brown, D. M. 1977. Response of maize to environmental temperatures: A review. In: *Agrometeorology of the Maize (Corn) Crop Proceedings*. No. 481. WMO, Geneva, Switzerland.
- Bulisani, E. A. and Warner, R. L. 1980. Seed protein and nitrogen effects upon seedling vigor in wheat. *Agron. J.* 72:657-662.
- Bunting, E. S. 1976. Accumulated temperature and maize development in England. *J. Agric. Sci., Camb.* 87:577-583.
- Bunting, E. S. 1979. The relationship between mean temperature and accumulated temperature totals for maize in the central lowlands of England. *J. Agric. Sci., Camb.* 93:157-169.
- Burnett, R. B., Falk, G. W. and Shaykewich, C. F. 1985. Determination of climatically suitable areas for soybean (Glycine max (L.) Merr.) production in Manitoba. *Can. J. Pl. Sci.* 65:511-522.
- Carr, J. K. V. 1977. The influence of temperature on the development and yield of maize in Britain. *Ann. Applied Biol.* 87:261-266.
- Carter, M. W. and Poneleit, C. G. 1973. Black layer maturity and filling period variation among inbred lines of corn (Zea mays L.). *Crop Sci.* 13:436-439.
- Choudhury, B. 1983. Simulating the effects of weather variables and soil water potential on corn canopy temperature. *Agric. Meteorol.* 29:169-182.

- Coelho, D. T. and Dale, R. F. 1980. An energy-crop growth variable and temperature-function for predicting corn growth and development: planting to silking. *Agron. J.* 72:503-510.
- Coligado, M. C. and Brown, D. M. 1975a. Response of corn (*Zea mays* L.) in the pre-tassel initiation period to temperature and photoperiod. *Agric. Meteor.* 14:357-367.
- Coligado, M. C. and Brown, D. M. 1975b. A bio-photo-thermal model to predict tassel-initiation time in corn (*Zea mays* L.). *Agric. Meteorol.* 15:11-31.
- Constantz, J. 1982. Temperature dependence of unsaturated hydraulic conductivity of two soils. *Soil Sci. Soc. Am. J.* 46:466-470.
- Cooper, P. J. M. and Law, R. 1978. Enhanced soil temperature during very early growth and its association with maize development and yield in the highlands of Kenya. *J. Agric. Sci., Camb.* 89:569-577.
- Couchat, Ph., Moutonnet, P., Houelle, M. and Picard, D. 1980. In situ study of corn seedling root and shoot growth by neutron radiography. *Agron. J.* 72:321-324.
- Creencia, R. P. and Bramlage, W. J. 1971. Reversibility of chilling injury to corn seedlings. *Plant Physiol.* 47:389-392.
- Cross, H. Z. and Zuber, M. S. 1972. Prediction of flowering dates in maize based on different methods of estimating thermal units. *Agron. J.* 64:351-355.
- Dasberg, S. 1971. Soil water movement to germinating seeds. *J. Exp. Bot.* 22:999-1008.
- Dasberg, S. and Mendel, K. 1971. The effect of soil water and aeration on seed germination. *J. Exp. Bot.* 22:992-998.
- Daughtry, C. S. T., Cochran, J. C. and Hollinger, S. E. 1984. Estimating silking and maturity dates of corn for large areas. *Agron. J.* 76:415-420.
- Daynard, T. B. 1972. Relationships among black layer formation, grain moisture percentage, and heat unit accumulation in corn. *Agron. J.* 64:716-719.
- de Jong, R. and Best, K. F. 1979. The effect of soil water potential, temperature and seeding depth on seedling emergence of wheat. *Can. J. Soil Sci.* 59:259-264.
- Denmead, O. T. and Shaw, R. H. 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. *Agron. J.* 54:385-390.
- Duncan, W. G., Shaver, D. L. and Williams, W. A. 1973. Insolation and temperature effects on maize growth and yield. *Crop Sci.* 13:187-191.

- Dwyer, L. M. and Stewart, D. W. 1984. Indicators of water stress in corn (Zea mays L.). Can. J. Plant Sci. 64:537-546.
- Eagles, H. A., Hardacre, A. K., Brooking, I. R., Cameron, A. J., Smillie, R. M. and Hetherington, S. E. 1983. Evaluation of a high altitude tropical population of maize for agronomic performance and seedling growth at low temperatures. New Zealand J. Agric. Res. 26: 281-287.
- Feddes, R. A. 1972. Effects of water and heat on seedling emergence. J. Hydrology. 16:341-359.
- Francis, C. A., Grogan, C. O. and Sperling, D. W. 1969. Identification of photoperiod insensitive strains of maize (Zea mays L.). Crop Sci. 9:675-677.
- Francis, C. A., Sarria, D., Harpstead, D. D. and Cassalet, D. C. 1970. Identification of photoperiod insensitive strains of maize (Zea mays L.) II. Field tests in the tropics with artificial lights. Crop Sci. 10:465-468.
- Francis, C. A. 1973. The effects of photoperiod on growth and morphogenesis in maize (Zea mays L.): Field trials in Colombia. In: R. O. Slatyer (ed.) Plant Response to Climatic Factors. Unesco, Paris. p. 57-60.
- Gardner, B. R., Blad, B. L. and Watts, D. G. 1981a. Plant and air temperatures in differentially-irrigated corn. Agric. Meteorol. 25:207-217.
- Gardner, B. R., Blad, B. L., Maureer, R. E. and Watts, D. G. 1981b. Relationship between crop temperature and the physiological and phenological development of differentially irrigated corn. Agron. J. 73:743-747.
- Gilmore, Jr., E. C. and Rogers, J. S. 1958. Heat units as a method of measuring maturity in corn. Agron. J. 50:611-615.
- Haber, A. H. 1962. Nonessentiality of concurrent cell divisions for degree of polarization of leaf growth. I. Studies with radiation-induced mitotic inhibition. Amer. J. Bot. 49:583-589.
- Hadas, A. 1982. Seed-soil contact and germination. In: A. A. Khan (ed.). The Physiology and Biochemistry of Seed Development, Dormancy and Germination. Elsevier Biomedical Press. p. 507-527.
- Hadas, A. and Russo, D. 1974a. Water uptake by seeds as affected by water stress, capillary conductivity, and seed-soil water contact. I. Experimental study. Agron. J. 66:643-647.
- Hadas, A. and Russo, D. 1974b. Water uptake by seeds as affected by water stress, capillary conductivity, and seed-soil water contact. II. Analysis of experimental data. Agron. J. 66:647-652.

