Evaluation of a Crop Simulation Model

by

Herb Cutforth

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ABSTRACT

A crop simulation model (van Keulen, 1975) for the growth of spring wheat was tested under Manitoba environmental conditions. The simulated crop growth - dry matter production, seed yield, water use, development rate, and leaf area index (1979 only) - was compared to field data collected during the growing seasons of 1978 and 1979 from experimental sites at Brandon and Glenlea. The spring wheat cultivar Sinton was used for the test. Climatic data - rainfall, solar radiation, maximum and minimum temperature, humidity, dew point temperature, windspeed, and vapor pressure - were collected at each site and used as input for the model.

Rainfall from planting to maturity for 1978 was about average but much below average for 1979. The model slightly underestimated dry matter production, overestimated water use and greatly overestimated seed yield for 1978. Leaf area index was measured during 1979. At Glenlea where moisture was not as limiting as at Brandon during 1979, the simulated maximum leaf area index was much lower than that occurring in the field. At both locations the simulated pattern of leaf area growth lagged behind the field observed leaf area growth. For 1979, the model greatly underestimated dry matter production and seed yield. The model simulated crop development reasonably accurately for 1978 but underestimated time to maturity for 1979.

The model needs revision, especially where conditions of moisture stress exist, to improve the simulation of crop growth and development of Sinton wheat. It is suggested that the simulation of leaf area growth and crop development be improved and tested before the remainder of the model is revised.

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INTRODUCTION

Recently there has been great interest in the use of computers to simulate some of the physical and biological processes involved in crop growth. Infiltration and redistribution of rain water, the microclimate of crops, nutrient and water uptake, photosynthesis and respiration are some of the processes that researchers are trying to simulate. If a simulation model of a particular process has been tested under a variety of situations and found to be accurate, the simulation model can then be used to study the response of the particular process to a changing environment. This could lead to savings in both money and time. Field experiments and growth chamber studies usually take weeks to complete and can require upwards of a few thousand dollars. The same results and conclusions may be reached with a reliable simulation model in a matter of hours and for a few hundred dollars.

The development of a simulation model leads to one other major benefit. A simulation model is only as accurate and reliable as the research upon which it has been based. Therefore because of the extensive review of the literature needed in developing the simulation model, the researchers soon become aware of the depth and quality of the research that has been done in a particular area. The researchers may make suggestions as to where further research is needed and/or do further research themselves to validate some of the assumptions they have made in developing the model.

Upon completion of the development of a simulation model, the model should be tested and validated under varying environments. This helps define the limitations and shortcomings of the model. This then leads to further improvement of the model through continuing research or by defining boundary conditions within which the model may be confidently used.

A simulation model was developed by Dutch researchers to simulate the overall process of crop growth and development of spring wheat. The Dutch researchers, noteably de Wit and van Keulen, conducted field trials and experiments in Israel in the course of developing and verifying their model. Because the growth of a crop is a highly complex process about which our knowledge is relatively limited, many assumptions were made when developing the model. The purpose of this research project was to: 1) review some of the literature to illustrate the complexity of crop growth and some of the aspects of crop growth that a researcher should be aware of when developing a simulation model, 2) test van Keulen's model under Manitoba conditions, 3) offer suggestions as to how the model may be improved and 4) determine the conditions under which the model may be inaccurate.

Chapter II

LITERATURE REVIEW

2.1 DEVELOPMENT RATE

The development of wheat is influenced by environmental conditions which includes moisture stress, photoperiod (daylength) and temperature.

2.1.1 Effect of Moisture Stress

Depending on its severity and the stage at which it occurs, moisture stress can increase or decrease the development rate of wheat. Ehlig and Le Mert (1976) found that plants in their driest treatment headed 7 to 10 days earlier and matured 5 to 6 days earlier than the wettest treatments of their study. Day and Intalop (1970) stressed wheat plants at three stages; jointing, flowering and dough stages. They found that plants that were water stressed at jointing flowered earlier but did not mature earlier than nonstressed plants. On the other hand plants stressed at flowering and dough stages matured earlier than nonstressed plants. El Hadi (1969) also found that moisture stress during and after the flowering phase caused wheat to mature earlier. Angus and Moncur (1977) subjected wheat plants to mild and severe water stress between floral initiation and anthesis. Mild stress hastened plant development while severe stress delayed development as compared to control plants. Early severe stress delayed anthesis to a lesser extent than did late applied severe stress.

The germination rate of wheat is also affected by soil moisture stress. Pawloski and Shaykewich (1972) found that the germination rate of Neepawa wheat decreases little between 0 and 7.8 bars suction but at 15.3 bars suction the time to germination approximately doubled. The final germination percentage was the same for all suctions. They also showed that hydraulic conductivity is an important component of soil moisture stress as it affects germination.

2.1.2 Effect of Daylength

Riddel et al. (1958) studied the effect of daylength on the development of spring wheat. They used 4 cultivars and found that increasing daylength increased the development rate. They concluded that this effect was independent of light intensity.

The response of spring wheat to changing daylength has been found to be cultivar dependent (Riddel and Gries, 1958; Halse and Weir, 1970; Major, 1980). Riddel and Gries (1958) and Major (1980) studied the response of spring wheat cultivars to changing daylength. They found that the cultivars flowered earlier with increasing daylength but that some cultivars were much less sensitive to changes in photoperiod than were the others. Halse and Weir (1970) found large variations in sensitivity to increasing photoperiod between the 14 Australian wheat cultivars of their study.

2.1.3 Effect of Temperature

Generally, increasing temperatures increase the development rate of wheat. Decreasing mean air temperatures increases the number of days between anthesis and heading (Campbell and Read, 1968; Bagga and Rawson, 1977) and increases the duration of grain growth (Warrington et al. 1977; Sofield et al., 1977). Warrington et al. (1977) found that increasing day temperature from 15 to 25C had little effect on the length of the vegetative stage of development but greatly reduced time required for ear development and grain growth stages.

Robertson (1968) used temperature and photoperiod in the development of a biometeorological time scale for wheat. The growth of Marquis wheat was divided into 5 stages: planting to emergence, emergence to jointing, jointing to heading, heading to soft dough and soft dough to ripeness. The model predicts the number of days required for each stage. Regression coefficients calculated using historical data gave an indication of the importance of photoperiod and temperature for each of the 5 stages. The time from planting to emergence was dependent on temperature but days from emergence to jointing was relatively insensitive to temperature but very responsive to photoperiod; increasing photoperiod increased the development rate. The last 3 stages were responsive to temperature; increasing temperature increased the development rate. Time between softdough and ripeness was negatively correlated to photoperiod. The temperature effects on the growth stages of Marquis wheat as indicated by Robertson's model are in close agreement with the observations of Warrington et al. (1977).

2.2 LEAF GROWTH

Leaf area is an important determinant in crop growth, especially in the early stages when most of the light energy used for photosynthesis is intercepted by crop leaves. The larger the leaf area, the more light intercepted and the greater the photosynthetic potential.

Leaf area per plant, leaf area index (leaf area per unit ground area) and leaf area ratio (leaf area per unit crop mass) depend upon the rate of leaf initiation and emergence, rate and extent of leaf growth and tiller production, and rate of leaf and tiller senescence; all of which are strongly influenced by environmental conditions and level of soil fertility.

2.2.1 Leaf Initiation and Emergence

Friend et al. (1962) found that increasing light intensity and increasing temperature to 25C can result in higher rates of leaf initiation, emergence and expansion. They also found that maximum area of individual leaves occurred at 20C. Light intensity did not affect leaf area except at very low intensities which resulted in lower leaf area. However, light intensity and soil moisture stress did not change individual leaf size under the experimental conditions of Campbell and Read (1968) while lowering air temperatures resulted in larger leaves.

2.2.2 Leaf Growth and Tiller Production

Leaf area per plant and leaf area index (LAI) depend to a large degree on tiller production. Campbell and Read (1968) observed increasing tiller numbers at maturity with increasing light intensity. Temperature had little effect on tillering (also noted by Bagga and Rawson, 1977). More tillers were produced initially under lower moisture stress but this early effect disappeared by heading time. Friend (1965, 1966) found tiller production increased with increase in light intensity and that the optimum temperature for tillering was 25C. Other researchers have observed greater tiller production at low than at high temperature (Canvin and Yao, 1967).

Increasing nitrogen supply results in increased leaf area (Puckridge, 1968) and tillering (Dubetz and Bole, 1973). For individual plants grown in isolation, the increase in tiller number with increasing nutrient supply can be quite dramatic but for plants growing at high densities, competition for light may limit tiller production (Puckridge, 1968).

Moisture stress can affect leaf area by hastening the rate of leaf senescence (Fischer, 1973; Slatyer, 1969) and by decreasing the rate of leaf expansion and initiation (Boyer, 1976; Slatyer, 1969). Therefore leaf growth can be a good indicator of moisture stress (Meyer and Green, 1980). Cell growth and enlargement is very sensitive to plant water stress (Hsiao and Acevedo, 1974). Turgor pressure or pressure potential is necessary for cell enlargement. A decrease in turgor pressure results in decreased cell growth which causes a reduction in leaf growth. Plants can recover from mild and short water stress so that leaf growth is relatively unimpaired. However, if the stress is long and severe the plants will not fully recover from the reduced growth caused by the stress (Boyer, 1976; Hsiao and Acevedo, 1974).

Leaf area ratio (LAR) is a measure of the relative area available for photosynthesis. In the study of LAR conducted by Friend (1965), increasing temperature from 10 to 30C caused LAR to increase to a maximum at 20 to 25C and then decrease. On the other hand Campbell and Read (1968) found that mean LAR was not affected by changes in temperature or moisture stress. Both studies indicated that LAR decreased with increasing light intensity.

For crop studies and simulation modeling an important component of crop growth to be measured and/or predicted is leaf area index (LAI). This measurement gives an indication of the magnitude of leaf area per unit ground area that is available for light interception and photosynthesis, expecially in the early stages of crop development when the majority of vegetative growth is in the form of leaves. Light interception is almost complete when LAI is about 4. Further increases in LAI have little effect on crop photosynthesis (Evans and Wardlaw, 1976).

The rate of increase and decrease and the maximum LAI largely depend on climatic conditions and fertility levels. Because of the large differences in environment and fertility from one season to the next, there can be large variations in seasonal patterns of LAI, as illustrated by the work of Conner (1975) and Puckridge (1971). Maximum LAI usually occurs well before anthesis with the subsequent rate of decrease very dependent on moisture conditions during the latter part of the growing season. The decline of LAI can be gradual if moisture conditions are favorable or rapid in the case of excessive moisture or drought (Puckridge, 1971). Restricted availability of water during early growth can contribute substantially to reduced rates of LAI increase (Conner, 1975).

Puckridge (1973) studied the effects of moisture and nitrogen on LAI (leaf laminae plus projected area of green parts of the stems). Maximum LAI occurred on plots which received supplementary water and nitrogen. Supplementary water increased both the maximum LAI and extended the period during which green leaves were present. Fertilizer nitrogen increased only the maximum LAI.

2.3 MOISTURE REGIME

2.3.1 Infiltration and Redistribution

Infiltration is the process of water entry into the soil through the soil surface. Redistribution is the movement of water within the soil profile upon completion of the infiltration process.

Rain infiltration can occur under three sets of conditions: 1) nonponding infiltration, i.e., rain not intense enough to produce ponding (rainfall intensity less than saturated hydraulic conductivity); 2) preponding infiltration, in which the intensity of rain can produce ponding but has not yet done so; and 3) rainpond infiltration, in which rain has produced ponding (Hillel, 1971). As the rain intensity fluctuates during a rain storm, so does the type of rain infiltration, i.e., rain-pond infiltration can be preceeded and/or followed by nonponding or preponding infiltration.

The infiltration rate is the quantity of water per unit time passing through the soil surface and entering the soil profile. It varies with time and depends on the initial soil wetness and suction (Hillel, 1971; Taylor and Ashcroft, 1972), texture, structure and uniformity (layering) of the profile (Hillel, 1971). The infiltration rate is usually high at first and then decreases to a constant rate which is characteristic for the soil (Hillel, 1971). For ponding infiltration, this rate is equal to the saturated hydraulic conductivity. For nonponded infiltration the infiltration rate approached is constant and equal to the rain intensity itself (Hillel, 1971). For ponded infiltration, the higher the saturated hydraulic conductivity the higher the infiltration rate. Generally, the finer textured soils have lower ponded infiltration rates than the coarser textured soils (Bodman and Colman, 1943). The infiltration rate and cumulative infiltration at a given time both decrease as the initial moisture content of the soil increases. Both are greater for dry soil than for wet soil (Taylor and Ashcroft, 1972). However, the rate at which the wetting front moves deeper into the soil profile decreases as moisture content decreases, because of the increased storage capacity of the soil. The condition of the soil surface can affect the infiltration rate. A crusted soil surface can impede the infiltration process by reducing both the initial and final infiltration rates (Hillel, 1971). Structural and textural layering of the soil profile strongly influences the infiltration of water into the soil profile. Alternating clay and sand layers impede infiltration. Clay usually has lower saturated and higher unsaturated hydraulic conductivity than does sand. Therefore, water movement from sand to clay is impeded because clay has the lower saturated hydraulic conductivity. Water movement from clay to sand is retarded because of the lower unsaturated hydraulic conductivity of the sand (Hillel, 1971).

Upon completion of the infiltration process, movement of water within the soil profile does not cease but can continue for long periods of time. Early researchers thought redistribution ceased at a water content, called field capacity, which was characteristic and constant for each soil. It is now known that field capacity varies depending on conditions during the redistribution process and is not a constant value. Hillel (1971) listed the following as some of the factors affecting redistribution and field capacity: 1) soil texture; finer textured soils hold more water for longer periods of time than do coarser textured soils, i.e., clay soils have higher field capacity than do sands; 2) depth of wetting and previous soil moisture status; usually, increasing the initial moisture content results in greater depth of wetting during infiltration, slower redistribution rate and higher field capacity; 3) presence of layers in the soil; layered profiles inhibit redistribution, can result in perched water tables when coarse soil overlies a finer soil and increase field capacity; 4) evapotranspiration; water uptake by plant and evaporation of water from soil surface can affect the redistribution process. Plants have been observed to use a substantial amount of water early in the infiltration and redistribution processes, especially during irrigation (Miller, 1967).

Soil temperature can also affect the movement of soil water. As the mean soil temperature rises, the rates of infiltration and redistribution increase because of the changes in viscosity and surface tension of water, both of which decrease as temperature increases. When thermal gradients exist in the soil, thermally induced flow occurs with a net movement of water from warm to cool regions of the soil. This movement results from both a vapor pressure difference and a matric potential gradient between the high and low temperature regions (Taylor and Ashcroft, 1972).

2.3.2 Evapotranspiration

Evaporation is the conversion of water into vapor and its transfer from the soil or water surface to the atmosphere; transpiration is evaporation from plant stomata. For soil in which plants are growing, evaporative water loss occurs from both plants and soil and is called evapotranspiration.

2.3.2.1 Energy Requirement

The evaporation of water is an energy requiring process. Evaporation rate is a function of a vapor pressure gradient, the resistance to water vapor flow and the ability of the soil and plant to transport water to the sites of evaporation (Begg and Turner, 1976). The main source of the latent energy required for vaporization of water is direct beam solar radiation. Other sources include scattered and reflected radiation from the sky and clouds, heat stored in the soil and advected sensible energy from adjacent sources, most notably bare soil surfaces (Rosenberg, 1974; Hanks et al., 1968). However, over long periods of time, the contribution of soil heat to evapotranspiration has been found to be small compared to advected energy and net radiation (Hanks et al., 1968). Advected energy can contribute substantially to the evapotranspiration process. Energy used in transpiration can exceed the net radiation received (Hanks et al., 1968; Ritchie, 1971). Hanks et al. (1968) found that when water was not limiting evapotranspiration was very dependent on the type of crop. They found that evapotranspiration from oats can be 2 times pan evaporation. The effects of advection can be considerable in small plots that differ from their surroundings (Hillel, 1971) and can also contribute to transpiration on a large land scale basis (de Wit, 1958). The leaf area index can often have values much greater than one. The greater leaf area is able to extract more sensible heat from advected air than is the unit area of bare soil or free water. Thus, evapotranspiration from vegetation well supplied with water, expressed per unit land area, may exceed that from a unit area of wet, bare soil or free water (Slatyer, 1967).

2.3.2.2 Factors Affecting Rate of Evapotranspiration

The rate of evapotranspiration depends on meteorological, plant and soil factors. Net radiation, temperature, humidity and wind are meteorological factors. Plant and soil factors include degree of plant cover, plant shape, stage of maturity, stomatal function and conductance, soil aeration, soil water potential and soil water content, and water transmission properties of the soil. When the soil and plants are well supplied with water, evapotranspiration is controlled by the environmental conditions and is often termed potential evapotranspiration.

Penman (1956) defined potential evapotranspiration as the amount of water evapotranspired in a unit time by a short green crop completely shading the ground, of uniform height and never short of water. Eventually, water cannot be supplied to the evaporation surfaces fast enough to meet the demand and the actual evapotranspiration falls below the potential. At this point, plant and soil factors become important in regulating evaporation.

2.3.2.3 Atmospheric Environmental Factors

Net radiation, vapor pressure of the atmosphere, wind and temperature are environmental factors that influence evapotranspiration. Resistances to vapor flow can be divided into those for single leaves or for crops. For leaves, the resistance to vapor flow is the sum of the internal leaf resistance, of which stomatal resistance plays an important role, and the boundary layer resistance. For crops, Monteith (1973) has defined two types of resistances, the canopy resistance which is related to the internal leaf resistance and the aerodynamic resistance. Both the boundary layer resistance and the aerodynamic resistance depend on wind speed; both decrease as wind speed increases. For surfaces that are not wet, this does not, however, mean that transpiration will increase. At low humidity, increasing wind speed increases evapotranspiration rate while at high humidity, increasing wind speed decreases the evapotranspiration rate. Lemon et al. (1973) and Monteith (1973) attributed this effect to the balance between sensible and latent heat flux; at high humidity increasing wind speed increases sensible heat loss from the leaves thereby decreasing leaf temperature and the latent heat loss (transpiration). This wind-humidity interaction becomes more pronounced at higher air temperatures. Monteith (1964, as cited by Seginer, 1971) has shown that for surfaces that are not wet, there is a critical internal resistance to diffusion above which transpiration decreases with increasing wind speed and below which it increases with increasing wind speed. For wet surfaces, the work of Penman (1948, 1956) shows that increasing wind speed increases evapotranspiration.

Generally, increasing air temperature and/or decreasing relative humidity of the air increases the evapotranspiration rate (Lemon et al., 1973). Rawson et al. (1977) observed increasing transpiration rates with decreasing relative humidity for nonstressed plants. Yang and de Jong (1972) stressed wheat plants growing in clay and loam soils to at least -15 bars and at all soil water potentials observed increasing transpiration rates with increasing temperature and decreasing relative humidity. They also observed greater changes in transpiration rates per unit change in relative humidity with higher temperatures. A unit change in relative humidity results in larger changes in vapor pressure gradients across a leaf boundary layer at higher temperatures than at lower temperatures. Movement of water vapor occurs in response to vapor pressure gradients. Therefore the change in transpiration rate with change in relative humidity will increase with increase in temperature.

2.3.2.4 Plant Factors

Fischer and Kohn (1966) found increasing evapotranspiration rates from wheat with an increase in leaf area index. One reason they gave for the increase is that greater leaf area, crop height and crop roughness reduce the proportion of intercepted net radiation lost as sensible heat and, under conditions of advection, can increase the amount of sensible heat gained from the air. Lemon et al. (1957) found that even after complete ground cover by a cotton crop, transpiration rates continued to increase with increase in LAI and plant height. They suggested that as LAI and plant height increase there is increased utilization of advected heat energy resulting in increased transpiration rates. These findings are in contrast to the definition of potential evapotranspiration which assumes that vegetation ceases to influence evapotranspiration after complete cover of the land surface occurs. Ritchie and Burnett (1971) studied evapotranspiration from cotton and grain sorghum and found that plant factors influenced evapotranspiration up to LAI values of about 2.7. Above this value plant factors had little influence on evapotranspiration, which was then controlled by meteorological and soil factors. They observed increasing transpiration rates with increasing LAI to 2.7.

Most of the water transpired by plants passes through the stomates to the atmosphere. Through control of stomatal aperature, plants can influence the amount of water that is transpired.

Intercellular CO_2 concentration, light, temperature and water stress are factors which affect stomatal aperature (Slatyer, 1967). Intercellular CO_2 concentration seems to be the primary factor controlling stomatal aperature. Depending on species and other factors such as water stress, there is a critical CO_2 concentration below which stomatal opening is initiated and above which closing movements begin. The degree of opening and closing depends on the magnitude of the CO_2 concentration change. Light has an indirect effect on stomatal opening, mainly due to photosynthetic reduction in CO_2 concentration. The main effect of temperature also appears to be associated with changing CO_2 concentrations. Increased respiration rates at high temperature may result in increased CO_2 concentrations thus causing stomatal closure. Also, temperature may have a direct effect on the rate of stomatal opening and closing. Slatyer (1967) stated that water deficits have a direct effect on stomatal closure by affecting the turgor of the guard and surrounding cells. He suggested water deficit will not cause stomatal closure until a critical leaf water potential is reached and then as water deficit increases there is a gradual decrease in stomatal aperature until almost complete closure occurs. This view was supported by Denmead and Millar (1976). The critical value varies with age and position of the leaf. As the plant matures, stomatal closure occurs at lower leaf water potentials but the recovery from water stress takes longer (Frank et al., 1973). The critical leaf water potential for stomatal closure increases from the top leaves to the lower leaves (Denmead and Millar, 1976).

2.3.2.5 Soil Factors

Soil water content, soil water potential and hydraulic conductivity are some of the soil factors affecting evapotranspiration. Soil evaporation is closely related to the water content of the 3 cm surface layer (Ritchie and Burnett, 1971). Soil evaporation decreased rapidly as the water content of this layer decreased. As stated earlier movement of water vapor occurs in response to vapor pressure gradients. As the soil dries, the evaporation zone moves farther below the soil surface. Movement of water from the evaporation zone to the soil surface then occurs in the vapor phase and the rate of movement is proportional to the vapor pressure gradient. The dry soil provides a boundary layer through which vapor movement must occur. The vapor pressure gradient decreases as the boundary layer thickness increases resulting in decreased evaporation rates.

Hillel (1971) categorized experimental investigations of transpiration rates in three ways: 1) transpiration rate is maintained at the potential rate until all available water is used; 2) transpiration begins to decline at some intermediate stage of soil water depletion, and 3) transpiration declines over the whole range of available water. Denmead and Shaw (1962) found that for lower potential transpiration rates, relative transpiration (actual/ potential transpiration) for corn was maintained over a greater range of soil water content and soil suction than for higher potential transpiration rates. However, Ritchie (1973) found that transpiration rates for corn were almost independent of available soil water content for all conditions of potential transpiration up to some critical soil water content level after which the rates started to decline. The work of Seaton et al. (1977) suggested a similar relationship for wheat as Denmead and Shaw (1962) found for maize. Yang and de Jong (1972) studied the effects of water content in a loam and a clay soil on transpiration from wheat and found that permanent wilting occurred at -20 to -25 bars for the loam and -45 to -50 bars for the clay. At these water potentials the hydraulic conductivities were about equal. This would suggest that at very low water potentials, plants growing in clay could have higher transpiration rates than those growing in sands.

At lower soil water contents heavier textured soils such as clay develop shrinkage cracks. Adams et al (1969) studied evaporation from simulated shrinkage cracks in soil. They found that cracks in the soil facilitated water loss due to evaporation from greater soil depths and that 50 to 60 percent of the total water lost in simulated cracks greater than 3 cm wide and 60 cm deep occurred from below 15 cm. Cracks of this kind are common on heavy clay soils during dry soil conditions. They also observed that if the depth of the shrinkage crack remains constant, wind speed rather than the width of the crack had the greatest effect on evaporation from the cracks.

2.3.2.6 Mathematical Description of Evapotranspiration

There have been many mathematical attempts to describe the evapotranspiration process. Two of these were developed by Penman (1948, 1956) and Monteith (1973).

Penman (1948, 1956) first developed an evaporation formula for open water and then adapted it to wet bare soil surfaces and soil completely covered with vegetation. To calculate the energy available for the evaporation process, he used the energy budget in the form

$$H = R_i (1 - r) - R_{lw}$$

where H is the energy available for evaporation; R_i is the short-wave incoming radiation; r is the reflection coefficient for water; R_{lw} is the net long-wave radiation outward. Penman did not take into account the effects of advected sensible heat on evaporation. Therefore, for conditions where advected energy contributes to evaporation, the Penman formula can be in error (Slatyer, 1967). In Penman's formula, open water evaporation is a function of the heat budget, wind speed, vapor pressure difference, and temperature. Penman (1956) calculated potential evapotranspiration using the following empirical relationship

$$E_t = fE$$

where E_t is the potential evapotranspiration; E is the open-water evaporation; f is a multiplication factor which varies with season. Potential evaporation from wet, bare soil is about 80 to 90% of that from open water when both are exposed to the same weather (Penman, 1948).

Monteith (1973) implies that Penman's formula is best suited to calculate open water evaporation for periods of a week or more but not on a daily basis. Monteith (1973) modified Penman's formula to include the canopy and aerodynamic resistances for a crop. Grant (1975) suggested that Monteith's formula can be used for any type of crop surface even if water supply is restricted. Grant developed a method to calculate the crop resistances and compared both Penman's and Monteith's formula to accumulated evapotranspiration from a barley crop for the whole growing season. Monteith's formula accurately simulated the seasonal evapotranspiration from the crop but Penman's formula overestimated the evapotranspiration throughout the whole season. This was to be expected because Penman's formula was developed to estimate transpiration from a well watered crop and not from a crop subjected to water deficits as would be the case throughout a normal growing season.

The partitioning of evapotranspiration into transpiration and soil evaporation is difficult. To separate potential evapotranspiration into potential transpiration and potential soil evaporation an estimate of the percentage net radiation intercepted by the crop canopy is needed. The intensity of radiation that reaches the soil surface can be estimated using Beer's Law

$$I = I_o \exp(-kL) \quad \text{(Monteith, 1965)}$$

where I, I_o are the light intensities at the soil and crop surfaces, respectively; L is the leaf area index; k is an extinction coefficient related to canopy structure. The amount of light intercepted by the crop canopy can therefore be given by:

$$I = I_o\ (1 - \exp(-kL)) \quad \text{(Ritchie, 1974).}$$

van Keulen (1975) has used these relationships to estimate the potential transpiration and potential soil evaporation from a wheat crop.

2.3.3 Water Uptake and Plant Roots

The water transpired by a crop is taken up through the root system. The ability of the roots to extract water from the soil is an important component in the crop's attempt to satisfy the transpirational demand placed on it by the atmosphere. Water uptake is closely related to root distribution. After a rain or from a wet soil profile, most of the water needed by a crop is taken up from the upper portion of the profile but as this portion dries and the roots are stressed, relatively more water is taken from the lower rooted portions (Hurd and Spratt, 1975). Lawlor (1973) was able to show that a decrease in water absorption by a stressed part of the wheat root system was compensated for by an increase in water absorption by the nonstressed part, although complete compensation did not occur.

Gardner (1964) studied the relation of root distribution to water uptake. He concluded that the relative distribution of roots with depth and the water retaining and transmitting properties of the soil determine the main features of the water uptake pattern. For a logarithmic root system (root density decreases logarithmically from a maximum at the soil surface), increasing root density by a factor of 100 resulted in little change in the water uptake pattern. Slightly more water would be taken up from the lower depths early in the uptake process but as time passes, root density has little effect on uptake pattern. However, the model of water uptake used by Hillel et al. (1976) predicted that root density becomes more important as the soil water content decreases. The hypothetical plant experienced stress on the 12th day with a sparse root system whereas the plant with the dense root system experienced stress on the 15th day. Both Gardner and Hillel et al. used a modeling approach to study the effect of rooting characteristics on water uptake.

2.4 OSMOTIC ADJUSTMENT

Water loss from plant tissue can result in reduced hydrostatic (turgor) pressure inside the cells. The reductions in turgor (Ψp) is thought to have direct effects on the metabolic activities of the cells. Activities such as cell growth and cell division, photosynthesis, respiration, stomatal opening, cell wall synthesis and protein synthesis are all adversely affected by the loss of water (and turgor) from the plant cells (Turner and Jones, 1980; Hsiao et al., 1976). Therefore, maintenance of turgor during periods of plant water stress would help maintain the plant metabolic processes (Turner and Jones, 1980).

Total tissue water potential, Ψ, and its components are related in the following manner:

$$\Psi = \Psi p + \Psi s + \Psi m$$

where Ψp = turgor, or pressure, potential; Ψs = solute, or osmotic, potential; Ψm = matric potential (Hsiao et al., 1976).

For mild to moderate stress the change in Ψm is very small. Therefore the more negative Ψ is, the more negative Ψs must become to maintain Ψp. Hsiao et al (1976) suggested that Ψs can be lowered by increasing the solute concentration of the cells, either by salt uptake (osmoregulation) or by internal production of osmotically active substances (osmotic adjustment). They suggested that the accumulation of solute under conditions of water stress would help maintain turgor and turgor-mediated processes.

Morgan (1977,1979; as cited by Turner and Jones, 1980) observed differences in osmotically induced turgor maintenance in wheat cultivars. One cultivar showed very little osmotic adjustment while another maintained full turgor over the plant water potential range of -1 to -15 bars.

Turner and Jones (1980) suggested several reasons why osmotic adjustment is important in drought tolerance of plants. Some of these are: 1) maintenance of cell enlargement; 2) maintenance of stomatal opening and higher stomatal conductance at lower leaf water potentials in plants that adjust osmotically than in plants that do not adjust osmotically. This would help to maintain transpiration rates over a wide range of plant water potentials. 3) maintenance of photosynthesis; Turner maintains that a decrease in stomatal conductance will cause a decrease in photosynthesis. Therefore at a given leaf water potential, maintenance of higher conductance by osmotic adjustment should maintain higher rates of photosynthesis. 4) exploration of greater soil volume for water; Roots may have a high capacity to adjust osmotically when under water stress (Hsiao et al., 1976). Therefore turgor maintenance could be a reason why the roots of some wheat cultivars can grow into drier soil than the roots of other cultivars, thus enabling the root system to explore greater volumes of soil (Turner and Jones, 1980).

2.5 GROWTH AND YIELD

2.5.1 Root Growth

Root growth is a highly complex process which, relative to shoot growth, is not well understood and is little studied. The few studies that have been done, show that wheat cultivars have widely differing root characteristics (Salim et al., 1965; Hurd, 1974) which are influenced by soil environment. Some of these factors are soil pH, nutrient supply, moisture regime, soil temperature, mechanical impedence (soil strength), soil aeration, and disease.

Hurd (1964, 1968, 1974) studied the response of a number of Canadian wheat cultivars to differing moisture conditions. He found that cultivars respond very differently to changing soil moisture status and to drought conditions. Hurd grew cultivars under two sets of moisture conditions: 1) well-watered and 2) drying conditions - wheat germinated in moist soil which received no additional water for the remainder of the growing period. Under these conditions, Thatcher wheat developed more roots by weight below 20 to 30 cm than Cypress wheat and had slightly greater root length under drying than well-watered conditions. However total root weight was greater for the well-watered treatment. The relative distribution with depth of Thatcher roots was altered by the moisture regime. Relatively more roots grew at the lower depths under dry than moist conditions. The relative distribution of Cypress wheat roots was not altered by moisture stress although the total length was much greater under moist conditions. Hurd (1964,1968) observed that Thatcher roots penetrated the soil more quickly and to greater depth than did the roots of other cultivars tested. Also, when the surface layer dried out, Thatcher grew a new network of roots in the moist layer below the dry surface layer. Hurd (1968, 1974) found that the roots of some cultivars, including Thatcher, penetrated the drying soil faster than the moist soil whereas the opposite was true for other cultivars. Many researchers agree that wheat roots do not penetrate soil drier than the permanent wilting point (Salim et al., 1965; de Jong and Rennie, 1967). Many researchers also agree that roots stop growing at about heading time (Evans and Wardlaw, 1976) but under favorable conditions, root growth has been observed to continue well into the period of grain development (Pinthus, 1969; Hurd, 1968).

Soil temperature affects both the growth and function of the roots. Top growth is usually optimum with root temperatures of about 20C (de Jong and Rennie, 1967; Nielson, 1974). Optimum soil temperature for root growth is usually lower than for shoot growth, between 12 to 16C (de Jong and Rennie, 1967; Woodbury, personal communication). Both nutrient and water uptake generally decrease as soil temperature decreases. This is due to a decrease in the ability of the roots to take up water as well as the alteration of the physical properties of soil water and change in concentration of the nutrients in the soil solution. The plant response to soil aeration is also affected by soil temperature. Lower temperature may cause a decrease in the minimum O_2 concentration required for full growth (Taylor and Ashcroft, 1972).

Root growth is very dependent upon O_2 concentration in the soil air. Lack of aeration can occur in soils that are too wet and/or too dense. Aeration problems for crop growth occur most often on heavier textured soils, such as clays, at high water contents. High tortuosity and low aeration porosity (volume of air filled pores) adversely influence O_2 movement into these soils. A lack of oxygen limits the growth of both roots and tops (Taylor and Ashcroft, 1972). The critical oxygen content for maximum growth varies with changing soil environment. The critical O_2 requirement increases with increasing soil temperature, soil water potential, and/or mechanical impedence (Taylor and Ashcroft, 1972).

Soil strength (mechanical impedence) can adversely affect root growth and penetration into the soil profile. Roots penetrate pores only if the pore diameter is larger than the root diameter or if the roots are able to enlarge the diameter of the pores (de Jong and Rennie, 1967). As soil strength increases more force is required to enlarge the pores and root elongation is considerably reduced (Taylor, 1974). The rate of extension can be greatly reduced even at low soil strength values of 0.5 bars or less (Scott Russell and Goss, 1974). The presence of hard layers (pans) within the soil profile affects the rooting pattern and root extension. When roots encounter a pan some of the roots are diverted horizontally while some grow into the pan. If the pans have high water contents, such as early in the growing season, most roots will penetrate the pan but as pans dry, the soil strength increases and fewer roots penetrate to lower soil depths (Taylor, 1974).

2.5.2 Top Growth

2.5.2.1 Dry Matter Yield

There are large variations between cultivars and, within a single cultivar, between seasons in the rates and total amounts of dry matter accumulation. Environmental conditions strongly affect the growth and dry matter accumulation of wheat cultivars. The total amount of dry matter accumulated decreases with increasing temperature (Lowe and Carter, 1972). Friend (1966) reported that the optimum temperature for the growth of Marquis wheat was 20 to 25C for both day and night temperature. Campbell and Read (1968) grew Chinook wheat under differing day-night temperatures and found that decreasing day or night temperature resulted in increased dry matter accumulation. For all growing temperatures, dry matter yields increase with increase in light intensity (Campbell and Read, 1968; Friend et al., 1962). Macdowell (1972) studied the effects of light intensity and temperature on the growth of Marquis wheat. At high light intensities the roots were a stronger sink for photosynthate than the stems but at lower intensities the stems became the stronger sink. In early stages of grain development Wardlaw (1970) found that dry matter yield of the stem was highest at lower temperatures, while the opposite was true for the ear. He also found that low light intensities reduced dry matter yield in both stem and ear. Campbell and Read (1968) observed increased dry matter yield at lower moisture stress. Conner (1975) stated that for the conditions of his experiments, moderate soil moisture stress influenced the early growth pattern of wheat and growth reserves were shifted in favor of root development. Moderate soil moisture stress early in the growing season had little effect on early root dry matter yield but greatly decreased early growth top dry matter yield. Other researchers have also found an increase in the root:shoot ratio with increase in water stress, although total plant growth is usually reduced (Begg and Turner, 1976). Increasing temperatures and/or increasing light intensity can increase the root:shoot ratio (Evans et al., 1975).