- Hardacre, A. K. and Eagles, H. A. 1980. Comparisons among populations of maize for growth at 13 degrees C. *Crop Sci.* 20:780-784.
- Herrero, M. P. and Johnson, R. R. 1981. Drought stress and its effects on maize reproductive systems. *Crop Sci.* 21:105-110.
- Hesketh J. D., Chase, S. S. and Nanda, D. K. 1969. Environmental and genetic modification of leaf number in maize, sorghum, and Hungarian millet. *Crop Sci.* 9:460-463.
- Hillel, D. 1980. *Fundamentals of Soil Physics*. Academic Press. Toronto, Ontario.
- Holt, R. F. and Van Doren, C. A. 1961. Water utilization by field corn in western Minnesota. *Agron. J.* 53:43-45.
- Hough, M. N. 1972. Weather factors affecting the development of maize from sowing to flowering. *J. Agric. Sci., Camb.* 78:325-331.
- Hunter, R. B., Hunt, L. A. and Kannenberg, L. W. 1974. Photoperiod and temperature effects on corn. *Can. J. Plant Sci.* 54:71-78.
- Iremiren, G. O. and Milbourn, G. M. 1979. The influence of soil temperatures as controlled by mulching on growth and development of maize. *Annals of Applied Biology* 91:397-401.
- Jackson, R. D. 1982. Canopy temperature and crop water stress. *Advances in Irrigation* 1:43-85.
- Kiniry, J. R., Ritchie, J. T., Musser, R. L., Flint, E. P. and Iwig, W. C. 1983a. The photoperiod sensitive interval in maize. *Agron. J.* 75:687-690.
- Kiniry, J. R., Ritchie, J. T. and Musser, R. L. 1983b. Dynamic nature of the photoperiod response in maize. *Agron. J.* 75:700-703.
- Lal, R. 1973. Effects of seed bed preparation and time of planting on maize (Zea mays) in Western Nigeria. *Expl. Agric.* 9:303-313.
- Lal, R. 1974. Effects of constant and fluctuating soil temperature on growth, development and nutrient uptake of maize seedlings. *Plant and Soil* 40:589-606.
- Landi, P. and Crosbie, T. M. 1982. Response of maize to cold stress during vegetative growth. *Agron. J.* 74:765-768.
- Landsberg, J. J. 1977. Some useful equations for biological studies. *Expl. Agric.* 13:273-286.
- Larson, W. E. and Hanway, J. J. 1977. Corn Production. In: G. F. Sprague (ed.). Corn and Corn Improvement. p. 625-669. ASA, Academic Press.
- Lehenbauer, P. A. 1914. Growth of maize seedlings in relation to temperature. *Physiol. Res.* 1:247-288.

- List, A. 1969. Transient growth responses of the primary roots of Zea mays. *Planta* 87:1-19.
- Major, D. J., Pelton, W. L., Shaykewich, C. F., Gage, S. H. and Green, D. G. 1976. Corn heat units in the prairies. Man. Corn Committee. Man. Dept. Agriculture, Winnipeg, Man. 4 p.
- Major, D. J., Brown, D. M., Bootsma, A., Dupuis, G., Fairey, N. A., Grant, E. A., Green, D. G., Hamilton, R. I., Langille, J., Sonmor, L. G., Smeltzer, G. C. and White, R. P. 1983. An evaluation of the corn heat unit system for short season growing regions across Canada. *Can. J. Plant Sci.* 63:121-130.
- Mallett, J. B. 1972. The use of climatic data for maize yield predictions. Ph.D. Thesis. Dept. of Crop Sci., Univ. of Natal, Pietermaritzburg, S. A.
- Miedema, P. 1982. The effects of low temperature on Zea mays. *Adv. Agron.* 35:92-128.
- Miller, D. E. 1968. Emergence and development of sweet corn as influenced by various soil mulches. *Agron. J.* 60:369-371.
- Mosher, P. N. and Miller, M. H. 1972. Influence of soil temperature on the geotropic response of corn roots (Zea mays L.). *Agron. J.* 64:459-462.
- Moss, G. I. and Downey, L. A. 1971. Influence of drought stress on female gametophyte development in corn (Zea mays L.) and subsequent grain yield. *Crop Sci.* 11:368-372.
- Mtui, T. A., Kanemasu, E. T. and Wassom, C. 1981. Canopy temperatures, water use, and water use efficiency of corn genotypes. *Agron. J.* 73:639-643.
- Onderdonk, J. J. and Ketcheson, J. W. 1973. Effect of soil temperature on direction of corn root growth. *Plant and Soil* 39:177-186.
- Pawloski, M. C. and Shaykewich, C. F. 1972. Germination of wheat as affected by soil water stress. *Can. J. Plant Sci.* 52:619-623.
- Peaslee, D. E., Ragland, J. L. and Duncan, W. G. 1971. Grain filling period of corn as influenced by phosphorus, potassium, and the time of planting. *Agron. J.* 63:561-563.
- Phipps, R. H. and Cochrane, J. 1975. The production of forage maize and the effect of bitumen mulch on soil temperature. *Agric. Meteorol.* 14:399-404.
- Priestley, C. H. B. and Taylor, R. J. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review* 100: 81-92.



- Reimer, A. and Shaykewich, C. F. 1980. Estimation of Manitoba soil temperatures from atmospheric meteorological measurements. *Can. J. Soil Sci.* 60:299-309.
- Rhoads, F. M. and Stanley, Jr., R. L. 1973. Response of three corn hybrids to low levels of soil moisture tension in the plow layer. *Agron. J.* 65:315-318.
- Riley, G. J. P. 1981. Effects of high temperature on the germination of maize (*Zea mays* L.). *Planta* 151:68-74.
- Ritchie, J. T. 1973. Influence of soil water status and meteorological conditions on evaporation from a corn canopy. *Agron. J.* 65:893-897.
- Ritchie, J. T. and Burnett, E. 1971. Dryland evaporative flux in a subhumid climate: II. Plant influences. *Agron. J.* 63:56-62.
- Ritter, W. F. and Beer, C. E. 1969. Yield reduction by controlled flooding of corn. *Trans. A.S.A.E.* 12:46-47, 50.
- Robertson, G. W. and Holmes, R. M. 1957. Crop-weather research in Canada. A paper presented before First Workshop on Agricultural Meteorology in Madison, Wisconsin. May 14-16.
- Robertson, G. W. 1968. A biometeorological time scale for a cereal crop involving day and night temperatures and photoperiod. *Int. J. Biometeor.* 12:191-223.
- Rood, S. B. and Major, D. J. 1980. Responses of early corn inbreds to photoperiod. *Crop Sci.* 20:679-682.
- Rood, S. B. and Major, D. J. 1981. Diallel analysis of the photoperiodic response of maize. *Crop Sci.* 21:875-878.
- Russell, W. K. and Stuber, C. W. 1983. Effects of photoperiod and temperature on the duration of vegetative growth in maize. *Crop Sci.* 23:847-850.
- Russell, W. K. and Stuber, C. W. 1984. Prediction of tassel initiation in corn. *Crop Sci.* 24:507-510.
- Sharp, R. E. and Davies, W. J. 1979. Solute regulation and growth by roots and shoots of water-stressed maize plants. *Planta* 147:43-49.
- Shaw, R. H. and Thom, H. C. S. 1951. On the phenology of field corn, the vegetative period. *Agron. J.* 43:9-15.
- Shaw, R. H. 1977. Climatic requirement. In: G. F. Sprague (ed.). *Corn and Corn Improvement*. p. 591-623, ASA, Academic Press.
- Shaykewich, C. F. 1965. The relationship between soil components and soil physical constants of some Manitoba soils. M.Sc. Thesis, University of Manitoba.