2.5.2.2 Photosynthesis and Respiration

The total dry matter production of a crop, except for the small mineral component, is equal to the net photosynthesis (Moss and Musgrave, 1972; Boyer, 1976). Gross photosynthesis can be taken to be the sum of net photosynthesis and dark respiration (Moss and Musgrave, 1971).

At low light intensities, the rate of photosynthesis increases with increase in light intensity. As light intensity increases, the carbon dioxide supply becomes more important and eventually limiting. When CO_2 supply is limiting, the rate of photosynthesis remains constant with increasing light intensity (Milthorpe and Moorby, 1974). This is referred to as light saturation of photosynthesis. There can be large fluctuations in daily atmospheric CO_2 levels (Denmead, 1970). The average daytime CO_2 concentration varied from 250 to 325 ppm. The extent of light saturation at high light intensities would therefore vary from day to day in the field (Evans et al., 1975). On days of high atmospheric CO_2 levels light saturation of crop photosynthesis may not occur, whereas on days of low atmospheric CO_2 levels light saturation can occur at relatively low light intensities (Evans et al., 1975; Denmead, 1970). At normal atmospheric CO_2 concentrations, many researchers agree that temperature has little effect on the rate of photosynthesis (Milthorpe and Moorby, 1974; Dowes, 1970) but the data of de Vos (1977) show that at temperatures above 20C the rate of photosynthesis decreases with increase in temperature. This decrease becomes more pronounced with increasing light intensity. Humidity has an affect on photosynthesis (Rawson et al., 1977). Increases in humidity can result in increased rates of photosynthesis for a cultivar of plant species.

Water stress can have direct and indirect effects on crop photosynthesis. Water stress can reduce crop photosynthesis through decreased production of new leaf area, stomatal closure and/or decreasing the activity of the photosynthetic system (Boyer, 1976; Slatyer, 1969). Boyer (1976) suggested that for plants under water stress, stomatal effects are more limiting to photosynthesis at high light intensities but as light intensity decreases, chloroplast effects become important. In general, net photosynthesis decreases with decrease in leaf water potential, with negative values of net photosynthesis occurring at severe plant water stress (Lawlor, 1976; Slatyer, 1969).

Dark respiration is very dependent upon temperature. Most researchers have found that dark respiration has a Q_{10} value of about 2 (Spierty, 1974; Milthorpe and Moorby, 1974). However, de Vos (1977) found dark respiration increased linearly with increase in temperature from 10 to 30C.

Todd et al. (1972) studied the effects of wind on plant respiration. They observed increases in plant respiration at windspeed of 3.6 m/s (13 km/hr) and higher. At a windspeed of 7.2 m/s (26 km/hr) increases in respiration of up to 40% were observed. The respiration rate returned to the initial rate a short period of time after the wind was stopped.

Recent studies suggested that dark respiration is relatively unaffected by plant water stress (Slatyer, 1969; Boyer, 1976). Hsiao (1973) stated that dark respiration is only slightly suppressed by moderate to severe water stress. Lawlor (1976) found that dark respiration was constant at all leaf water potentials.

Crop photosynthesis and crop respiration have similar relationships with LAI. Both increase with increase in LAI to values of between 4 and 6. Further increases in LAI have little effect on crop photosynthesis and respiration (Evans et al., 1975; de Wit et al., 1970). Stems and inflorescences can also contribute substantially to net crop photosynthesis. Rawson and Evans (1971) found net photosynthesis of the stems plus leaf sheaths of wheat to be one quarter to one third that of the flag leaf blade. Net photosynthesis of the ear can be greater than that of the supporting stem and leaf sheaths (Evans and Rawson, 1970). The contribution of ear photosynthesis to dry matter and grain yields varies greatly between cultivars. Evans and Rawson (1970) found the contribution of ear photosynthesis to grain requirements to be as high as 33 percent for one of the wheat cultivars tested. One of the factors which contributes to the varietal differences in ear photosynthetic rates is the presence of awns (Teare and Peteerson, 1971). Teare et al. (1972) found net photosynthesis per head for awned wheat ears to be 40 percent greater than that for awnless wheat. Awned cultivars usually outyield awnless cultivars under dry conditions but under wet conditions the yield differences are slight (Evans et al., 1975). The contribution of stems, leaf sheaths and ears to crop photosynthesis can be particularly important in the later stages of grain growth (Evans and Wardlaw, 1976). Toward the end of grain growth, and under water stress conditions, stems and ears remain green after the leaves have dried and they then become the major source of current photosynthate for further increase in yields (Evans and Wardlaw, 1970). McNeal and Berg (1977) concluded that the head, leaf sheaths and other leaf areas as well as the flag leaf have to be considered as contributors to grain yield.

Respiratory losses of CO_2 fixed by crop photosynthesis can be substantial. For wheat losses as high as 25 percent can occur (Evans and Wardlaw, 1976). McCree (1970) studied respiration of clover and concluded that there are two components to respiration. One is proportional to the rate of photosynthesis, called growth respiration; and the other, called maintenance respiration, is proportional to the total dry weight of the living plant material. Growth respiration represents the cost of producing new material. Maintenance respiration refers to the replacement and renewal of older tissue (Evans and Wardlaw, 1976). Growth respiration has been found to be unaffected by temperature whereas maintenance respiration is dependent on temperature (Evans and Wardlaw, 1976).

Studies have been done to evaluate the variation in photosynthetic rates between cultivars. However, conditions prior to measurement, for example the light environment, plant age and the internal demand for assimilates may have a large affect on the measured light-saturated photosynthetic rate (Evans, 1975). Evans (1975) concluded that because of these sources of variations, comparisons of photosynthetic rates of wheat cultivars can be difficult. However, of the studies that have been done, many suggested that there is little difference in photosynthetic rates per unit plant material between wheat cultivars. de Vos (1977) found little difference in net photosynthetic rates between two spring wheat cultivars. Puckridge (1970) concluded that variations in photosynthesis of two wheat cultivars grown in the field were mainly due to changes in LAI. A similar conclusion was reached by Rawson and Evans (1971). They found that photosynthetic rates per unit flag leaf area were similar in all cultivars studied. They also found large variations in rates of stem respiration between wheat cultivars. de Vos (1977) found little difference in dark respiration between the two spring wheat cultivars of his study.

2.5.2.3 Transpiration and Crop Growth

de Wit (1958) studied the relationship between transpiration and crop growth and found that for climates similar to that of the Great Plains of the U.S.A., dry matter production is proportional to transpiration. For climates with a large percentage of sunshine, de Wit (1958) developed the relationship

$$P = mW/E$$

where P is the total dry matter yield, W is the total transpiration during growth, E is the free water evaporation and m is a proportionality constant. For a given set of conditions, the value of m varies with crop species and possibly with cultivars within a species. de Wit suggested that the constant m is relatively independent of weather, nutrient level of the soil and availability of water, provided the nutrient level is not "too low" and availability of water not "too high". de Wit concludes these conditions are met if growth in the field is limited by the supply of water.

Arkley (1963) studied the same data as did de Wit (1958). Arkley developed a similar relationship but substituted a relative humidity term in place of free water evaporation. Arkley's relationship is of the form

$$P = kW/(100 - H) \quad \text{(fertility constant)}$$

where P is the amount of dry matter produced, W is the amount of water transpired, H is the mean daily relative humidity in percent , and k is a proportionality constant for a given plant type. Arkley (1963) showed that the use of relative humidity gives results as good as those obtained using free water evaporation. The data of Hanks et al. (1969) indicated that production and transpiration are directly related in the Great Plains region as de Wit (1958) suggested.

The proportional relationship between transpiration and dry matter production as proposed by de Wit (1958) implies that plants maintain a constant water use efficiency, or constant photosynthesis:transpiration ratio, over a range of environmental conditions (Hagen and Skidmore, 1974). However, Hagen and Skidmore found that both theory and experiments show that decreasing windspeed can increase water use efficiency. Dowes (1970) found that the net photosynthesis:transpiration ratio decreased with increased temperature. There are also cultivar differences in water use efficiency. Passioura (1977) found a large range in water use efficiency among wheat cultivars.

2.5.2.4 Grain Growth and Yield

Thorne (1966) suggested that approximately 80 percent of the carbon assimilated after flowering and remaining in the plant eventually reaches the grain. This is a rather simplified explanation of the complicated process of grain growth. Grain growth and yield depend to a large degree on the supply and demand, source and sink strengths, for photosynthate. The source strength depends on the photosynthetic area available to supply assimilate for the growing grains and on the duration or length of the grain growth period. The sink strength depends on the ear number per plant or per unit ground area, spikelet number per ear and grains per spikelet; or more simply, the grain number per unit ground area. Both the source and sink strengths are strongly influenced by the environment.

Ear number is a major component of crop yield (Campbell, 1968; Hsu and Walton, 1971). Ear number per plant or per unit ground area is dependent upon tiller production and the number of tillers which reach maturity; both of which are influenced by environmental factors including crop density and nutrient supply. Dubetz and Bole (1973) found that increasing nitrogen supply to 112 kg/ha increased the number of ears per plant reaching maturity. Further increases in N did not influence ear number per plant at maturity.

Temperature is an important factor affecting grain yield. Bagga and Rawson (1977) observed a decrease in floret numbers with increasing temperatures during floret formation. They also noticed that temperature effects differ between cultivars, some cultivars being more sensitive to temperature change than others. Grain size and weight decreased with increasing temperatures during grain growth. Temperature also affects the rate and duration of grain growth. The growth rate of the grains generally increases with increases in temperature but the duration is decreased with the net result that grain yields decrease with increasing temperature (Spierty, 1974; Sofield et al., 1977).

Growth rate per grain varies between cultivars (Sofield et al., 1977). At low light intensities, Sofield et al. (1977) found that growth rate per grain was greatly influenced by illuminance. For cultivars in which grain numbers per ear were strongly affected by illuminance, growth rates per grain were little influenced by light conditions. They also noticed that light had little effect on the duration of grain growth. Evans and Wardlaw (1970) stated that only at very low light intensities, combined with high temperature, does increasing light intensity increase rates of grain growth.

The setting of grains following anthesis is sensitive to high temperatures and low light intensity (Wardlaw, 1970). Increasing light intensity during the grain growth and development period usually results in increased yield, especially at low light intensities (Wardlaw, 1970; Partridge and Shaykewich, 1972; Campbell and Read, 1968; Spierty, 1974). Wardlaw (1970) studied light-temperature interaction for a single wheat cultivar (cv. Gavo). Reduction in light intensity from full sunlight to 17.5% of full sunlight resulted in reduced yields. The magnitude of the reduction varied with temperature, i.e., larger reductions occurred at higher temperatures.

Moisture stress is another environmental factor affecting grain yield. Moisture stress can decrease the number of ears reaching maturity. Day and Intalop (1970) concluded that moisture stress at any stage of growth decreased grain yield. Wheat stressed at jointing had fewer heads per unit ground area. El Nadi (1969) concluded that moisture stress before ear emergence does not affect yields while stress during and after ear emergence results in decreased yields. Stress during ear emergence and early grain growth reduced yields by decreasing the number of ears per plant. During late grain growth, reduction in yield due to water stress was mainly due to decreased grain weight. Campbell (1968) reported similar observations as El Nadi (1969). However, in a later publication, Campbell et al. (1969) concluded that for their previous experiments the major cause of poor seed set and reduced yields was not high moisture stress but poor aeration conditions associated with low moisture stress (excess water). Wardlaw (1971) and Fischer (1973) found that moisture stress at anthesis reduced seed set and ultimately resulted in reduced yield.

Stem reserves, i.e., photosynthate fixed prior to anthesis, can contribute substantially to grain yield in water stressed wheat. The contribution of stem reserves to grain yield for nonstressed wheat has been estimated to be 5 to 15 percent (Stoy, 1963; Rawson and Evans, 1971). However, with increased moisture stress Wardlaw (1967) observed increased movement of stem reserves to the growing grains. Rawson and Evans (1971) also observed increased movement of reserves from stem to ear as photosynthesis was reduced due to stress. In severely water stressed wheat, Passioura (1976) found that grain filled largely (up to two-thirds) from reserves, rather than from current photosynthate.

2.6 SUMMARY

A review of the literature reveals the complexities of the soil-crop-atmosphere continuum. The response of wheat cultivars to the changing atmospheric conditions and soil environment can be very complex and the numerous interactions that occur are very difficult to study and interpret. For example, wheat cultivars respond differently to moisture stress. Some have a greater capacity for osmotic adjustment and therefore may be able to withstand greater degrees of stress. The response of root growth to moisture stress also varies with cultivar. Also, some cultivars are more sensitive to temperature changes than others (Bagga and Rawson, 1977).

A further complexity may be encountered when relating events occurring under controlled versus field environments. Many crops have been shown to respond differently under controlled than under field conditions, particularly in response to water stress (Begg and Turner, 1976). Restricted root volume often associated with controlled environment studies may be the major cause of the differences in crop response between controlled and field environments.

From a review of the literature, some factors which may be important to crop growth (and if not included in a simulation model may result in error) are summarized and listed below.

1) Depending on its severity and the development stage at which it occurs, moisture stress can increase or decrease the development rate of wheat.

2) Moisture stress influences leaf area growth. Increasing moisture stress can result in reduced LAI and earlier and faster decline in LAI. However, plants may recover from mild and short water stress periods so that leaf growth is relatively unimpaired.

3) Evapotranspiration is one of the complex processes involved in changing the soil moisture regime. Evapotranspiration is an energy requiring process to which advected energy may make a substantial contribution. Also, the interaction of wind and humidity may influence the evapotranspiration process. At low humidities, increasing windspeed may increase or decrease evapotranspiration. Finer textured soils have higher water holding capacity and higher hydraulic conductivity at low soil water potentials than do coarse textured soils. Therefore, fine textured soils might support crops for longer periods of time under drought conditions than would coarser soils.

4) Nutrients and water are taken up by the root system. Wheat cultivars have widely differing root characteristics. Wheat roots usually stop growing at about heading time but under favorable conditions can grow well into the grain growth period. An important component of root growth and function is the ability of non-moisture stressed portions of a root system to compensate for lack of water uptake by the stressed portion. The non-stressed portion may take up more water than it would under optimum conditions.

5) Osmotic adjustment may be of importance in the ability of a crop to tolerate water stress (drought).

6) CO_2 levels of the atmosphere fluctuate daily. The change in CO_2 levels causes a change in the light saturated photosynthetic rate. This would result in changes in daily photosynthesis of a growing crop. Plant respiration can also be affected by changes in the environment. Increasing windspeed above 13 km/hr may result in substantial increases in plant respiration.

7) de Wit (1958) found a relationship between dry matter yield and transpiration that suggests a constant water use efficiency over a range of environmental conditions. However, changing windspeed, temperature and/or water stress may cause changes in water use efficiency.

8) Temperature and moisture are two of the many factors that affect grain yield. The duration of grain growth increases with decreasing temperature resulting in increased yield. Moisture stress can result in reduced tiller numbers reaching maturity and/or reduced grain weight.

9) Water stress can result in increased movement of stem reserves to developing ears. For severely stressed wheat, stem reserves can contribute up to two-thirds of the grain weight (Passioura, 1976).

Chapter III

DESCRIPTION OF THE CROP GROWTH MODEL

3.1 BRIEF OUTLINE OF THE MODEL

The simulation model (Appendix C) tested assumes that wheat growth is limited by soil moisture and calculates dry matter production and soil moisture regime below the crop from plant and soil properties and from daily meteorological observations. Plant properties such as the affect of air temperature on the leaf area per unit dry matter increase, the relationship between soil temperature and root function, and maintenance respiration per unit dry weight are incorporated into the model. The soil properties, field capacity and wilting point, are used to determine the available water for plant growth. The daily weather inputs of the model include solar radiation, maximum-minimum air temperature, average humidity or dew point temperature, rainfall and windspeed. Many processes related to the soil moisture regime and crop growth are simulated on a daily basis. These simulated processes include average soil temperature, infiltration, evaporation, transpiration, germination, development rate, leaf area growth, root growth, dry matter production and seed growth.

Germination and development stage of the crop are calculated as functions of accumulated heat units. Germination occurs when the sum of the daily soil temperature equals the soil heat units required for germination. When germination is completed, crop growth begins and growth processes such as development, transpiration and dry matter production are initiated. The daily development rate is estimated as a function of the average air temperature. The sum of the daily development rates, i.e., accumulated heat units, equals the development stage of the crop.

Leaf area growth is also a function of the daily average air temperature or heat units. It is assumed that the leaf area per unit daily dry matter increase is a function of the air temperature. The leaf area of the crop is needed to calculate daily values of soil evaporation, transpiration and photosynthesis.

Both soil evaporation and transpiration are energy requiring processes. The solar radiation or energy intercepted by the vegetation increases with increasing leaf area. Therefore as the crop grows and leaf area increases, transpiration increases and evaporation from the soil surface decreases. Transpiration also depends on the evaporative demand of the atmosphere (calculated as a function of solar radiation, windspeed, air temperature and humidity) and the availability of soil water to the roots. The availability of soil water to the roots depends on the soil water status, or the amount of soil water available for crop growth, and rooting depth. Daily increases in root length are assumed to be a function of the water content of the soil. The roots continue to grow deeper as long as the rooting front is in soil which has a water content above the wilting point.

Dry matter production is calculated as a function of transpiration and the potential growth rate. The potential daily growth rate depends on the potential gross photosynthetic rate and maintenance respiration. The potential gross photosynthetic rate is the photosynthetic rate for a well watered crop and depends upon the solar radiation, leaf area index, air temperature and daylength. The photosynthate available for overall plant growth is then partitioned to the root and shoot. The portion going to the shoot contributes to the dry matter increase of the aerial portion of the crop.

Outputs from the model include cumulative values for evaporation, transpiration, dry matter production of the aerial portion of the crop and the change in water content of the soil profile as the crop grows.

3.2 DETAILED DESCRIPTION OF THE MODEL

The model is partitioned into various sections. The sections deal with processes involved in the growth of the wheat crop and running of the model.

3.2.1 Initial Conditions

In the initial section, initial conditions are defined and variables that remain constant throughout the running of the program are calculated. Daily contributions to variables such as total water transpired or total dry matter produced are summed and stored in integrals. The initial root weight and initial leaf area are calculated as fractions of the initial living biomass. The initial living biomass (initial above ground portion) is the fraction of the seeding rate which is thought to be the portion of the seed that develops into the aerial portion of the crop. The initial root weight and the initial living biomass are each assumed to be equal to 40 percent of the seeding rate, i.e., 40 percent of the seed gives rise to the aerial portion of the crop while another 40 percent gives rise to the root system. The initial soil temperature is calculated as a fraction of the average air temperature of the first day that the program is run. The soil profile has been divided into 8 successive layers. Begining with the surface layer, the layer thicknesses are 2, 3, 5, 20, 30, 30, 30 and 60 cm respectively. The initial water content and the maximum amount of water each layer can hold is calculated from the thickness and average field capacity of each compartment or layer. The air dry water content is defined to be 1/3 of the wilting point.

3.2.2 Weather

In the weather section, the daily values for rainfall, solar radiation, windspeed, maximum-minimum temperatures and dew point temperature or humidity are read from tabulated functions. Also, average daily vapor pressure is obtained from the daily dew point temperature or humidity reading; daylength is calculated; and the average air temperature is used to calculate the saturated vapor pressure. The potential soil evaporation is calculated following the procedure described by Penman (1956). The average daily weather data are used to calculate the solar energy available for evaporation and the evaporative power of the atmosphere. These values are then used to calculate the potential soil evaporation.

3.2.3 Soil Temperature and Soil Moisture

The temperature of the soil profile is assumed uniform throughout and proportional to a 10-day running average of the air temperatures. This is achieved by changing the value each day by the temperature difference between that day and 10 days previous.

The soil moisture regime is determined by the processes of infiltration, evaporation and transpiration. The infiltration and redistribution of rainwater to the 8 soil compartments is assumed to be instantaneous. It is also assumed that each compartment must fill to field capacity before water will drain to the next lower compartment. When all 8 compartments are at field capacity, the excess rain water is assumed to be lost as deep drainage. The bottom of the 8th compartment is at a depth of 1.8 m.

3.2.4 Evaporation

The potential evaporation rate from the soil is calculated from the potential soil evaporation and the fraction of light transmitted through the canopy. The fraction of light transmitted through the canopy is a function of the leaf area index. The actual evaporation rate is obtained by multiplying the potential rate by a reduction factor due to the dryness of the upper soil compartment. The water evaporated from the soil is partitioned over the 8 compartments by the use of an exponential function. The ease of water withdrawal from each compartment is assumed to be inversely proportional to the exponential function of the depth to the center of a compartment and an extinction coefficient. Decreasing the extinction coefficient increases the proportion of water extracted from the lower compartments.

3.2.5 Growth of the Crop

3.2.5.1 Emergence

The soil temperatures for the days when one or more of the 3 upper compartments is above the wilting point are summed. When this sum equals the temperature sum needed for emergence (120 degree days above 0.0C), emergence will occur.

3.2.5.2 Development Stage

The development rate of the wheat crop is a function of the average air temperature. The development stage is the sum of the daily development rate. A development stage of 0.0 corresponds to germination while a development stage equal to 1.0 signifies maturity.

3.2.5.3 Root Growth

The vertical extension of the root system is obtained from the daily growth rate of the roots adjusted to account for the affects of temperature and moisture stress. If the rooting front is in a compartment which has a water content equal to or below the wilting point, root growth ceases.

3.2.5.4 Leaf Area Index

Leaf area index is calculated as the sum of the daily leaf area growth rate minus the rate of leaf senescence. The leaf area growth rate is calculated by multiplying the growth rate of the shoot by the leaf area ratio. The leaf area ratio, leaf area per unit crop mass, is entered into the model as a function of the average air temperature.

3.2.5.5 Transpiration

The actual amount of water transpired is calculated as a fraction of the potential transpiration that could occur from a crop well supplied with water. Transpiration is assumed to occur only during the daytime. Therefore daytime values for average temperature and windspeed, saturated vapor pressure and net radiation (daytime radiant energy available for transpiration) are calculated. The resistance to water vapor diffusion from the canopy to the atmosphere is calculated from the wind speed data. When calculating potential transpiration, stomatal resistance is assumed to be at a minimum. However depending on the leaf area index and the radiation intensity, light may not penetrate the canopy to the lower leaves. The stomates of the lower leaves may therefore be closed or partially closed, i.e., stomatal resistance will not be at a minimum value. A reduction factor has been incorporated into the model to account for this occurrence. The potential transpiration is calculated as the sum of two terms; one term represents the contribution of absorbed solar radiation and the other, the contribution of the drying power of the atmosphere. The absorbed radiation is a function of the leaf area index. The actual transpiration rate is calculated as a fraction of the potential transpiration depending on the ability of the plant roots to take up water. In the model, actual transpiration does not become less than the potential transpiration until 50 percent of the available water has been used. However, Meyer and Green (1980) found that for the wheat cultivar used in their study actual evapotranspiration did not become much less than potential evapotranspiration until 70 to 80 percent of the available soil water has been extracted. The water available for crop growth is the amount of water present above the wilting point within the rooting zone. An attempt has been made to model the ability of the roots to compensate for moisture stress. As the soil dries the roots attempt to compensate by taking up more water from the wet soil zone than they would from the same soil zone if the whole rooting zone was at field capacity. Water uptake by the roots is also affected by the temperature of the rooting zone. Water uptake is assumed to be optimal at an average soil temperature of 20C. These factors are accounted for when calculating actual transpiration from potential transpiration.

3.2.5.6 Growth Rate and Dry Matter Production

The growth rate is calculated by multiplying the actual transpiration rate by the water use efficiency (WUE). van Keulen (1975) defines WUE as the ratio of potential growth to potential transpiration. The growth rate is therefore equal to the potential growth rate multiplied by the ratio actual transpiration: potential transpiration. To estimate the potential growth rate, the potential daily gross assimilation is determined as a function of leaf area index, radiation intensity, and air temperature. A portion of the gross assimilation is used for maintenance respiration. Maintenance respiration is calculated from the total dry weight, assuming a constant maintenance respiration per unit dry weight. The temperature effect on respiration is assumed to have a Q_{10} value of 2. The potential growth rate is found by multiplying the difference of gross assimilation minus maintenance respiration by a conversion efficiency factor of 0.75. The total dry matter is then partitioned to aerial and root portions of the crop. As the crop develops, relatively more assimilate contributes to aerial crop growth than to root growth. After the model predicts the crop has completed one-half its development, 80% of the dry matter increase in the aerial portion of the crop is assumed to be used for seed growth. The growth rate of the shoot equals the actual growth rate of the whole crop multiplied by the fraction of assimilate which contributes to aerial growth. From this term the seed growth rate is then subtracted. The weight of seed produced is the sum of the daily growth rate of the seeds.

3.2.5.7 Senescence

The crop can die as a result of water shortage or completion of development. The rate of dying depends on the relative death rate and the amount of biomass (living plant material) present. The amount of available water in the rooting zone determines the death rate due to moisture stress (drought). The crop is assumed to die at a fast rate only when the soil is practically at the wilting point. When moisture conditions are optimum, a portion of the crop dies in the process of normal development. After the crop has completed approximately one-half its development, relatively more of the crop senesces as it approaches maturity. Complete senescence occurs at maturity. The relative death rate assumes a value corresponding to the death rate due to moisture stress or due to normal development. When the living biomass falls below a calculated limiting biomass, the crop is assumed to be completely dead.

Chapter IV

METHODS AND MATERIALS

To evaluate the crop simulation model field experiments were conducted in the spring and summer of 1978 and 1979. Site description, soil test data and seeding dates are given in Table 1. The plots were sown with spring wheat (*Triticum aestivum* cv. Sinton) at seeding rates of 120 kg/ha. The Brandon plots were situated on stubble land while the Glenlea plots were on fallow land. Type, rate and method of fertilizer application are given in Table 2.

4.1 MEASUREMENTS

4.1.1 Soil Characteristics and Soil Moisture

All soil measurements were determined for successive 15 cm thick layers from the soil surface to a depth of 135 cm. Bulk densities were determined using the auger method described by Zwarich and Shaykewich (1969). Field capacities were determined using the method described by Peters (1965). Permanent wilting points (PWP) were calculated using the formula

$$PWP = 0.02 + 0.8FAP$$

derived by Shaykewich (1965). The 15-atmosphere percentages (FAP) were determined using the standard pressure membrane technique. Field capacities, wilting points and bulk densities are given in Appendix A.

In 1978, weekly soil moisture contents were determined using the neutron scattering method. There were two neutron moisture meter(1) tubes per plot. A separate calibration curve was used to determine the moisture content of the surface layer (0 - 15 cm). In 1979, soil moisture contents were measured using the standard gravimetric oven drying method. Four random samples of each layer were taken per plot every 2 weeks. Soil moisture contents were determined for the period of plant-

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(1)Nuclear-Chicago model 5920 d/M-Guage Scaler
Nuclear-Chicago model 5810 Subsurface Moisture Probe
Texas Nuclear Box 9267 Austin, Texas 78766

Table 1. Description of plots, seeding dates, and soil test results.

Location	Soil Type	Texture % sand	Texture % silt	Texture % clay	Seeding Date 1978	Seeding Date 1979	Soil Test (Kg/Ha)* Nitrate-N 1978	Nitrate-N 1979	Available P 1978	Available P 1979
Brandon S 1/2 32-9-19W	Carroll	20.1	56.5	23.4	May 6	May 26 June 2	37	70	10	17
Glenlea Lot 6-8-3E	Red River	8.6	22.7	68.7	May 23	June 9	50	200	45	50

*Analyses performed by Provincial Soil Testing Laboratory, University of Manitoba.

Table 2: Rates, method and time of fertilizer applications.

Location	Year	Fertilizer Regime
Brandon	1978	85 kg N/ha banded before seeding as anhydrous ammonia 12 kg N/ha + 50 kg P_2O_5/ha with the seed as monoammonium phosphate
	1979	200 kg N/ha broadcast before seeding as ammonium nitrate 12 kg N/ha + 50 kg P_2O_5/ha with seed as monoammonium phosphate
Glenlea	1978	70 kg N/ha broadcast before seeding as ammonium nitrate
	1979	60 kg N/ha broadcast before seeding as ammonium nitrate 10 kg P_2O_5/ha with seed as monoammonium phosphate

ing to final harvest.

4.1.2 Crop Measurements

Starting two to three weeks after emergence, 4 random 1 m^2 samples were harvested each week from each plot to determine the above ground dry matter production of the crop. The fresh weight of the samples was taken before being oven dried. At maturity 10 random 1 m^2 samples per plot were used to determine final harvest dry matter yield and grain yield. The wheat plants were all harvested at ground level.

In 1979, a leaf area meter(2) was used to determine the leaf area of 20 plants collected weekly from each plot. Five plants were randomly selected from each of the 4 replicates used to determine dry matter yield. The leaf area per unit mass, leaf area ratio (LAR), of the 20 plants was determined on a fresh weight basis. For each weekly harvest for each plot, the leaf area index was calculated by multiplying the leaf area ratio by the fresh weight harvested.

4.1.3 Weather Data

Daily measurements of rainfall, windrun, maximum-minimum temperature, and solar radiation were taken from May 1 to September 30, 1978 and 1979. At Brandon, daily vapor pressure during 1978 and daily humidity during 1979 were recorded. At Glenlea Research Station, early morning dew point temperatures were recorded daily. All weather data were collected at the experimental sites except at Brandon where daily windrun and vapor pressure readings were obtained from Environment Canada, Brandon Airport, approximately 10 km North-East of the plots. A standard climatological station is located at the Glenlea Research Station. Rainfall and solar radiation at both sites were measured using recording rain gauges(3) and pyrheliographs,(4) respectively. At Brandon, temperature and humidity were measured with a hygrothermograph.(5)

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(2)Portable Area Meter model Ll-3000 Lambda Instruments Corporation
Lambda Instruments Corp. Lincoln, Nebraska 68504

(3)Belfort Instruments Weighing Rain Gauge Cat. # 5-780
Belfort Instruments 1600 S. Clinton St. Baltimore, Md. 21224

(4)Belfort Instruments Pyrheliograph Cat. # 5-3850
Weather Measure Mechanical Pyranograph model R401

4.1.4 Computer Models

A computer model (Appendix B) was written using the biometeorological time scale concept of Robertson (1968). The model uses daily maximum-minimum temperatures and photoperiod to predict the times for planting to emergence and emergence to maturity. The predicted times were compared to those obtained in the field experiments.

Crop growth processes were simulated using the simulation model (Appendix C) developed by van Keulen (1975). The output from the model- dry matter production, soil moisture regime, grain yield, development rate, leaf area index- was compared to field data collected in 1978 and 1979.

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(5)Weather Measure Hygrothermograph model H311
Weather Measure PO Box 41257 Sacramento, Calif. 95841

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Chapter V

RESULTS AND DISCUSSION

5.1 MODIFICATIONS TO THE MODEL

A number of alterations were made to the original model. The final modified model was then evaluated. The original model contained a soil nitrogen section which included processes such as mineralization, uptake of soil and fertilizer N and distribution of N within the plant. Fertilizer N was applied at the start of the growing season and the assumption was made that nitrogen was not limiting crop growth. This assumption was based on the study by Alkier et al. (1972). They found that wheat yields on nonfallow land increased with increase in N to 67 kg N/ha. Further increases in N did not increase yields but did increase protein content of the grain. Therefore the soil N section was excluded from the modified model. Another assumption made was that at the beginning of each growing season, the soil profile was at field capacity. The starting days for the model were chosen to correspond with days of heavy rainfall to ensure the soil profile was near field capacity.

5.1.1 Germination

A major problem of the original model was the effect of moisture deficit on the process of germination and growth of the crop for the first 1 or 2 weeks. In the model, the rate of germination is a function of soil heat units. After planting, daily soil heat units are summed and when this sum equals a predetermined value, germination occurs. Germination is also dependent upon soil moisture (Pawloski and Shaykewich, 1972). The simulated germination process continues when the surface 8 cm of soil is above the wilting point. The process ceases when the soil surface dries below the wilting point. However, in the original model when germination stopped because of moisture deficit, the sum of heat units was emptied and set equal to 0. The germination process started again when rains increased the moisture content of the soil surface above the wilting point. Therefore the contribution to germination by the soil heat units accumulated before the moisture deficit was lost.

Calculating soil heat units needed for germination in this way resulted in predicted times of 20 to 40 days between planting and germination. In the modified model, the sum of the heat units for germination was not set equal to 0 because of a moisture deficit. For those days when germination ceased because of lack of moisture, the soil heat units did not contribute to the accumulating heat units needed for germination, i.e., the seed was assumed to be dormant. The germination process was only interrupted by those days when moisture was limiting. The number of days from planting to emergence calculated by the modified model were similar to field observations (Tables 6 and 7).

The soil heat units needed for germination was set equal to 120 degree-days. However, the actual soil heat units needed for germination are probably much higher than 120. The model calculates the average daily soil temperature of the profile. This average value was approximately equal to the soil temperature of the 60 cm depth. The average daily temperature of the soil surface where the seed was placed would be greater than the temperature at 60 cm. Therefore, to state that 120 degree-days are needed for the germination of wheat, as the model suggests, is misleading. To make the model more physiologically correct, studies are needed to improve the simulation of both the soil temperature profile and the effect of soil temperature on plant growth and function. For example, Tew et al. (1963) found that low soil temperature could be a major factor in controlling transpiration rates.

5.1.2 Root Growth

In the original model, after the crop germinated the initial rooting depth was set equal to 10 cm. In the modified model, the initial rooting depth was changed to 5 cm, approximately equal to the seeding depth. However, with the 5 cm initial rooting depth the model predicted the crop would die within the first 2 weeks of growth because of a water deficit. This early death did not occur in the field. The model may have predicted this early death because the simulated root growth was not fast enough to grow through the surface layer of soil before it dried below the wilting point. Also the simulated soil evaporation may have proceeded at a faster rate than what actually occurred in the field. The model was refined in a number of ways to try to prevent the predicted early death of the crop. Changes were made to increase the growth rate of the roots and to decrease the soil evaporation rate. In the original model, the growth rate of the roots (increase in depth) under optimal conditions was considered to be constant and continuous throughout the period of crop development (Figure 1, Curve 1). In the modified model, the growth rate of the roots in the early stages of crop growth was assumed to be twice that of the original model with the growth rate decreasing linearly to 0 at maturity (Figure 1, Curve 2). Based on the review of literature by van Keulen (1975) and the agreement of many researchers that root growth ceases at about heading time (Evans and Wardlaw, 1976), Curve 3 (Figure 1) would probably be a better representation of optimal root growth than Curve 2. The areas under the 3 curves are equal indicating that under optimal conditions the final root depths would be similar. The increased early root growth resulting from the use of the growth function represented by Curve 2 (Figure 1) should help to overcome the incorrectly predicted early death of the crop because of water deficit.