- Sheppard, S. C. and Miller, M. H. 1977. Temperature changes and the geotropic reaction of the radicle of Zea mays L. Plant and Soil 47:631-644.
- Singh, N. T. and Dhaliwal, G. S. 1972. Effect of soil temperature on seedling emergence in different crops. Plant and Soil 37:441-444.
- Stevenson, J. C. and Goodman, M. M. 1972. Ecology of exotic races of maize. I. Leaf number and tillering of 16 races under four temperatures and two photoperiods. Crop Sci. 12:864-868.
- Struik, P. C. 1982. Effect of a switch in photoperiod on the reproductive development of temperate hybrids of maize. Neth. J. Agric. Sci. 30:69-83.
- Tataryn, J. H. 1974. Evaluation of the corn heat unit for south western Manitoba. M. Sc. Thesis, University of Manitoba.
- Taylor, A. O. and Rowley, J. A. 1971. Plant under climatic stress. I. Low temperature, high light effects on photosynthesis. Plant Physiol. 47: 713-718.
- Taylor, S. A. and Ashcroft, G. L. 1972. Physical Edaphology: The Physics of Irrigated and Nonirrigated Soils. W. H. Freeman and Company, San Francisco.
- Tollenaar, M., Daynard, T. B. and Hunter, R. B. 1979. Effect of temperature on rate of leaf appearance and flowering date in maize. Crop Sci. 19:363-366.
- Tollenaar, M. and Hunter, R. B. 1983. A photoperiod and temperature sensitive period for leaf number of maize. Crop Sci. 23:457-460.
- Turner, N. C. 1980. Turgor Maintenance by Osmotic Adjustment: A Review and Evaluation. In: N. C. Turner and P. J. Kramer (eds.). Adaptation of Plants to Water and High Temperature Stress. Wiley Interscience, New York.
- van Keulen, H. 1975. Simulation of water use and herbage growth in arid regions. Centre for Agriculture Publishing and Documentation, Wageningen. Netherlands.
- Walker, J. M. 1969. One-degree increments in soil temperatures affect maize seedling behavior. Soil Sci. Soc. Amer. Proc. 33:729-736.
- Wall, D. A. and Stobbe, E. H. 1983. The response of eight corn (Zea mays L.) hybrids to zero tillage in Manitoba. Can. J. Plant Sci. 63:753-757.
- Wall, D. A. and Stobbe, E. H. 1984. The effect of tillage on soil temperature and corn (Zea mays L.) growth in Manitoba. Can. J. Plant Sci. 64:59-67.
- Wang, J. Y. 1960. A critique of the heat unit approach to plant response studies. Ecology 4:785-790.

- Ward, J. and Shaykewich, C. F. 1972. Water absorption by wheat seeds as influenced by hydraulic properties of soil. Can. J. Soil Sci. 52:99-105.
- Warrington, I. J. and Kanemasu, E. T. 1983a. Corn growth response to temperature. I. Seedling emergence, tassel initiation, and anthesis. Agron. J. 75:749-754.
- Warrington, I. J. and Kanemasu, E. T. 1983b. Corn growth response to temperature and photoperiod. II. Leaf initiation and leaf-appearance rates. Agron. J. 75:755-761.
- Warrington, I. J. and Kanemasu, E. T. 1983c. Corn growth response to temperature and photoperiod. III. Leaf number. Agron. J. 75:762-766.
- Watts, W. R. 1972. Leaf extension in Zea mays. II. Leaf extension in response to independent variation of the temperature of the apical meristem, of the air around the leaves, and of the root zone. J. Exp. Bot. 23:713-721.
- Watts, W. R. 1973. Soil temperature and leaf expansion in Zea mays. Expl. Agric. 9:1-8.
- Wenkert, W., Fausey, N. R. and Watters, H. D. 1981. Flooding responses in Zea mays L. Plant and Soil 62:351-366.
- Williams, J. and Shaykewich, C. F. 1971. Influence of soil water matric potential and hydraulic conductivity on the germination of rape (Brassica napus L.). J. Exp. Bot. 22:586-597.
- Wolfe, T. K. 1927. A study of germination, maturity and yield in corn. Va. State Tech. Bull. 30.
- Zwarich, M. A. and Shaykewich, C. F. 1969. An evaluation of several methods of measuring bulk density of soils. Can. J. Soil Sci. 49:241-245.

PART VI

APPENDIX

Appendix A  
SOIL MOISTURE MODEL

```

//EVAP JOB '0290-02,BREH.,T=2,L=4,I=30',H.CUTFORTH
//TSO SOIL
//EXEC WATFIV
//FT08F001 DD DSN=CUTFORT.GROUPC,DISP=SHR,
//          SUBSYS=(JESX,ALLSTNDATA,HERB),
//          DCB=(RECFM=F,LRECL=132,BLKSIZE=132)
//FT09F001 DD DSN=CUTFORT.GROUPC,DISP=SHR,
//          SUBSYS=(JESX,SOILDATA,HERB),
//          DCB=(RECFM=F,LRECL=132,BLKSIZE=132)
//GO.SYSIN DD *
SJOB WATFIV
SNOEXT
      INTEGER ENDATA, DAY, STN, A, B, END(12), BEGIN(12), STNA
      REAL TCK(8), TCD(8), MW(12,8), WCLIM(12,8), IW(12,8), FCA,
      SWPA, FCB, WPB, SUMVAR, RWFB(8), W(8), RAIN, TMAX, TMIN, Q,
      SVAR(8), WCPR, REDUCT, AEVAP, PEVAP, LE1, EVAP(8), RANGE
      S, TX, FC(12,8), THETA(8), Z(8), PROP(12)
      ENDATA=0
C   DEFINING INITIAL CONDITIONS
      READ, (PROP(A), A=1, 12)
      READ, (TCK(A), A=1, 8)
      READ, (TCD(A), A=1, 8)
      DO 14 A=1, 12
100      READ (9, 100) STN, FCA, FCB, WPA, WPB
          FORMAT (8X, I2, 25X, 4F5.0)
          DO 15 B=1, 4
              MW(STN, B)=FCA*TCK(B)
              WCLIM(STN, B)=WPA*.333
              FC(STN, B)=FCA
15          CONTINUE
              DO 16 B=5, 8
                  MW(STN, B)=FCB*TCK(B)
                  WCLIM(STN, B)=WPB*.333
                  FC(STN, B)=FCB
16          CONTINUE
14      CONTINUE
          DO 19 STN=1, 12
              READ, (IW(STN, A), A=1, 8), BEGIN(STN), END(STN)
19      CONTINUE
C   CALCULATE INFILTRATION, EVAP AND SOIL WATER CONTENT
      WHILE (ENDATA .EQ. 0) DO
          EXECUTE RDDATA
          STNA=STN
          DO 21 A=1, 8
              W(A)=IW(STN, A)*TCK(A)
21          CONTINUE
              WHILE (DAY .LT. BEGIN(STN)) DO
                  EXECUTE RDDATA
              END WHILE
              WHILE (DAY .LE. END(STN)) DO
                  EXECUTE PEVAP
                  SUMVAR=0.0
                  EXECUTE SOAKIN
                  EXECUTE PRINT
                  EXECUTE RDDATA
              END WHILE
              WHILE (STN .NE. STNA .AND. ENDATA .EQ. 0) DO
                  EXECUTE RDDATA
              END WHILE
          END WHILE
          STOP
C   READ ALLSTNDATA
          REMOTE BLOCK RDDATA
          READ (8, 101) STN, TMIN, TMAX, DAY, RAIN, Q
          AT END DO
              ENDATA=1
          END AT END
101      FORMAT (3X, I2, 7X, 2F5.0, 7X, I3, 6X, F6.0, 50X, F7.0)
          END BLOCK
C   CALCULATE POTENTIAL EVAP USING BAIER AND ROBERTSON'S EQUATION
          REMOTE BLOCK PEVAP
              TX=9./5.*TMAX+32.
              RANGE=9./5.*(TMAX-TMIN)+32.
              LE1=.928*TX+.933*RANGE+.0486*Q-87.03
              PEVAP=.0085*LE1*.8
              IF (PEVAP .LE. 0.0) PEVAP=0.0
          END BLOCK
C   INFILTRATION AND ACTUAL EVAP CALCULATION
          REMOTE BLOCK SOAKIN
              Z(1)=AMAX1(0., MW(STN, 1)-W(1))
              RWFB(1)=AMAX1(0., RAIN-Z(1))
              W(1)=W(1)+RAIN-RWFB(1)
              DO 13 A=2, 8
                  B=A-1
                  Z(A)=AMAX1(0., MW(STN, A)-W(A))
                  RWFB(A)=AMAX1(0., RWFB(B)-Z(A))
                  W(A)=W(A)+RWFB(B)-RWFB(A)