5.1.3 Evaporation

Changes were made to the original model to decrease the rate of soil evaporation. In the original model, van Keulen calculated open water surface evaporation using the procedure of Penman (1948) and defined this to be equal to the potential evapotranspiration. However, Penman (1948) stated the potential evaporation from a wet bare soil was 0.9 times that from an open water surface. Penman (1948) also stated that evapotranspiration during the summer from turf with plentiful water supply was 0.7 to 0.8 times that from an open water surface. Therefore in the modified model, potential evapotranspiration was multiplied by a factor of 0.8. The model calculates potential soil evaporation from a wet soil surface as a function of the calculated potential evapotranspiration and the amount of solar radiation passing through the canopy to provide the energy needed for evaporation. Actual evaporation is then calculated from the potential soil evaporation. Because the calculated potential evapotranspiration has been reduced through the use of the

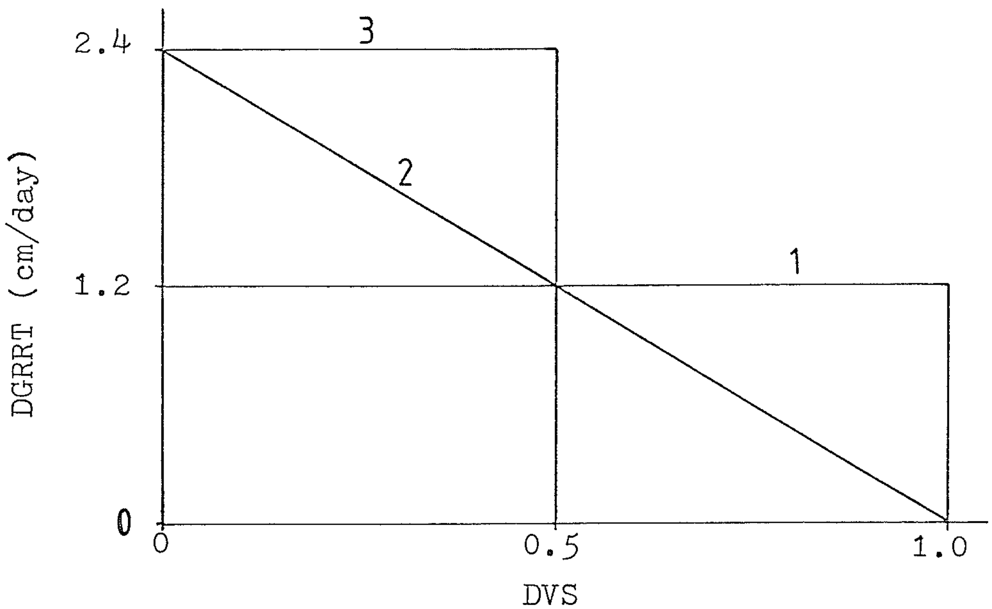

Figure 1: Growth rate of the roots under optimal conditions (DGRRT) in relation to the development stage (DVS) of the crop.

multiplication factor, the potential and actual evaporation from the soil will also be reduced. However, the work of Penman (1948) suggests this method of estimating potential soil evaporation from potential evapotranspiration may not be entirely correct. Potential soil evaporation should probably be estimated by multiplying open water evaporation by the factor 0.9. In the model potential transpiration is not calculated as a fraction of the Penman open water evaporation. Therefore, it may be better to estimate potential evapotranspiration by summing the calculated potential evaporation and potential transpiration terms instead of using the Penman (1948) method.

The amount of water evaporated from the soil is very dependent upon the water content of the soil surface. Ritchie and Burnett (1971) found evaporation decreased rapidly as the surface 3 cm dried. The model is programmed so that evaporation from the soil surface was limited by the water content of the surface layer. The lower the water content of the surface layer, the greater the resistance to evaporation. The thicker the surface layer the more water the layer holds. Therefore the longer is the time required to dry the surface layer to provide a given resistance to evaporation. The shallower the surface layer the lower is the evaporative loss. The thickness of the first and second layers were changed from 2 and 3 cm in the original model to 1 and 2 cm respectively in the modified model.

Much of the evaporative water loss occurs from the first 3 layers with a smaller portion obtained from the fourth layer. The depth to the bottom of the third layer was 9 cm and to the bottom of the fourth layer was 30 cm. The total amount of water evaporated can be partitioned between the soil layers or compartments by the partitioning factor called PROP. An exponential function, of which PROP is a component, is used to estimate the portion of the total evaporation that comes from each compartment. Decreasing PROP increases the amount of water lost from the lower depths through evaporation. The PROP factor is affected by soil texture (Shaykewich, unpublished data). Finer textured soils usually have a lower PROP value than coarser soils, i.e., clay soils lose more water by evaporation from the lower depths than loam soils. However, when running the model, the PROP factor was assumed to be the same at both locations. When PROP was set equal to 5.0, the model predicted moisture stress conditions, which resulted in poor dry matter production throughout the growing season, because of the relatively large evaporative losses from the lower depths. With a PROP factor of 20.0, germination and subsequent growth was impaired by moisture stress because of the large evaporative water loss from the surface compartment. Therefore the PROP factor was set equal to 10.

After these changes were made there was some improvement in the predicted dry matter yields when the initial rooting depth was set equal to 5 cm. However, when using an initial root depth of 5 cm the model still predicted the crop would die in 1979 at Brandon during the early stages of growth because of moisture stress. As stated earlier, the field crop did not die. Therefore, the initial rooting depth was set equal to 10 cm for all runs of the modified model. The interactions of evaporation, root growth, germination and soil moisture content for the early stages of crop development need further study to lead to improvement of the model.

5.1.4 Senescence

As a normal process of development, the crop senesces as it approaches maturity. van Keulen (1975) incorporated the process of senescence into the model through a function relating the rate of senescence (or relative death rate) and the development stage of the crop. He based this relationship on intelligent guesswork using field data because he found quantitative data lacking. The relationship of relative death rate caused by completion of development (RDRD) versus the development stage (DVS) is given in Figure 2. Curves 1 and 2 are the relative death rates for winter wheat grown in Texas and spring wheat grown in Israel, respectively. Curve 2 shows that the spring wheat grown in Israel did not start to senesce until crop development was near completion. Sinton wheat started to noticeably senesce shortly after heading. From heading to maturity, the crop progressively senesced, starting with drying of the lower leaves followed by the upper leaves and stem. The relationships represented by Curves 1 and 2 obviously did not apply to Sinton wheat. Therefore, the relationship represented by Curve 3 was developed and used in the modified model. More study is needed to verify and improve this proposed relationship.

5.2 SIMULATION

5.2.1 Moisture Regime

5.2.1.1 Seasonal Water Use

One of the main objectives of this study was to evaluate the simulated moisture use and dry matter production of the crop simulation model developed by van Keulen (1975). Estimated values of cumulative daily potential evapotranspiration and actual evapotranspiration from planting to maturity and the final dry matter yields are recorded in Table 3. An indication of the degree of moisture stress predicted by the model can be obtained by subtracting total actual evapotranspiration (AE) from the total potential evapotranspiration (PE - calculated using Penman's (1956) formula). As the moisture deficit, PE - AE, increases the predicted final dry matter yield decreases. The final dry matter yields and the magnitude of the difference PE - AE predicted by the model suggests severe moisture stress at Brandon and slight to moderate stress at Glenlea during 1979. For 1978, the model predicts adequate moisture for crop growth at both locations.

Rainfall, total water use and final dry matter yield obtained from field data are recorded in Table 4. The total water use is a measure of the amount of water lost from the soil through soil evaporation and plant transpiration. The total water use was calculated as the sum of the rainfall between planting and harvest plus the soil moisture content to a depth of 120 cm at planting minus the soil moisture content to 120 cm at harvest. The amount of soil water available for crop growth depends on the rooting depth. The maximum rooting depth calculated by the model did not exceed 120 cm at either location. The field measured moisture content below 120 cm at each location for 1978 remained relatively constant for much of the growing season. The constant moisture content below 120 cm would indicate that rooting depth in the field probably did not exceed 120 cm. When calculating total water use of

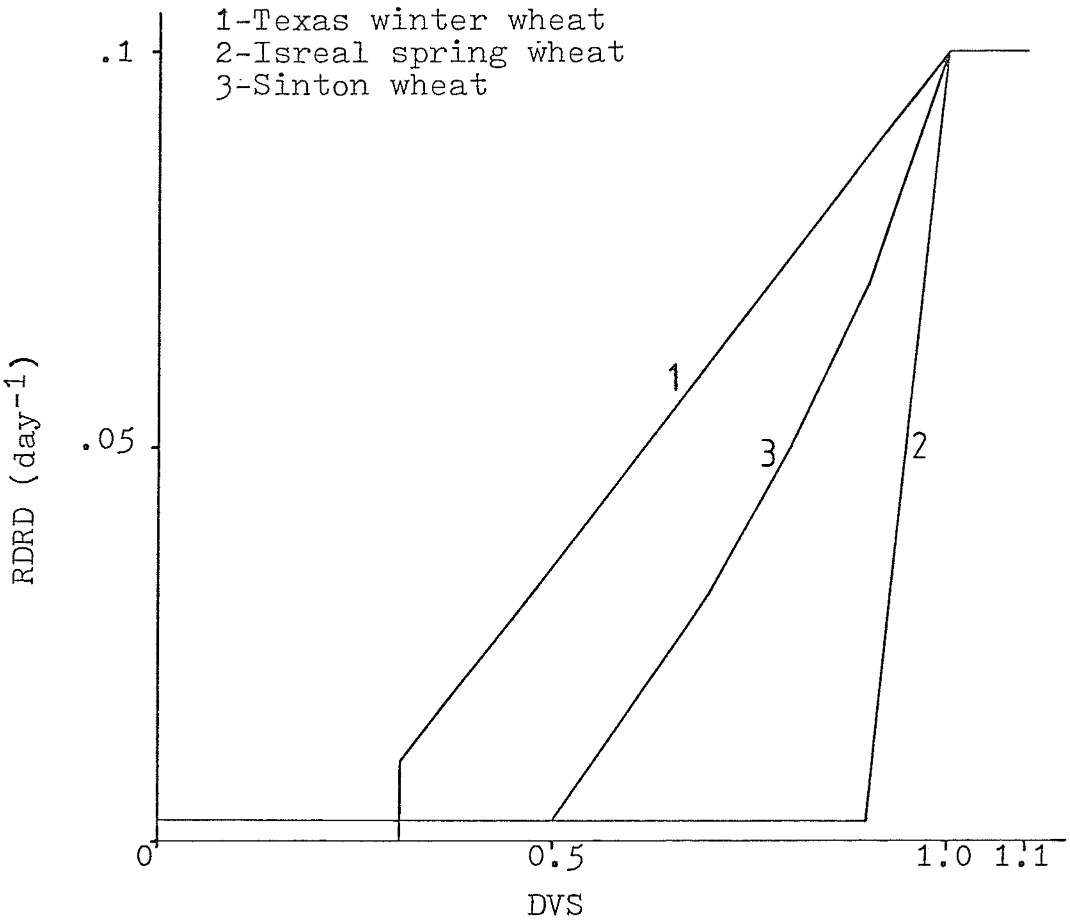

Figure 2: Relative death rate (rate of senescence-RDRD) of the crop in relation to the stage of crop development (DVS).

Table 3: Simulated seasonal evapotranspiration and final dry matter yield.

Location	Year	Potential Evapotranspiration (PE) (mm)	Actual Evapotranspiration (AE) (mm)	PE-AE (mm)	Final Dry Matter Yield (g/m^2)
Glenlea	1978	361	358	3	745
	1979	379	306	73	610
Brandon	1978	412	365	47	700
plot 1	1979	381	278	103	465
plot 2	1979	370	259	111	450

Table 4: Measured soil moisture conditions at planting and harvest, rainfall data and final dry matter yields.

Location	Year	30 Year Average Rainfall (mm) for June, July and August	Rainfall (mm)	Soil Moisture to 120 cm (mm)		Total Water Use* (mm)	Final Dry Matter Yield (g/m²)
				Planting	Harvest		
Glenlea	1978	230	186	565	452	299	900
	1979		159	600	445	314	1075
Brandon	1978	210	201	433	305	329	850
plot 1	1979		95	344	179	260	1000
plot 2	1979		71	398	225	244	925

* Total Water Use = Rainfall + Soil Moisture to 120 cm at Planting - Soil Moisture to 120 cm at Harvest

Table 4, it was assumed that water loss by deep drainage below 120 cm. was negligible. The soil profile at the beginning of the growing season was near field capacity and heavy rains at this time may have resulted in water loss through deep drainage. The rainfall data (Table 4) indicate nearly average rainfall for 1978 and below average rainfall for 1979. For 1979, the rainfall at Brandon was well below average.

The data of Tables 3 and 4 show that the model overestimated the actual evapotranspiration, or water use, for 1978. During 1979, the drier year, the model estimate of water use was approximately equal to that which occurred in the field. The model also underestimated the final dry matter production. The general trend of decreasing total dry matter production with decreasing water use depicted by the model was not evident from the field data. In the field, decreasing water use did not result in lower dry matter yields. Dry matter yields for 1978 were similar to those for 1979.

The moisture stress situation predicted by the model for 1979 was not reflected in the final dry matter yields of the plots, although the rainfall and total water use data (Table 4) indicate moisture stress conditions existed at Brandon. The data of Tables 3 and 4 suggest that the field crop might be able to adjust to moisture stress by improving water use efficiency, as was observed by Rawson et al. (1977).

5.2.1.2 Daily Total Water Content of the Soil Profile

Figures 3 to 7 are graphs of the water content of the soil profile to 120 cm (WTOT) versus the simulation day (DAY); day 0 was May 1. The figures give an indication of the gradual change in the water content of the profile as the growing season progresses. The model underestimated the water content of the profile throughout the growing season at both locations during 1978; i.e., the model overestimated water use (evapotranspiration). For 1979, the estimated soil water content to 120 cm was generally similar to the field measured soil water content except for the early part of the season. Figures 5 to 7 show that for the early portion of the growing season the model may underestimate the water content of the profile, i.e., overestimates evapotranspiration.

At this time of year most or all of the soil surface was not covered by the crop canopy and therefore evaporative water loss from the soil would be much greater than transpirational water loss. This would indicate that the modified model was overestimating actual evaporation. To reduce the predicted actual evaporation the process of estimating potential soil evaporation from open water evaporation should be corrected by multiplication with the appropriate factor (Penman, 1948). Also, increasing the PROP factor would decrease the amount of water lost by evaporation. Actual evaporation is calculated by multiplying the potential soil evaporation by a reduction factor. The reduction factor is a function of the dryness, water content, of the surface layer. Increasing PROP increases the evaporation rate from the soil surface. With higher PROP values less time is required for evaporation to dry the soil surface layer to a given water content corresponding to a given reduction factor. Therefore, the overall result is decreased evaporation with increased PROP value. Increasing PROP also decreases the amount of water lost from the lower depths through evaporation.

5.2.1.3 Water Uptake from the Soil Profile

Another important component of the soil moisture regime is the withdrawal pattern of water from the soil profile. The variation in volumetric water content with depth during the growing season illustrates the moisture withdrawal pattern by the roots (Figures 8 to 12). Generally, the model was overestimating the water withdrawal from the upper portion of the soil profile and underestimating water withdrawal from the lower portion. The withdrawal pattern is related to the growth function of the roots (Figure 1). The root growth function (Curve 2, Figure 1) used in the modified model assumed that roots grow at a decreasing rate from germination to maturity. If the root growth function was represented by Curve 3 (Figure 1), the roots would be assumed to grow at a continuous rate from germination to heading. The roots would reach their maximum depth before those roots represented by growth Curve 2. Therefore because of the faster root growth represented by Curve 3 compared to Curve 2 (Figure 1), relatively more water would have been used from the lower portion and less from the upper portion of the soil profile. The

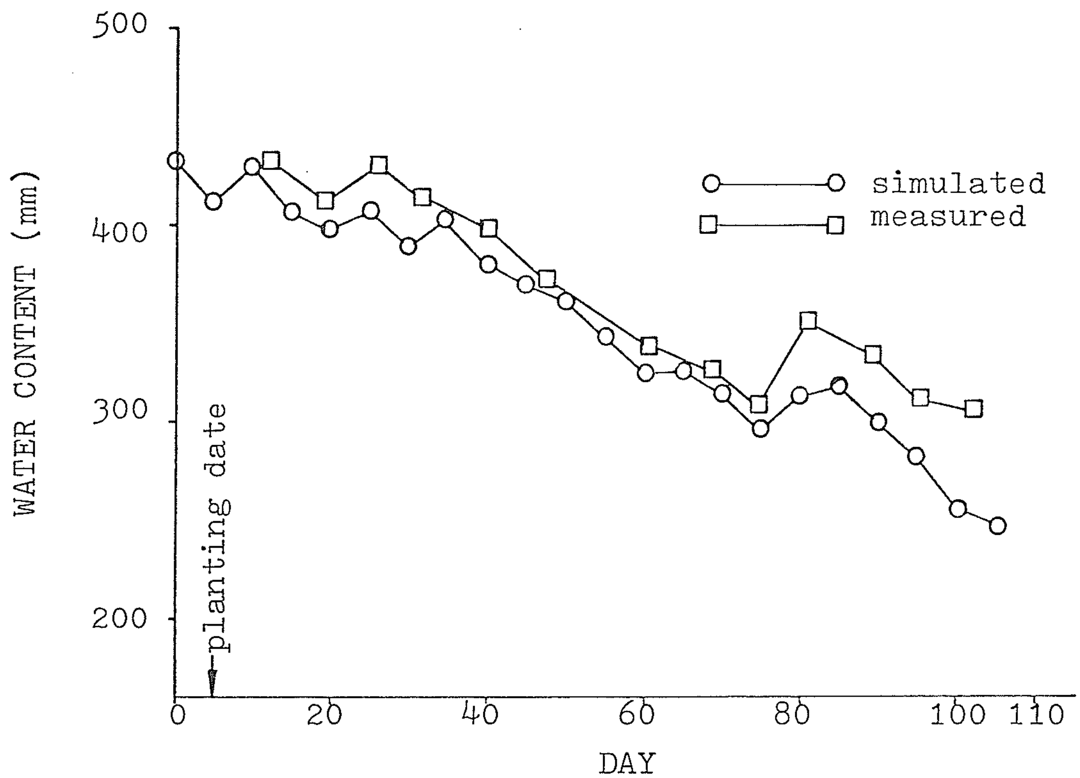

Figure 3: Comparison between measured and simulated daily total soil water content to 120 cm. for Brandon, 1978. (DAY 0 is May 1).