```

```

      IF (W(A) .LE. WCLIM(STN,A)) W(A)=WCLIM(STN,A)
13    CONTINUE
      DO 20 A=1,8
        VAR(A)=AMAX1(W(A)/TCK(A)-WCLIM(STN,A),0.)*
        SEXP(-PROP(STN)*TCD(A))
        SUMVAR=SUMVAR+(VAR(A)*TCK(A))
20    CONTINUE
      WCPR=(W(1)/TCK(1)-WCLIM(STN,1))/(PC(STN,1)-WCLIM(STN,1))
      IF (WCPR .LE. 0.0) WCPR=0.0
      IF (WCPR .GE. 0.5) THEN DO
        REDUCT=.9+.1*WCPR
      ELSE DO
        REDUCT=.075-.067*WCPR+3.568*WCPR*WCPR
      END IF
      AEVAP=PEVAP*REDUCT
      DO 23 A=1,8
        EVAP(A)=AMAX1(0.,AEVAP*(TCK(A)*VAR(A)/SUMVAR))
        W(A)=W(A)-EVAP(A)
        IF (W(A) .LE. WCLIM(STN,A)) W(A)=WCLIM(STN,A)
23    CONTINUE
      END BLOCK
C    PRINT OUT CALCULATED WATER CONTENTS OF THE SOIL LAYER'S
C    ON DAILY BASIS
      REMOTE BLOCK PRINT
      DO 27 A=1,8
        THETA(A)=W(A)/TCK(A)
27    CONTINUE
      PRINT 105,STN,DAY,(THETA(A),A=1,8),(W(A),A=1,8)
105   FORMAT (' ',12,2X,I3,8F6.3,8F6.2)
      END BLOCK
      END
SENTRY
.7 .25 .2 .25 .7 .5 .5 .2 .8 .4 .65 .7
2. 3. 5. 5. 5. 20. 30. 50.
1. 3.5 7. 5 12.5 17.5 30. 55. 95.
.08 .12 .25 .27 .15 .15 .15 .15 130 150
.08 .16 .24 .33 .35 .41 .44 .48 132 152
.08 .12 .32 .42 .48 .50 .52 .53 134 152
.30 .30 .30 .30 .25 .20 .15 .15 148 163
.15 .26 .35 .40 .45 .43 .43 .50 132 165
.08 .14 .36 .40 .44 .42 .44 .50 132 153
.07 .30 .45 .45 .46 .54 .54 .54 139 163
.08 .20 .24 .26 .27 .27 .34 .44 129 153
.45 .45 .45 .45 .48 .50 .52 .52 136 170
.02 .13 .15 .15 .14 .32 .45 .50 143 172
.08 .20 .22 .28 .29 .35 .35 .35 130 168
.15 .30 .42 .45 .46 .52 .52 .52 137 166

```

Appendix B  
EMERGENCE MODEL



```

//TIPOUT JOB '0290-02,BREH,,T=2,L=4,I=10',H.CUTFORTH
//TSO SOIL
//EXEC WATFIV
//FT08F001 DD DSN=CUTFORT.GROUPC,DISP=SHR,
//          SUBSYS=(JESX,DUMPI,HERB),
//          DCB=(RECFM=F,LRECL=132,BLKSIZE=132)
//FT09F001 DD DSN=CUTFORT.GROUPC,DISP=SHR,
//          SUBSYS=(JESX,SOILDATA,HERB),
//          DCB=(RECFM=F,LRECL=132,BLKSIZE=132)
//GO.SYSIN DD *
SJOB WATFIV
SNOEXT
      INTEGER ENDATA,DAY,STN,STNA,DAYA,PLDAY,OBS(12),DIFF,SDIFF
      REAL TEMP,W(5),T(6),FC(12),PWP(12),DEPTH(12),RMAX,K,RATE,TMAX,
      STMIN,SUMRAT,A,B,C,TRATIO,R1,R2,REDUCT,TBASE,E,N
      ENDATA=0
      SDIFF=0
      TBASE=10.8
      SUMRAT=0.0
      READ (OBS(J),J=1,12)
      DO 21 J=1,12
      READ (9,100) STN,DEPTH(STN),FC(STN),PWP(STN)
100    FORMAT (8X,I2,7X,F3.1,15X,F5.0,5X,F5.0)
      DEPTH(STN)=DEPTH(STN)
C      DEPTH(STN)=6.0
21    CONTINUE
      EXECUTE RDDATA
10    WHILE (ENDATA .EQ. 0) DO
      STNA=STN
      DAYA=DAY
      N=1.
      SUMRAT=0.0
      WHILE (SUMRAT .LT. .98 .AND. ENDATA .EQ. 0) DO
      IF (STN .NE. STNA) THEN DO
      PRINT 201,STNA
201    FORMAT(' ','STATION=',1X,I2,5X,'NO EMERGENCE')
      GO TO 10
      END IF
      EXECUTE PRECAL
      EXECUTE RATE
      IF (N .EQ. 1.0) RATE=0.5*RATE
      N=N+1.
      SUMRAT=SUMRAT+RATE
      EXECUTE RDDATA
      END WHILE
      EXECUTE PRINT
11    WHILE (STN.EQ.STNA .AND. ENDATA .EQ. 0) DO
      EXECUTE RDDATA
      END WHILE
      SDIFF=SDIFF+DIFF
      END WHILE
      PRINT 250,SDIFF
250    FORMAT (' ',30X,'SUM OF DIFFERENCES=',I3)
      STOP
C
C READ SOIL TEMP AND SOIL MOISTURE
      REMOTE BLOCK RDDATA
      READ (8,101) STN,TN,TX,DAY,RAD,T(1),T(2),T(3),T(4),T(5),T(6),
      SW(2),W(3),W(4)
      AT END DO
      ENDATA=1
      END AT END
101    FORMAT (9X,I2,1X,2(1X,F5.0),2X,I3,1X,F6.0,6(1X,F5.1),24X,
      S3(1X,F5.2))
C      EXECUTE SOILT
      END BLOCK
C
C CALCULATE THETA, TEMP
      REMOTE BLOCK PRECAL
      IF (SUMRAT .LT. .50) THEN DO
      WATER=(3*W(3)+W(4))/20.0
      ELSE DO
      WATER=(W(3)+3*W(4))/20.
      END IF
      IF (DEPTH(STN) .GE. 5.0) THEN DO
      TMAX=T(4)-(((T(4)-T(6))/5.)*(DEPTH(STN)-5.0))