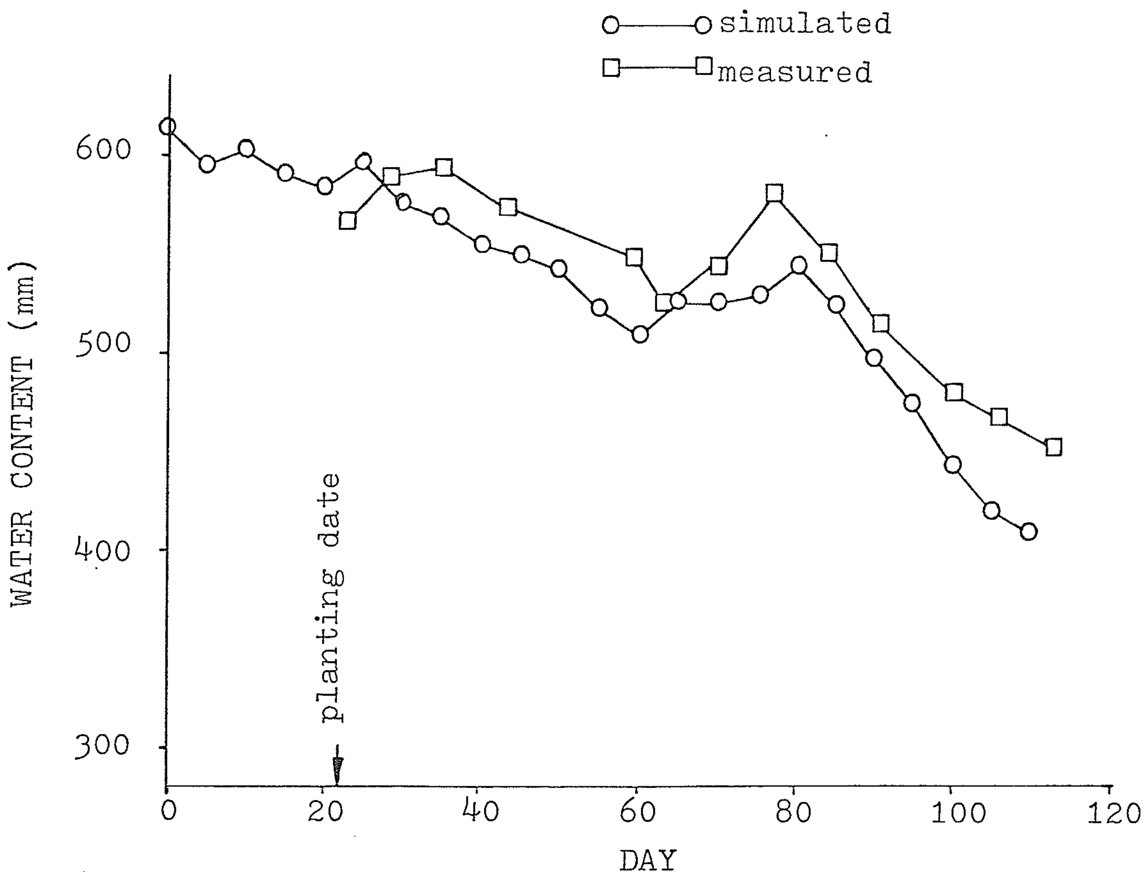

Figure 4: Comparison between measured and simulated daily total soil water content to 120 cm. for Glenlea, 1978. (DAY 0 is May 1).

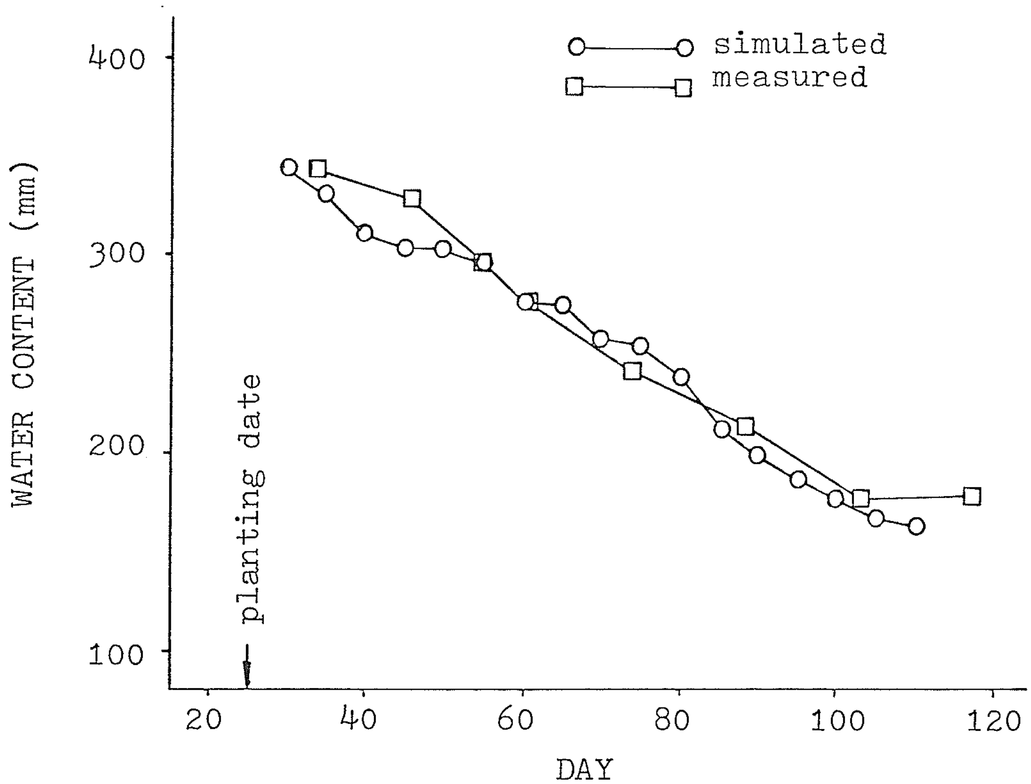

Figure 5: Comparison between measured and simulated daily total soil water content to 120 cm. for Brandon plot 1, 1979. (DAY 0 is May 1).

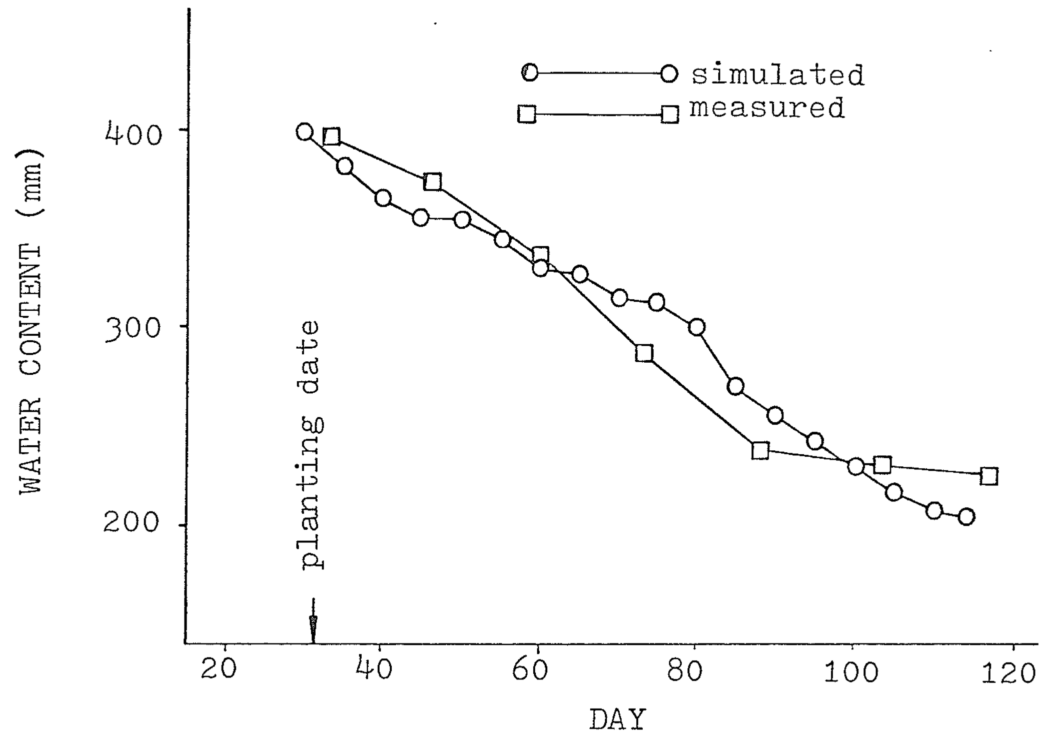

Figure 6: Comparison between measured and simulated daily total soil water content to 120 cm. for Brandon plot 2, 1979. (DAY 0 is May 1).

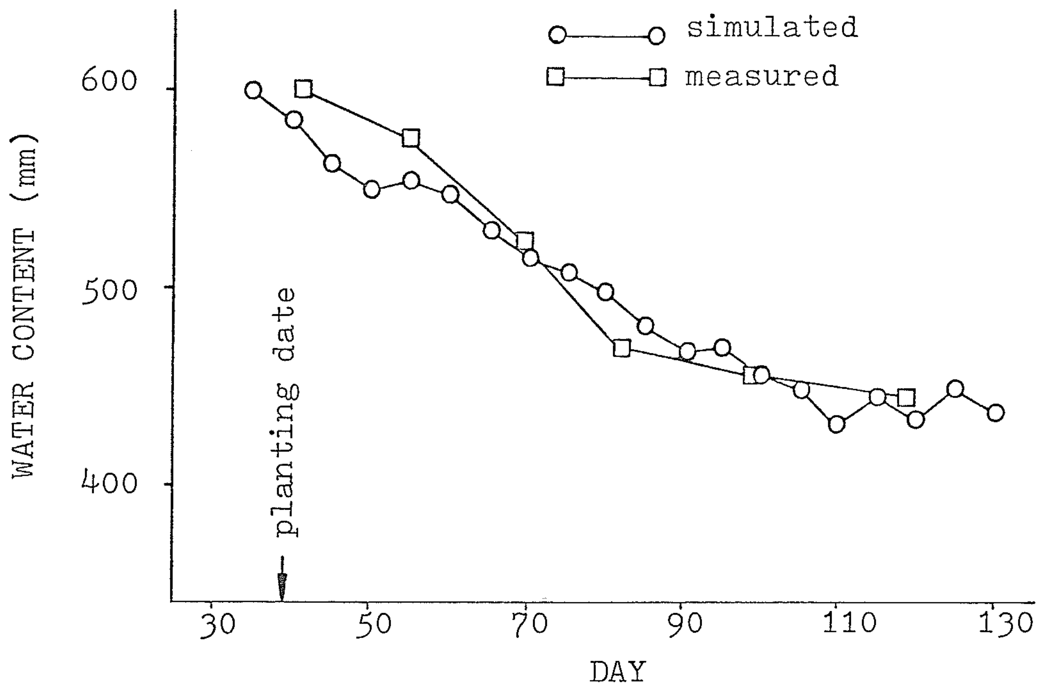

Figure 7: Comparison between measured and simulated daily total soil water content to 120 cm. for Glenlea, 1979. (DAY 0 is May 1).

predicted water withdrawal patterns would probably have been more representative of the actual withdrawal patterns if the root growth function was represented by Curve 3 instead of Curve 2.

When dealing with water uptake by the roots, van Keulen (1975) made two assumptions: 1) water uptake was a function of rooting depth and relatively independent of root density and; 2) upward water flux from below the root zone was insignificant and therefore did not contribute to crop growth. When moisture stress conditions exist, many researchers do not agree with these assumptions. Hillel et al. (1976) found that a crop with a sparse root system experienced moisture stress at higher soil water contents than with a dense root system. However, Hurd (1964, 1968) found that wheat cultivars respond very differently to changing soil moisture conditions. A wheat cultivar with a relatively sparse root system may or may not be able to withstand a greater degree of stress than a wheat cultivar with a denser root system. Other responses of plants, such as osmotic adjustment (Turner and Jones, 1980), should be considered when comparing root systems and response to moisture stress. Rickman et al. (1978) state that upward movement of water into the root zone can contribute as much as 10% to the daily soil water use during the midseason. Van Bavel and Ahmed (1976) simulated water depletion in the root zone during a long dry period. They found the model predicted that a substantial amount of the water used by the crop would be from the soil moisture reserve below the root zone. The model was based on earlier experimental work by van Bavel et al. (1968). Because relatively little is known about root response to environmental changes, modeling of water uptake by plants is a difficult task. More research on root systems is needed if understanding and modeling of root systems is to improve.

5.2.2 Crop Growth

5.2.2.1 Dry Matter Production and Leaf Growth

The model underestimates dry matter production throughout crop development (Figures 13 to 17). The magnitude of the underestimation was greater for 1979 than 1978. When germination occurs, the initial dry weight of the roots and of the shoots are both set equal to 40% of the

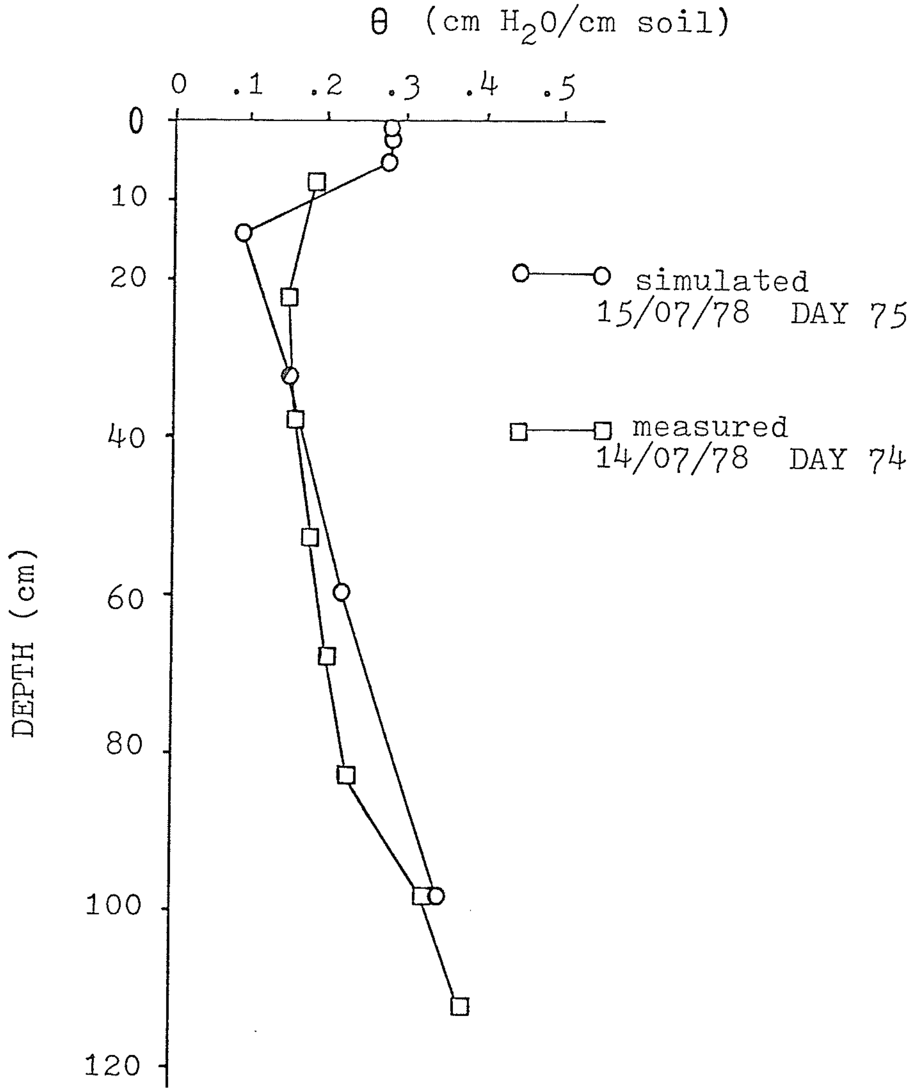

Figure 8: Comparison of measured and simulated volumetric water content (θ) profiles for Brandon, 1978.

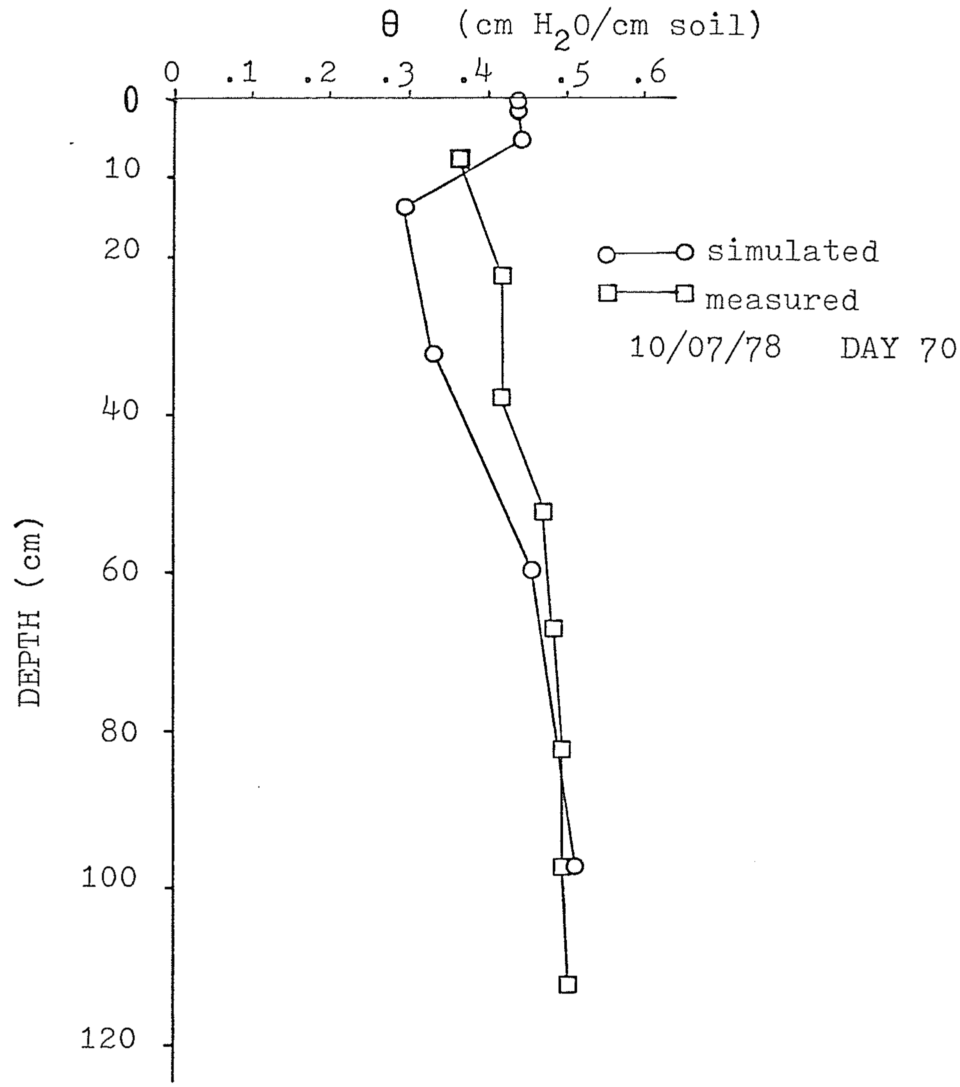

Figure 9: Comparison of measured and simulated volumetric water content (θ) profiles for Glenlea, 1978.

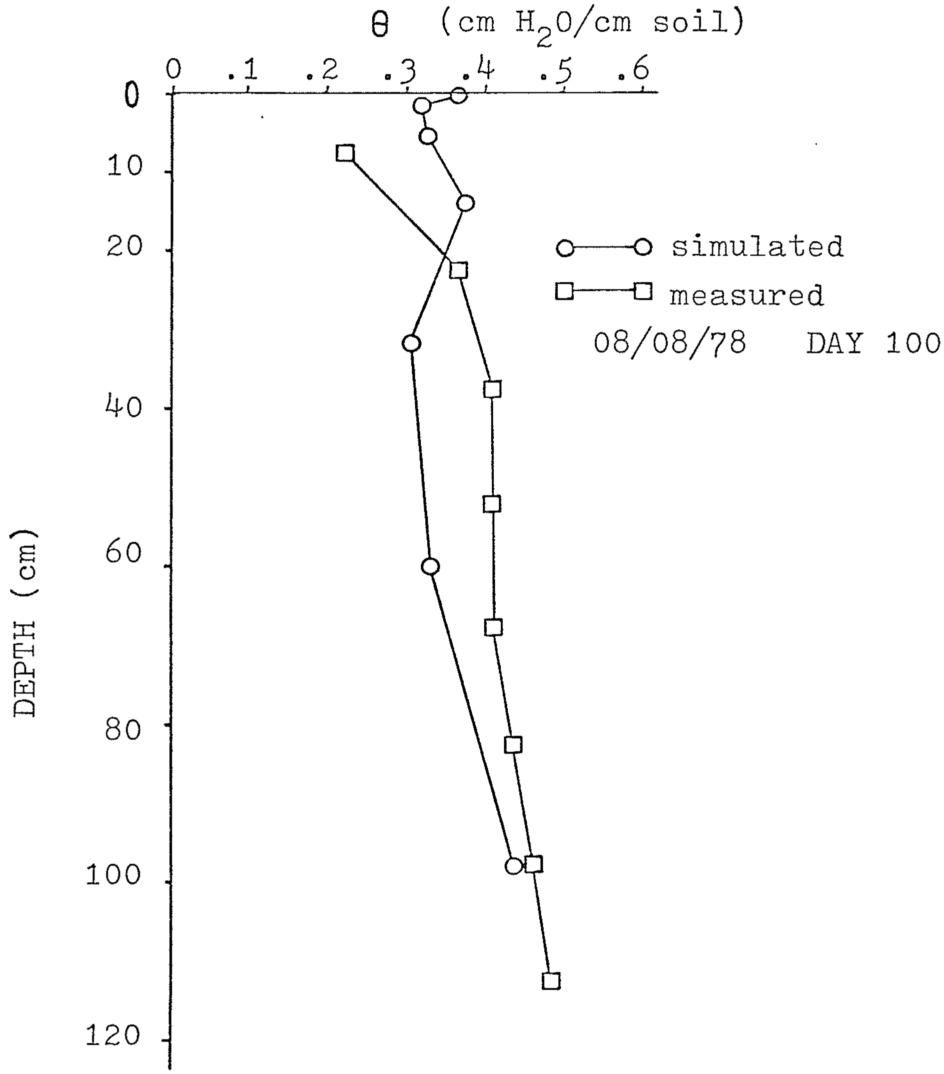

Figure 10: Comparison of measured and simulated volumetric water content (θ) profiles for Glenlea, 1978.

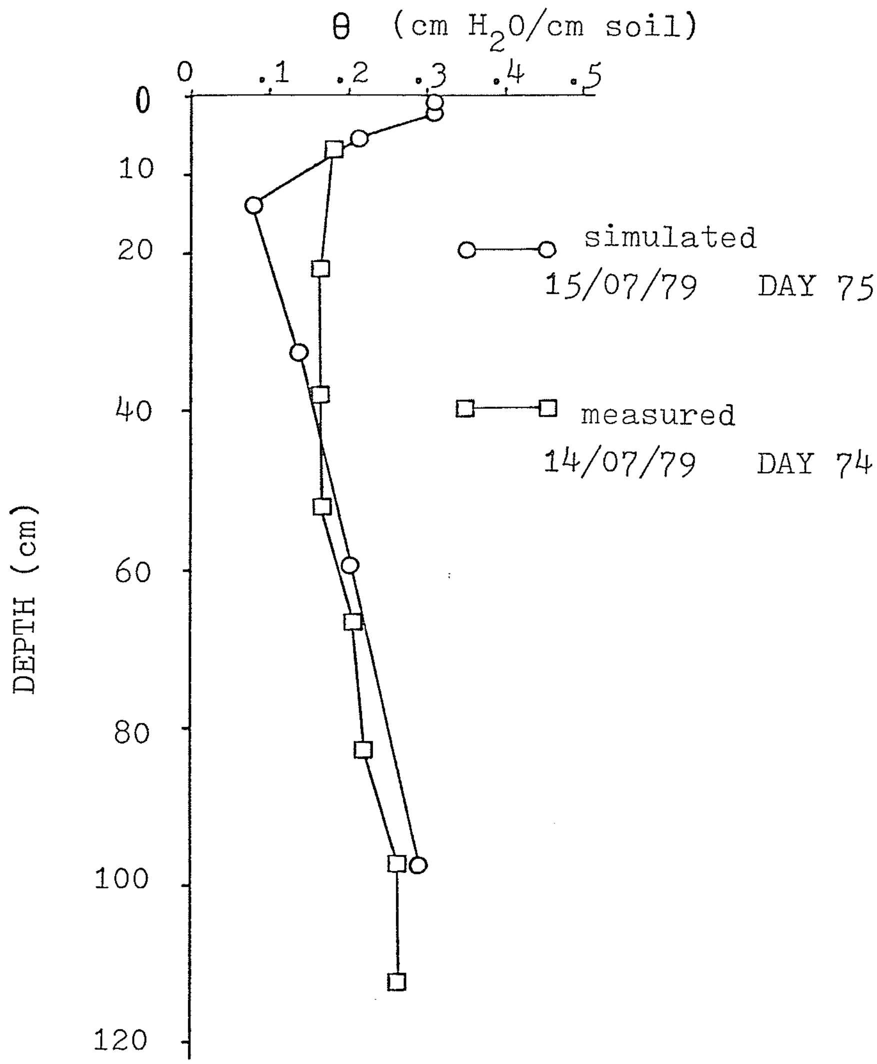

Figure 11: Comparison of measured and simulated volumetric water content (θ) profiles for Brandon plot 1, 1979.

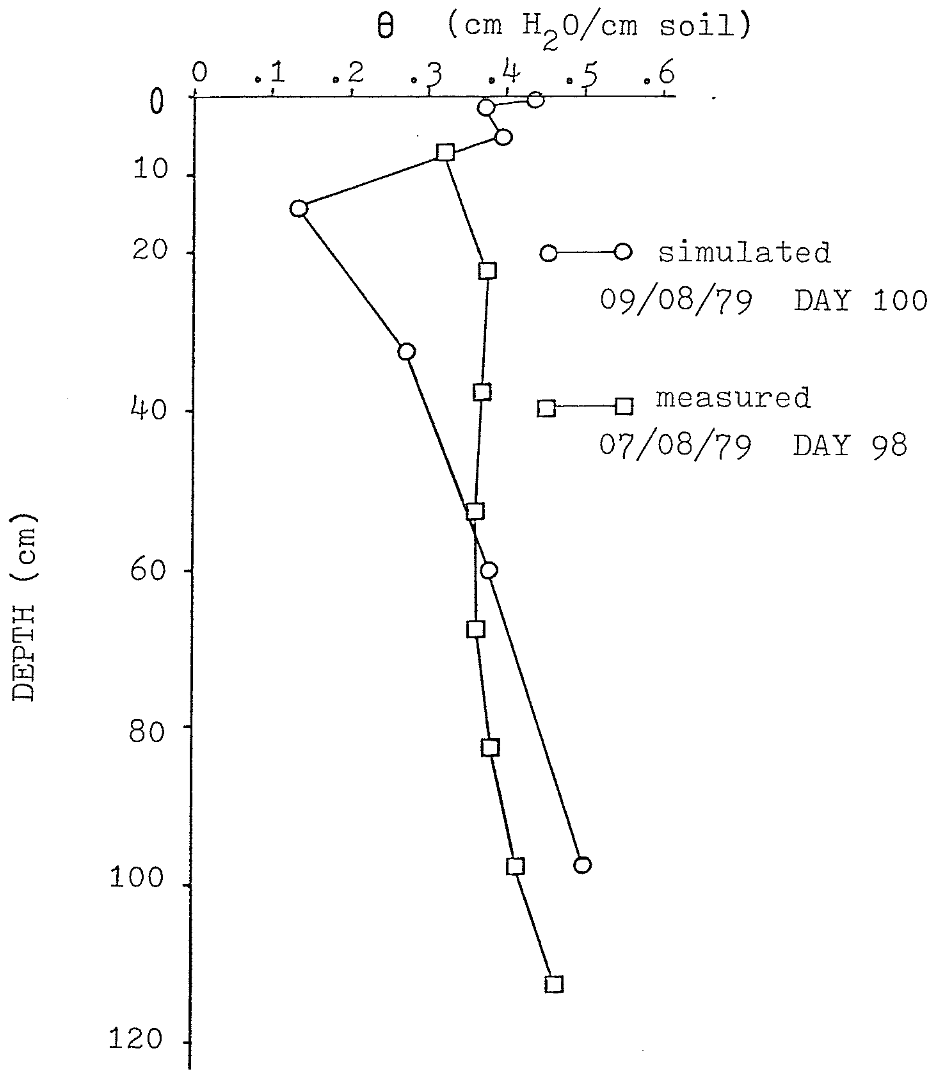

Figure 12: Comparison of measured and simulated volumetric water content (θ) profiles for Glenlea, 1979.

seeding rate. The initial leaf area is a multiple of the inital dry weight of the shoot. The model greatly underestimated the maximum leaf area index (LAI) at Glenlea during 1979 (Figure 20) and slightly underestimated maximum LAI at Brandon (Figures 18 and 19). The increase in LAI and the maximum LAI for the field plots occurred earlier than predicted by the model. Leaf growth is very sensitive to water stress (Hsiao and Acevedo, 1974). The large differences in LAI between the field plots at Brandon and Glenlea may have occurred because of differing levels of moisture stress. Leaf growth can recover from short, mild stress (Boyer, 1976). The crop at Glenlea may not have been stressed or only mildly stressed but the Brandon plots were probably more severely stressed. The large difference between the predicted and actual LAI at Glenlea (Figure 20) supports the conclusion that the model does not correctly predict crop response to moisture stress or predicts stress before it occurs.

The daily photosynthetic rate and partitioning of solar energy to be used in either transpiration or soil evaporation are dependent upon LAI. Therefore the prediction of LAI is an important component of the model. LAI is calculated as a function of the leaf area per unit dry matter produced (leaf area ratio - LAR). The leaf area ratio is stored in the model as a function of temperature. However, Campbell and Read (1968) found LAR to be unaffected by changing temperature. Both Campbell and Read (1968) and Friend (1965) found LAR to be influenced by changing light intensity; LAR increases with decreasing light intensity. It may therefore be more beneficial to model LAR as a function of light intensity rather than temperature. Because of the importance of leaf area prediction, this portion of the model should be tested and corrected to suit Canadian spring wheat cultivars before major changes are made to other parts of the model. More accurate prediction of LAI throughout crop development would improve simulation of dry matter production. Increasing predicted leaf growth in the early stages of crop development would result in increased transpiration and dry matter production in these early stages. The time of maximum LAI and subsequent decline in LAI occurred earlier in the field than predicted by the model. Incorporating this observation into the model would

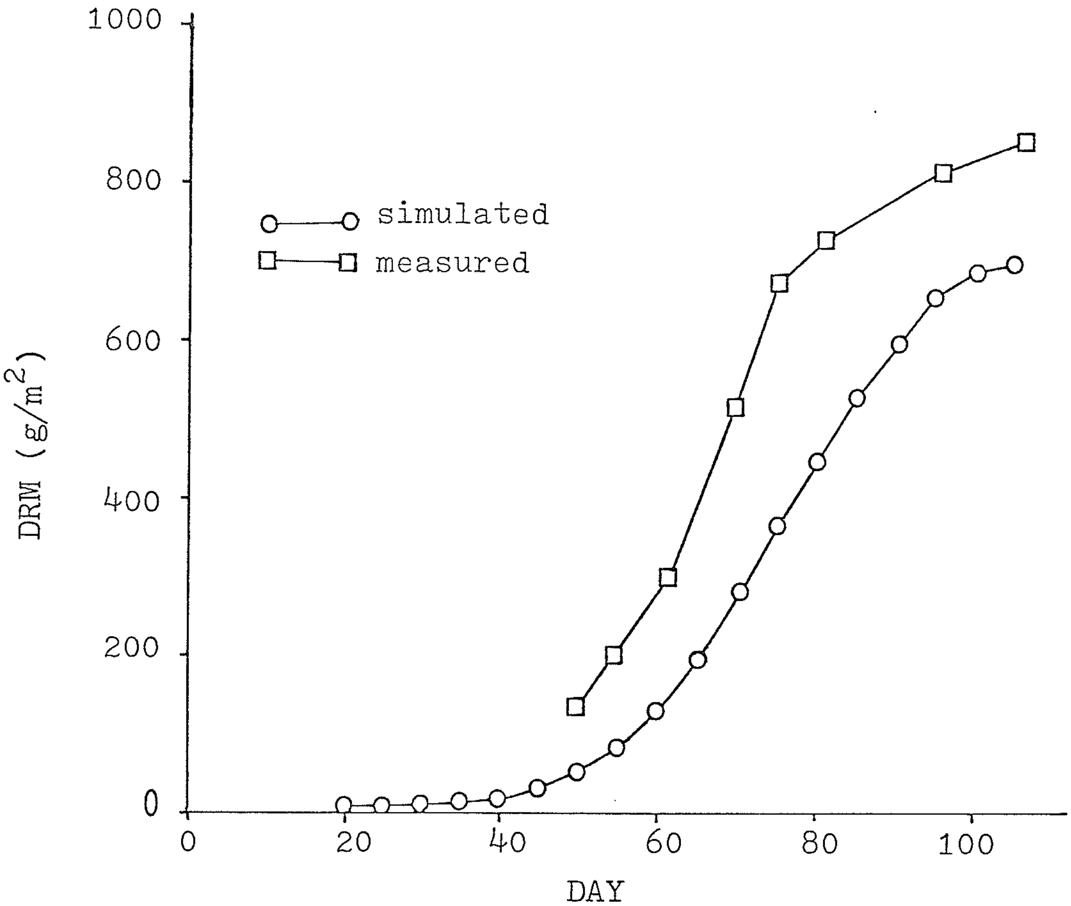

Figure 13: Comparison between simulated and measured daily dry matter production (DRM) for Brandon, 1978. (DAY 0 is May 1).