```

```

      TMIN=T(3)-(((T(3)-T(5))/5.)*(DEPTH(STN)-5.0))
      ELSE DO
      TMAX=T(2)-(((T(2)-T(4))/2.5)*(DEPTH(STN)-2.5))
      TMIN=T(1)-(((T(1)-T(3))/2.5)*(DEPTH(STN)-2.5))
      END IF
    END BLOCK
  C
  C CALCULATE DAILY RATE OF EMERGENCE
  REMOTE BLOCK RATE
  E=TMAX-TMIN
  IF (E .LE. 0.0) THEN DO
    TRATIO=0.0
  ELSE DO
    TRATIO=(TMAX-TBASE)/E
  END IF
  IF (TMAX .LE. TBASE) TRATIO=0.0
  REDUCT=.015+1.589*TRATIO-.657*(TRATIO**2)+.027*(TRATIO**4)
  A=TMAX-10.8
  B=TMIN-10.8
  C=(WATER-PWP(STN))/(FC(STN)-PWP(STN))
  IF (C .LE. 0.0) C=0.0
  IF (A .LT. 0.0) A=0.0
  IF (B .LT. 0.0) B=0.0
  R1=.00089*A**12*(1-EXP(-(8.1965-.3229*TMAX+.0055*TMAX*TMAX)*C))
  R2=.00089*B**12*(1-EXP(-(8.1965-.3229*TMIN+.0055*TMIN*TMIN)*C))
  RATE=(R1+R2)*REDUCT
  END BLOCK
  C
  C PRINT SUCCESSFULL CALCULATION OF EMERGENCE
  REMOTE BLOCK PRINT
  PLDAY=DAY-DAYA+1
  DIFF=PLDAY-OBS(STN)
  PRINT 200,STNA,PLDAY,OBS(STN),DIFF,SUMRAT
200  FORMAT (' ',STN=',1X,I2,3X,
  S'PE(DAYS)=',1X,I2,3X,'OBS=',1X,I2,3X,
  S'DIFF=',1X,I3,3X,'SUMRAT=',1X,F6.4)
  END BLOCK
  C
  C CALCULATE SOIL TEMP FROM AIR TEMP
  REMOTE BLOCK SOILT
  IF (STN .EQ. 1 .OR. STN .EQ. 4 .OR. STN .EQ. 8 .OR.
  S STN .EQ. 10 .OR. STN .EQ. 11) THEN DO
    T(1)=2.49+.8*TN
    T(2)=1.32+.82*TX+.0092*RAD
    T(3)=3.87+.69*TN
    T(4)=2.92+.53*TX+.22*TN+.0094*RAD
    T(5)=1.98+.9*T(3)
    T(6)=.07+.77*T(4)
  ELSE DO
    T(1)=2.84+0.72*TN
    T(2)=.85+.72*TX+.0093*RAD
    T(3)=5.22+.6*TN
    T(4)=3.25+.55*TX+.006*RAD
    T(5)=2.56+.82*T(3)
    T(6)=2.19+.52*T(4)+.32*T(3)
  END IF
  END BLOCK
  END
SENTRY

```

Appendix C  
ITERATIVE (IF) MODEL

```

//ITFIT JOB '0290-02,BREH,,T=2M,L=4,I=15',H.CUTFORTH,CLASS=F
//TSO SOIL
//EXEC WATFIV
//FT08F001 DD DSN=CUTFORT.GROUPC,DISP=SHR,
//          SUBSYS=(JESX,ALLSTNDATA,HERB),
//          DCB=(RECFM=F,LRECL=132,BLKSIZE=132)
//FT09F001 DD DSN=CUTFORT.GROUP,DISP=SHR,
//          SUBSYS=(JESX,SOILDATA,HERB),
//          DCB=(RECFM=F,LRECL=132,BLKSIZE=132)
//GO.SYSIN DD *
SJOB WATFIV
SNOEXT
      CHARACTER TITLE(80)
C PR2  AIR TEMP
      INTEGER STN,DAY,HYB,STNHYB(12,2),DAYNUM(12,5),ROW,COL
      S ,START,B,M,N
      S,FINISH
      REAL TX(12,300),TMINN,TMINX,TOPTN,TOPTX,TMAXX,TMAXN,
      S TN(12,300),VAR(12),MEAN,SUM,CV,SD,C,AN1,AN2,BN1,BN2
      S ,Z,IF(12),IFX,IFN,BX,BN,CN,CX,TEMP(10)
      S,AX1,AX2,BX1,BX2,AO1,AO2,BO1,BO2
      M=0
      N=0
      AN1=TMINN-05.
      AN2=09.
      AX1=TMAXN-31.
      AX2=35.
      AO1=TOPTN-30.
      AO2=34.
      BN1=TMINX-13.
      BN2=17.
      BX1=TMAXX-37.
      BX2=41.
      BO1=TOPTX-31.
      BO2=35.
      C=02.
900  READ (8,200,END=800) STN,TEMP(1),TEMP(2),DAY,(TEMP(B),B=3,10)
200  FORMAT ( 3X,12,7X,2F5.0,6X, 14,12X,8F5.0)
      TX(STN,DAY)=TEMP(2)
      TN(STN,DAY)=TEMP(1)
      GO TO 900
800  READ 14,TITLE
14   FORMAT (80A1)
      DO 61 ROW=1,12
      READ 100, (STNHYB(ROW,COL),COL=1,2),(DAYNUM(ROW,COL),COL=1,5)
100  FORMAT (2I2,5(4X,I3))
61   CONTINUE
      HYB=STNHYB(1,2)
      WHILE(AN1 .LE. TMINN .AND. TMINN .LE. AN2) DO
          TMAXN=AX1
          WHILE(AX1 .LE. TMAXN .AND. TMAXN .LE. AX2) DO
              IF (TMAXN .LE. TMINN) GO TO 2
              TOPTN=AO1
              WHILE(AO1 .LE. TOPTN .AND. TOPTN .LE. AO2) DO
                  IF (TOPTN .LE. TMINN) GO TO 3
                  IF (TOPTN .GE. TMAXN) GO TO 3
                  TMINX=BN1
                  WHILE(BN1 .LE. TMINX .AND. TMINX .LE. BN2) DO
                      TMAXX=BX1
                      WHILE(BX1 .LE. TMAXX .AND. TMAXX .LE. BX2) DO
                          IF (TMAXX .LE. TMINX) GO TO 5
                          TOPTX=BO1
                          WHILE(BO1 .LE. TOPTX .AND. TOPTX .LE. BO2) DO
                              IF (TOPTX .LE. TMINX) GO TO 6
                              IF (TOPTX .GE. TMAXX) GO TO 6
999  DO 8 STN=1,12
              IF (HYB .EQ. 1 .AND. STN .EQ. 8) GO TO 60
              IF (STN .EQ. 8 .AND. HYB .EQ. 2) GO TO 39
              IF (M .EQ. 1 .AND. STN .EQ. 4) GO TO 67
              IF (M .EQ. 1 .AND. STN .EQ. 10) GO TO 68
              IF (STN .EQ. 6 .AND. N .EQ. 1) GO TO 69
              START=DAYNUM(STN,2)+1
              FINISH=DAYNUM(STN,3)
              IF (STN)=0.0
              DO 7 DAY=START,FINISH
                  IF (TMINN .LE. TN(STN,DAY) .AND.

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-5 TMAXN .GE. TN(STN, DAY)) THEN DO
  BN=(TMAXN-TOPTN)
  BN=BN/(TOPTN-TMINN)
  CN=(TOPTN-TMINN)*((TMAXN-TOPTN)**BN)
  IFN=(TN(STN, DAY)-TMINN)*((TMAXN-TN(STN, DAY))**BN)/CN
  ELSE DO
    IFN=0.0
  END IF
  IF (TMINK .LE. TX(STN, DAY) .AND.
5 TMAXX .GE. TX(STN, DAY)) THEN DO
    BX=(TMAXX-TOPTX)
    BX=BX/(TOPTX-TMINX)
    CX=(TOPTX-TMINX)*((TMAXX-TOPTX)**BX)
    IFX=(TX(STN, DAY)-TMINX)*((TMAXX-TX(STN, DAY))**BX)
5 /CX
    IF(STN)=IF(STN)+IFX/2.+IFN/2.
  ELSE DO
    IFX=0.0
    IF(STN)=IF(STN)+IFX/2.+IFN/2.
  END IF
7 CONTINUE
60 IF (HYB .EQ. 1 .AND. STN .EQ. 8) IF(8)=0.0
39 IF ( STN .EQ. 8 .AND. HYB .EQ. 2) IF(8)=0.0
67 IF (M .EQ. 1 .AND. STN .EQ. 4) IF(4)=0.0
68 IF (M .EQ. 1 .AND. STN .EQ. 10) IF(10)=0.0
69 IF (STN .EQ. 6 .AND. N .EQ. 1) IF(6)=0.0
8 CONTINUE
  IF (HYB .EQ. 3) THEN DO
    Z=12.
  ELSE DO
    Z=11.
  END IF
  IF (M .EQ. 1) Z=Z-2.
  IF (N .EQ. 1) Z=Z-1.
  SUM=0.0
  DO 29 STN=1, 12
    SUM=SUM+IF(STN)
29 CONTINUE
  MEAN=SUM/Z
28 CONTINUE
  DO 30 STN=1, 12
    VAR(STN)=(IF(STN)-MEAN)**2
30 CONTINUE
  IF (HYB .EQ. 1) VAR(8)=0.0
  IF (HYB .EQ. 2) VAR(8)=0.0
  IF (M .EQ. 1) VAR(4)=0.0
  IF (M .EQ. 1) VAR(10)=0.0
  IF (N .EQ. 1) VAR(6)=0.0
  SD=0.0
  DO 33 STN=1, 12
    SD=SD+VAR(STN)
33 CONTINUE
  SD=(SD/(Z-1.))**.5
  CV=(SD/MEAN)*100
  PRINT 101, CV, TMINK, TMAXX, TOPTN,
101 S TMINK, TMAXX, TOPTX
  FORMAT (' ', F6.2, 6(2X, F4.1))
6 TOPTX=TOPTX+C
  END WHILE
5 TMAXX=TMAXX+C
  END WHILE
  TMINK=TMINK+C
  END WHILE
3 TOPTN=TOPTN+C
  END WHILE
2 TMAXN=TMAXN+C
  END WHILE
  TMINN=TMINN-C
  END WHILE
  STOP
  END
SENTRY

```

# Appendix D

DATES AND DAY NUMBERS ON WHICH THE PHENOLOGICAL EVENTS -  
PLANTING, EMERGENCE, STEM ELONGATION, SILKING - OCCURRED.

Station Number	Planting		Emergence		Stem Elongation		Silking	
	Date	Day #	Date	Day #	Date	Day #	Date	Day #
Pioneer 3995								
1	May 10	131	May 23	144	June 24	176	July 19	201
2	May 12	133	May 25	146	June 24	176	July 15	197
3	May 14	135	May 25	146	June 22	174	July 19	201
4	May 29	150	June 7	159	July 4	186	August 2	215
5	May 12	132	June 7	158	July 8	189	August 5	217
6	May 12	132	May 26	146	July 1	182	July 24	205
7	May 19	139	June 5	156	July 6	187	July 28	209
8		--		--		--		--
9	May 25	145	June 7	158	July 14	195	August 9	221
10	May 23	143	June 7	158	July 17	198	August 7	219
11	May 10	130	June 10	161	July 11	192	August 2	214
12	May 17	137	June 8	159	July 3	184	July 28	209
Northrup King 403								
1	May 10	131	May 23	144	June 25	177	July 25	207
2	May 12	133	May 25	146	June 24	176	July 22	204
3	May 14	135	May 25	146	June 24	176	July 21	203
4	May 29	150	June 7	159	July 4	186	August 4	217
5	May 12	132	June 6	157	July 9	190	August 4	216
6	May 12	132	May 27	147	July 1	182	July 28	209
7	May 19	139	June 5	156	July 7	188	August 2	214
8	May 11	131	May 26	146		--		--
9	May 25	145	June 7	158	July 15	196	August 16	228
10	May 23	143	June 7	158	July 16	197	August 8	220
11	May 10	130	June 10	161	July 11	192	August 10	222
12	May 17	137	June 7	158	July 4	185	August 2	214
Pride 1108								
1	May 10	131	May 23	144	June 25	177	July 27	209
2	May 12	133	May 25	146	June 24	176	July 23	205
3	May 15	136	May 25	146	June 24	176	July 25	207
4	May 29	150	June 7	159	July 4	186	August 5	218
5	May 12	132	June 6	157	July 10	191	August 13	225
6	May 12	132	May 25	145	July 1	182	July 30	211
7	May 19	139	June 6	157	July 7	188	August 5	217
8	May 9	129	May 26	146	July 10	191	August 9	221
9	May 25	145	June 7	158	July 17	198	August 16	228
10	May 23	143	June 7	158	July 17	198	August 13	225
11	May 10	130	June 10	162	July 10	191	August 8	220
12	May 17	137	June 7	158	July 5	186	August 1	213

## Appendix E

AVERAGE AIR AND SOIL TEMPERATURES, PHOTOPERIOD, RAINFALL, INCOMING SOLAR RADIATION AND THE DURATION IN DAYS OF THE STAGES ESE, SESI AND ESI FOR HYBRID PIONEER 3995.

Station Number	Duration (Days)	Average Air Temp( C)		Average Daylength (h)	Average Solar Radiation Rad(MJ/m <sup>2</sup> -DAY)	Average Rainfall (cm)	Average Soil Temperature (C)							
		ATmin	ATmax				2.5 cm		5.0 cm		10.0 cm		20.0 cm	
		ASTmin	ASTmax				ASTmin	ASTmax	ASTmin	ASTmax	ASTmin	ASTmax	ASTmin	ASTmax
<u>ESE</u>														
12	25	12.8	24.1	16.26	22.8	0.25	14.4	24.1	15.2	22.2	15.6	19.9	15.4	17.2
4	27	11.5	24.7	16.25	24.5	0.28	-	-	-	-	-	-	-	-
3	28	8.7	24.2	16.14	26.5	0.25	-	-	-	-	-	-	-	-
2	30	10.9	24.8	16.21	24.9	0.05	10.6	25.4	12.5	21.9	13.8	17.7	13.7	15.4
5	31	11.6	23.4	16.46	23.5	0.21	13.3	26.1	14.9	22.8	16.0	19.9	15.9	17.5
7	31	11.1	23.6	16.24	24.1	0.27	12.0	23.4	13.2	21.1	14.1	17.7	13.2	14.4
11	31	11.7	22.7	16.47	20.7	0.31	12.5	23.5	13.6	21.7	14.4	19.1	14.6	16.6
1	32	10.2	23.7	16.34	25.3	0.06	13.2	26.0	14.2	24.0	15.2	20.8	15.4	17.9
6	36	10.4	21.5	16.23	23.9	0.27	13.5	27.0	15.0	24.0	16.0	21.5	15.8	18.7
9	37	8.8	22.4	16.20	24.0	0.19	12.2	23.2	13.2	20.9	14.3	18.5	14.3	15.9
10	40	9.4	21.2	16.10	23.5	0.16	11.0	21.7	12.1	19.3	12.8	17.1	12.8	14.4
<u>SESI</u>														
2	21	13.4	25.1	16.19	21.6	0.25	15.6	26.0	16.9	23.7	17.7	21.8	17.8	19.8
10	21	13.2	24.5	15.34	22.9	0.23	-	-	-	-	-	-	-	-
7	22	11.7	25.3	15.81	24.7	0.13	16.0	26.4	17.4	24.6	18.5	22.3	18.8	20.4
11	22	14.0	28.4	15.83	24.3	0.01	16.8	32.0	18.2	29.0	19.2	25.0	19.4	21.6
6	23	15.2	26.5	16.01	24.8	0.10	-	-	-	-	-	-	-	-
1	25	13.3	24.0	16.29	22.7	0.28	15.4	25.7	16.5	23.8	17.2	22.4	17.5	20.5
12	25	15.6	28.7	15.86	25.3	0.00	18.2	30.8	19.3	27.7	20.1	24.7	19.9	21.7
9	26	13.5	26.0	15.42	21.8	0.18	15.5	22.6	16.3	21.2	16.7	19.8	17.0	18.0
3	27	12.2	26.4	16.09	22.9	0.19	14.7	24.8	16.2	22.5	17.0	19.6	17.1	18.5
5	28	11.8	25.2	15.80	23.1	0.36	14.3	26.6	16.1	25.0	17.8	21.6	17.9	19.1
4	29	13.0	25.6	15.71	23.5	0.06	-	-	-	-	-	-	-	-
<u>ESI</u>														
12	50	14.2	26.4	16.06	24.1	0.13	16.3	27.5	17.2	25.0	17.9	22.3	17.7	19.5
2	51	11.9	24.9	16.21	23.5	0.13	14.3	26.0	15.7	23.2	16.7	20.7	16.7	18.4
7	53	11.3	24.3	16.06	24.4	0.21	14.0	24.8	15.2	22.9	16.1	20.4	16.3	18.2
11	53	12.6	25.1	16.20	22.2	0.19	14.7	28.5	15.9	26.1	16.9	22.6	17.1	19.4
3	55	10.4	25.3	16.12	24.8	0.22	12.6	25.1	14.4	22.2	15.4	18.6	15.4	16.9
4	56	12.3	25.2	15.97	24.0	0.17	-	-	-	-	-	-	-	-
1	57	11.5	23.8	16.32	24.1	0.16	14.3	26.4	15.6	23.9	16.5	21.9	16.6	19.5
5	59	11.7	24.2	16.15	23.3	0.28	13.1	24.9	14.6	23.0	15.8	19.5	15.4	16.6
6	59	12.3	23.4	16.15	24.3	0.20	-	-	-	-	-	-	-	-
10	61	10.7	22.4	15.84	23.3	0.19	-	-	-	-	-	-	-	-
9	63	10.7	23.8	15.88	23.1	0.19	12.9	22.1	13.8	20.1	14.4	18.2	14.5	15.9

## Appendix F

AVERAGE AIR AND SOIL TEMPERATURES, PHOTOPERIOD, RAINFALL, INCOMING SOLAR RADIATION AND THE DURATION IN DAYS OF THE STAGES ESE, SESI, AND ESI FOR HYBRID NORTHROP KING 403.

Station Number	Duration (Days)	Average Air Temp( C)		Average Daylength (h)	Average Solar Radiation Rad(MJ/m <sup>2</sup> -DAY)	Average Rainfall (cm)	Average Soil Temperature (C)							
		ATmin	ATmax				2.5 cm		5.0 cm		10.0 cm		20.0 cm	
		ASTmin	ASTmax				ASTmin	ASTmax	ASTmin	ASTmax	ASTmin	ASTmax	ASTmin	ASTmax
<u>ESE</u>														
4	27	11.5	24.7	16.25	24.5	0.28	-	-	-	-	-	-	-	-
12	27	12.7	23.6	16.25	23.0	0.24	14.2	23.8	15.0	21.9	15.5	19.7	15.3	17.1
2	30	10.9	24.8	16.21	24.9	0.05	13.3	26.1	14.9	22.8	16.0	19.9	15.9	17.5
3	30	9.3	24.7	16.15	26.5	0.24	11.0	25.7	12.9	22.2	14.1	18.0	14.0	15.7
11	31	11.7	22.7	16.47	20.7	0.31	13.2	26.0	14.2	24.0	15.2	20.8	15.4	17.9
7	32	11.4	23.8	16.24	24.3	0.26	12.8	23.9	13.9	21.9	14.7	19.3	14.8	16.8
1	33	10.2	23.6	16.34	25.2	0.06	13.6	26.9	15.1	23.9	16.1	21.5	15.9	18.8
5	33	11.7	23.5	16.45	23.8	0.20	12.1	23.7	13.3	21.3	14.2	17.8	13.3	14.5
6	35	10.5	21.6	16.24	24.0	0.28	12.3	23.3	13.3	20.9	14.4	18.6	14.5	16.0
9	38	9.0	22.5	16.20	23.9	0.19	11.2	21.9	12.3	19.4	12.9	17.3	12.9	14.6
10	39	9.3	21.3	16.11	23.7	0.14	-	-	-	-	-	-	-	-
8	47	9.9	21.9	16.10	22.0	0.33	12.0	26.9	12.6	25.4	14.2	20.9	14.5	17.9
<u>SESI</u>														
6	23	11.1	23.4	15.51	20.6	0.21	15.2	28.9	16.0	28.2	17.9	23.6	18.7	22.0
10	23	13.0	24.1	15.34	22.5	0.27	-	-	-	-	-	-	-	-
5	26	11.4	25.2	15.80	23.5	0.30	14.2	26.6	16.0	25.1	17.7	21.6	17.9	19.1
7	26	11.8	25.0	15.70	23.8	0.21	15.8	25.8	17.1	24.0	18.1	21.9	18.5	20.1
3	27	11.6	25.8	16.05	22.7	0.20	14.5	24.1	16.1	21.9	16.8	19.2	17.0	18.3
6	27	14.4	26.1	15.94	25.0	0.09	-	-	-	-	-	-	-	-
2	28	13.4	24.6	16.09	21.1	0.21	15.7	25.8	17.0	23.6	17.8	21.7	17.8	20.0
12	29	15.7	29.3	15.74	25.4	0.07	18.3	30.6	19.4	27.6	20.1	24.6	20.1	21.8
1	30	13.3	24.0	16.18	22.6	0.27	15.0	25.5	16.1	23.7	17.0	22.4	17.5	20.4
11	30	14.2	28.8	15.64	23.8	0.02	16.9	32.2	18.3	29.1	19.3	25.0	19.5	21.6
4	31	13.0	25.2	15.67	23.0	0.14	-	-	-	-	-	-	-	-
9	32	12.7	25.9	15.23	21.8	0.15	14.9	22.0	15.8	20.6	16.2	19.3	16.6	17.8
<u>ESI</u>														
12	56	14.3	26.5	15.99	24.2	0.15	16.3	27.3	17.3	24.8	17.9	22.3	17.7	19.5
3	57	10.4	25.3	16.10	24.7	0.22	12.7	25.0	14.4	22.1	15.4	18.6	15.4	16.9
2	58	12.1	24.7	16.16	23.1	0.13	14.5	25.9	15.9	23.2	16.9	20.8	16.8	18.7
4	58	12.3	25.0	15.94	23.7	0.21	-	-	-	-	-	-	-	-
7	58	11.6	24.4	15.99	24.1	0.24	14.1	24.7	15.3	22.9	16.2	20.5	16.5	18.3
5	59	11.6	24.3	16.17	23.6	0.24	13.0	24.9	14.5	23.0	15.7	19.5	15.3	16.5
11	61	12.9	25.7	16.06	22.2	0.17	15.0	29.0	16.2	26.5	17.2	22.9	17.5	19.7
6	62	12.2	23.5	16.11	24.4	0.19	-	-	-	-	-	-	-	-
10	62	10.7	22.3	15.82	23.2	0.19	-	-	-	-	-	-	-	-
1	63	11.7	23.8	16.27	23.9	0.16	14.3	26.2	15.6	23.8	16.5	21.9	16.6	19.6
8	70	10.3	22.4	15.90	21.6	0.29	13.0	27.6	13.7	26.3	15.4	21.8	15.9	19.2
9	70	10.7	24.0	15.75	23.0	0.17	12.9	21.9	13.9	20.0	14.4	18.2	14.6	16.0



Appendix G

AVERAGE AIR AND SOIL TEMPERATURES, PHOTOPERIOD, INCOMING SOLAR RADIATION AND THE DURATION IN DAYS OF THE STAGES ESE, SESI, ESI FOR HYBRID PRIDE 1108.

Station Number	Duration (Days)	Average Air Temp( C)		Average Daylength (h)	Average Solar Radiation Rad(MJ/m <sup>2</sup> -DAY)	Average Rainfall (cm)	Average Soil Temperature (C)							
		ATmin	ATmax				2.5 cm		5.0 cm		10.0 cm		20.0 cm	
							ASTmin	ASTmax	ASTmin	ASTmax	ASTmin	ASTmax	ASTmin	ASTmax
<u>ESE</u>														
4	27	11.5	24.7	16.25	24.5	0.28	-	-	-	-	-	-	-	-
12	28	12.3	23.4	16.25	23.2	0.23	-	-	-	-	-	-	-	-
11	29	11.4	22.4	16.48	20.6	0.33	14.0	23.8	14.9	21.9	15.4	19.7	15.2	17.1
2	30	10.9	24.8	16.21	24.9	0.05	13.0	25.8	14.1	23.9	15.1	20.8	15.3	17.8
3	30	9.3	24.7	16.15	26.5	0.24	13.3	26.1	14.9	22.8	16.0	19.9	15.9	17.5
7	31	11.5	23.9	16.24	24.2	0.27	11.0	25.7	12.9	22.2	14.1	18.0	14.0	15.7
1	33	10.2	23.6	16.34	25.2	0.06	13.0	23.8	14.0	21.9	14.8	19.3	14.9	16.8
5	34	11.7	23.6	16.45	23.8	0.19	13.6	26.9	15.1	23.9	16.1	21.5	15.9	18.8
6	37	10.5	21.5	16.22	24.1	0.26	12.1	24.0	13.3	21.5	14.3	17.9	13.4	14.6
9	40	9.4	22.7	16.18	23.6	0.20	12.0	23.2	13.1	20.8	14.1	18.4	14.2	15.8
10	40	9.4	21.2	16.10	23.5	0.16	11.5	21.9	12.5	19.5	13.2	17.5	13.2	14.8
8	45	9.6	21.6	16.10	22.1	0.33	-	-	-	-	-	-	-	-
<u>SESI</u>														
10	27	12.1	23.6	15.20	22.9	0.20	11.7	26.6	12.4	25.1	14.0	20.6	14.2	17.6
12	27	16.2	29.6	15.75	21.1	0.05	-	-	-	-	-	-	-	-
2	29	13.5	24.8	16.08	21.3	0.20	18.7	30.9	19.7	27.9	20.4	24.9	20.3	22.0
6	29	14.5	26.1	15.90	24.4	0.17	15.8	26.0	17.1	23.7	17.9	21.7	17.8	20.2
7	29	11.7	24.9	15.64	23.0	0.26	-	-	-	-	-	-	-	-
11	29	14.4	28.8	15.71	24.0	0.01	15.8	25.7	17.1	23.9	18.1	21.8	18.5	20.1
8	30	11.7	23.4	15.44	20.1	0.28	17.0	32.2	18.4	29.2	19.4	25.0	19.6	21.7
9	30	12.5	25.8	15.18	22.1	0.13	15.3	28.5	16.1	27.8	17.9	23.3	18.6	21.8
3	31	11.6	26.0	15.99	23.3	0.18	14.8	22.0	15.7	20.5	16.1	19.2	16.5	17.5
1	32	13.1	24.0	16.14	22.6	0.30	14.4	24.1	16.0	22.0	16.9	19.2	17.0	18.3
4	32	12.9	25.1	15.65	22.7	0.14	14.9	25.5	16.0	23.6	17.0	22.4	17.4	20.3
5	34	12.2	25.2	15.57	22.3	0.35	-	-	-	-	-	-	-	-
<u>ESI</u>														
12	55	14.2	26.4	16.00	24.2	0.14	14.5	25.7	16.2	24.3	17.7	21.2	17.8	18.9
11	58	12.9	25.6	16.09	22.3	0.17	16.3	27.3	17.2	24.8	17.9	22.2	17.7	19.5
2	59	12.2	24.8	16.15	23.2	0.12	15.0	29.0	16.2	26.5	17.2	22.9	17.5	19.8
4	59	12.3	24.9	15.92	23.5	0.20	14.5	26.0	16.0	23.2	16.9	20.8	16.9	18.8
7	60	11.6	24.4	15.95	23.6	0.27	-	-	-	-	-	-	-	-
3	61	10.5	25.4	16.07	24.9	0.21	14.3	24.7	15.5	22.9	16.4	20.5	16.6	18.4
1	65	11.6	23.8	16.25	23.9	0.18	12.7	24.9	14.5	22.1	15.5	18.6	15.5	17.0
6	66	12.2	23.5	16.08	24.2	0.22	14.2	26.2	15.5	23.8	16.5	21.9	16.6	19.6
10	67	10.5	22.2	15.74	23.2	0.17	-	-	-	-	-	-	-	-
5	68	11.9	24.4	16.01	23.0	0.27	-	-	-	-	-	-	-	-
9	70	10.7	24.0	15.75	23.0	0.17	13.3	24.8	14.8	22.9	16.0	19.6	15.6	16.8
8	75	10.5	22.3	15.84	21.3	0.30	12.9	21.9	13.9	20.0	14.4	18.2	14.6	16.0
							13.2	27.3	13.9	26.2	15.5	21.7	16.0	19.3