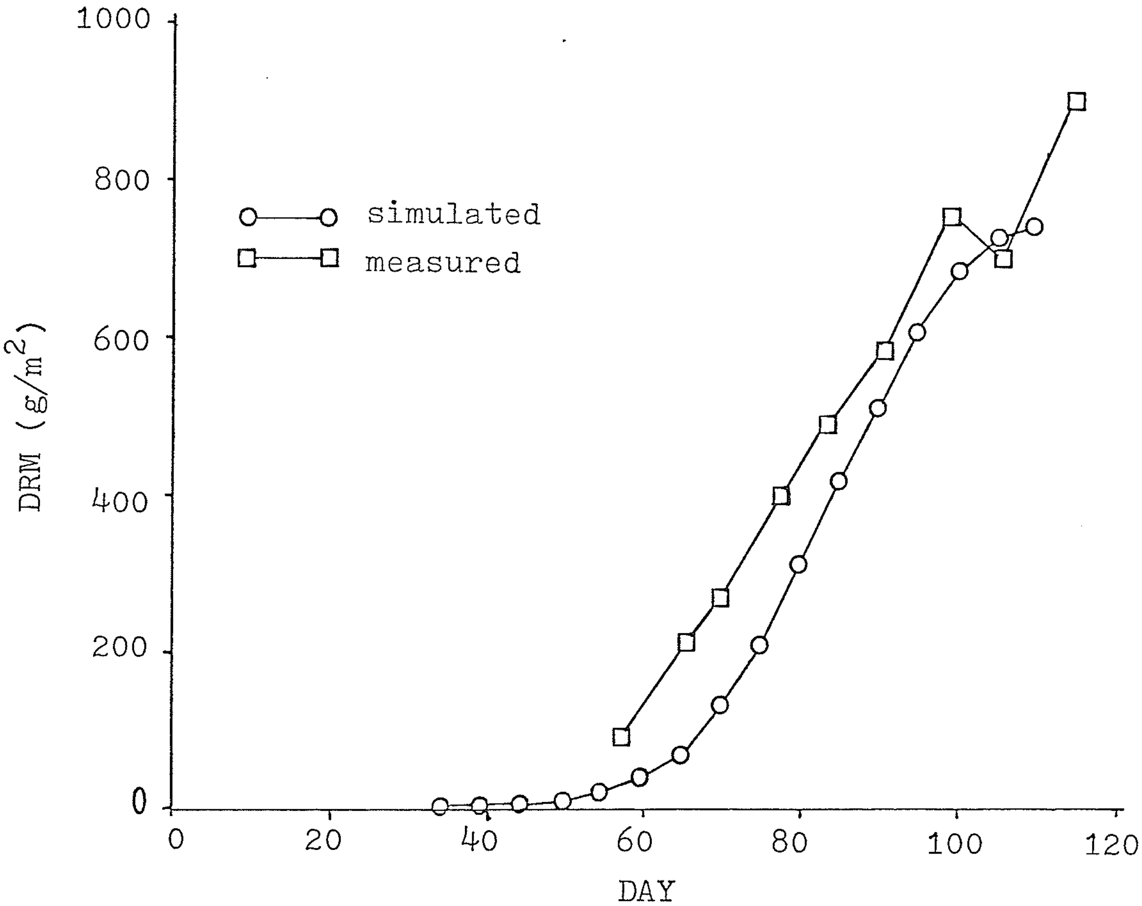

Figure 14: Comparison between simulated and measured daily dry matter production (DRM) for Glenlea, 1978. (DAY 0 is May 1).

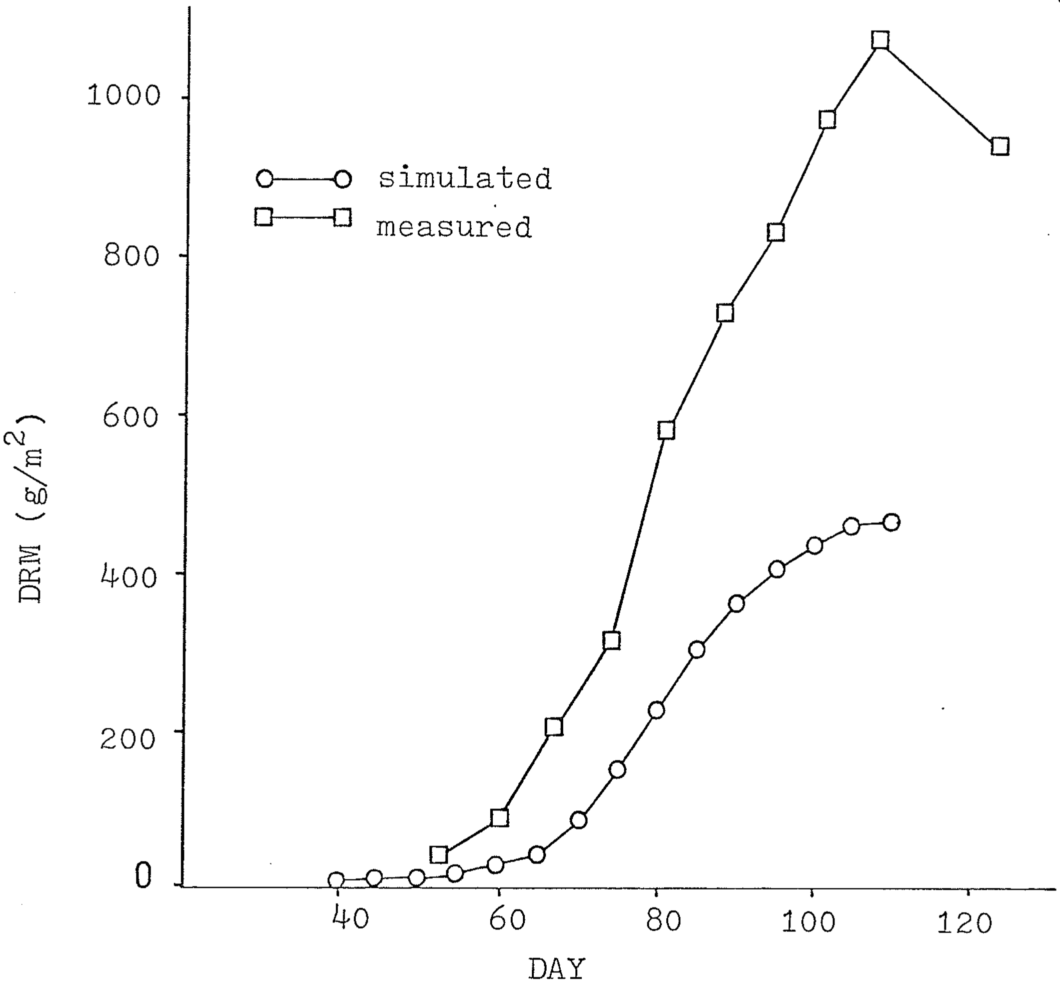

Figure 15: Comparison between simulated and measured daily dry matter production (DRM) for Brandon plot 1, 1979. (DAY 0 is May 1).

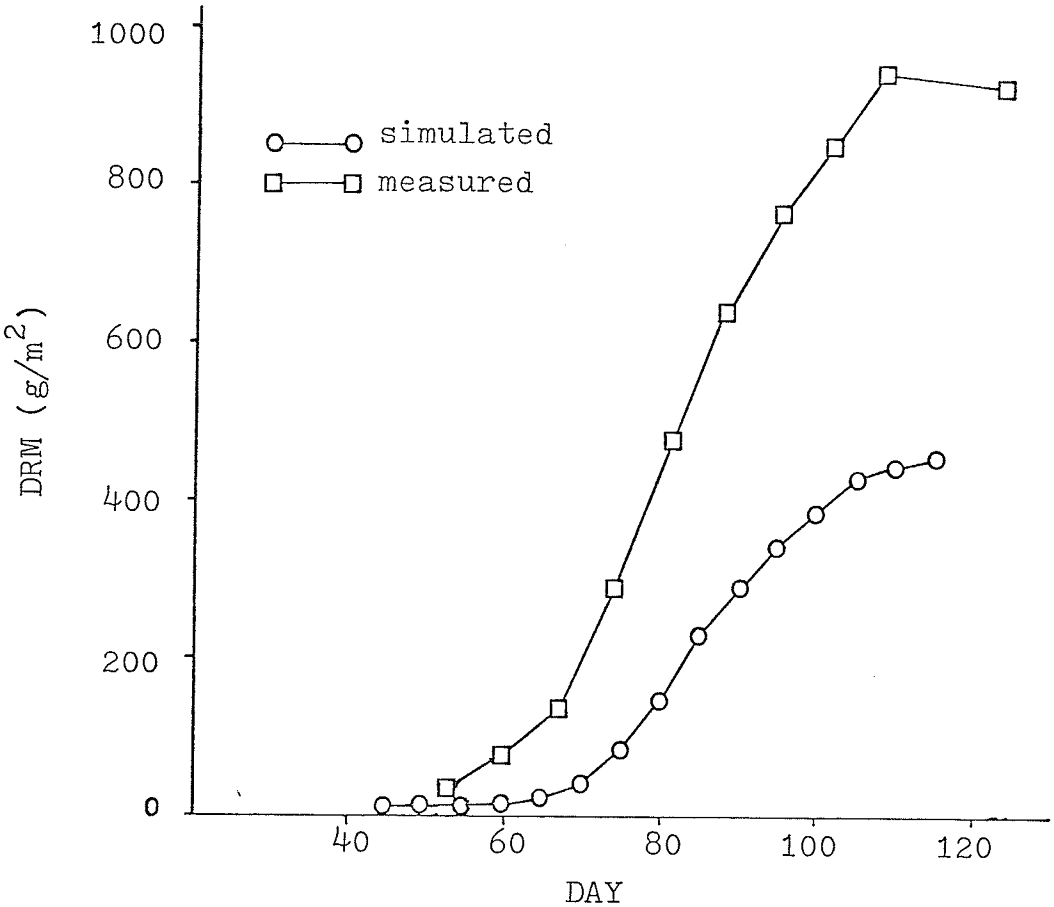

Figure 16: Comparison between simulated and measured daily dry matter production (DRM) for Brandon plot 2, 1979. (DAY 0 is May 1).

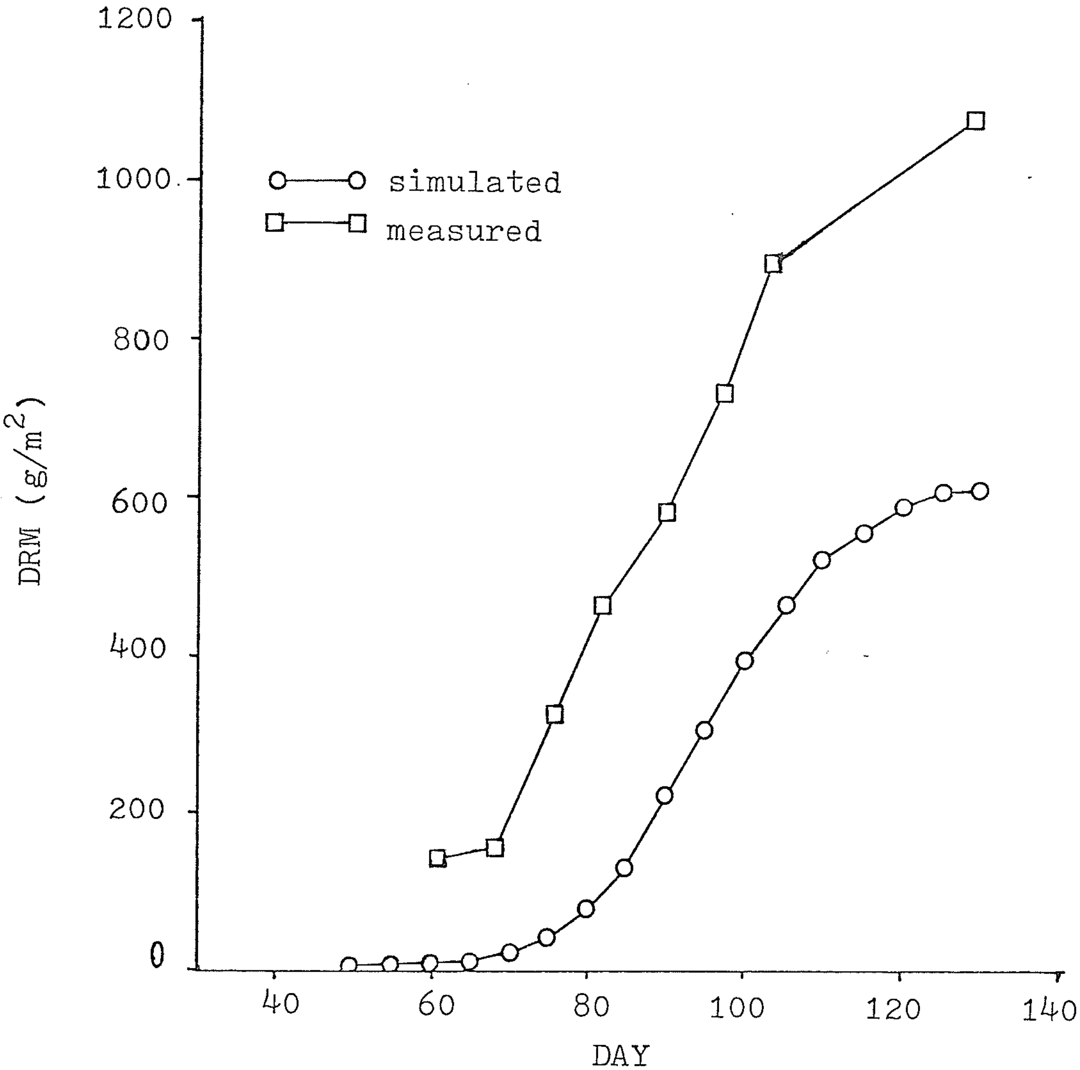

Figure 17: Comparison between simulated and measured daily dry matter production (DRM) for Glenlea 1979. (DAY 0 is May 1).

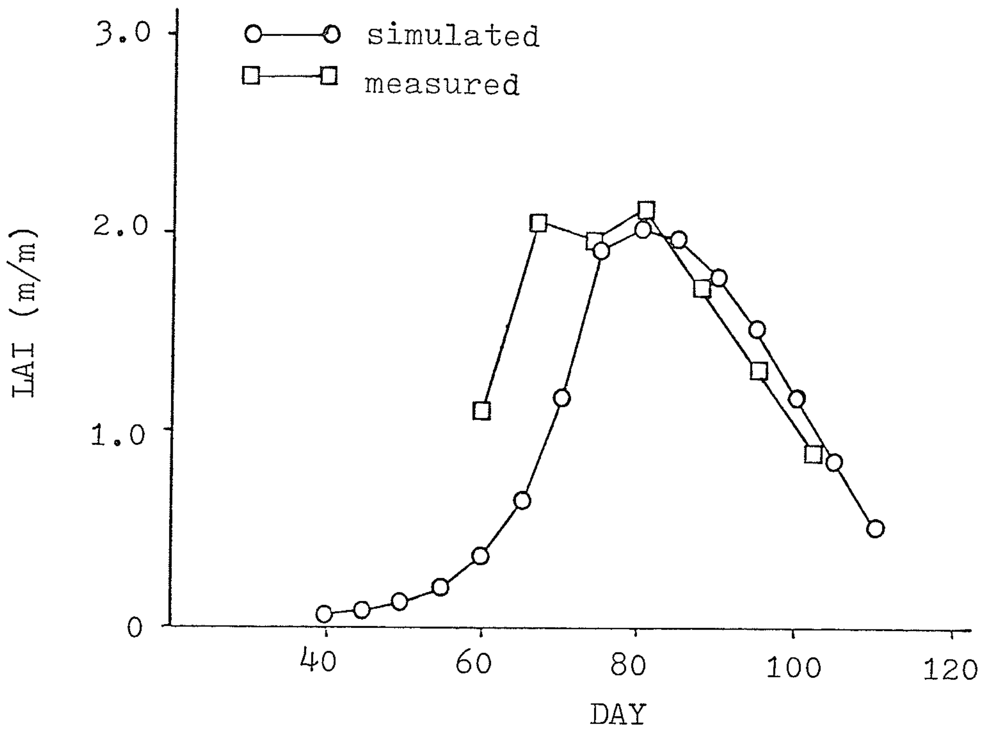

Figure 18: Comparison between measured and simulated daily leaf area index (LAI) for Brandon plot 1, 1979. (DAY 0 is May 1).

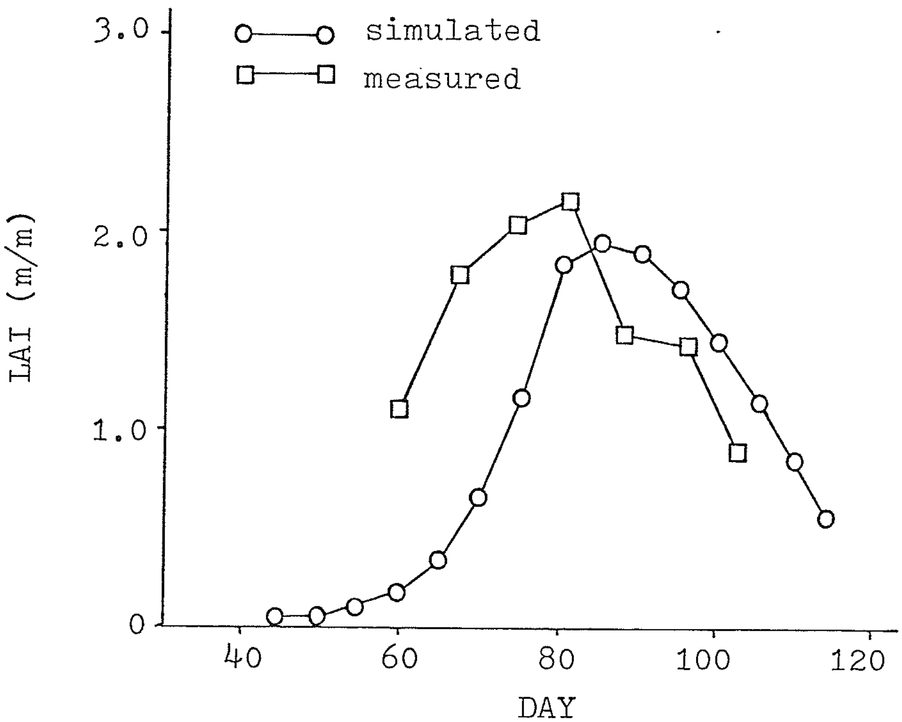

Figure 19: Comparison between measured and simulated daily leaf area index (LAI) for Brandon plot 2, 1979. (DAY 0 is May 1).

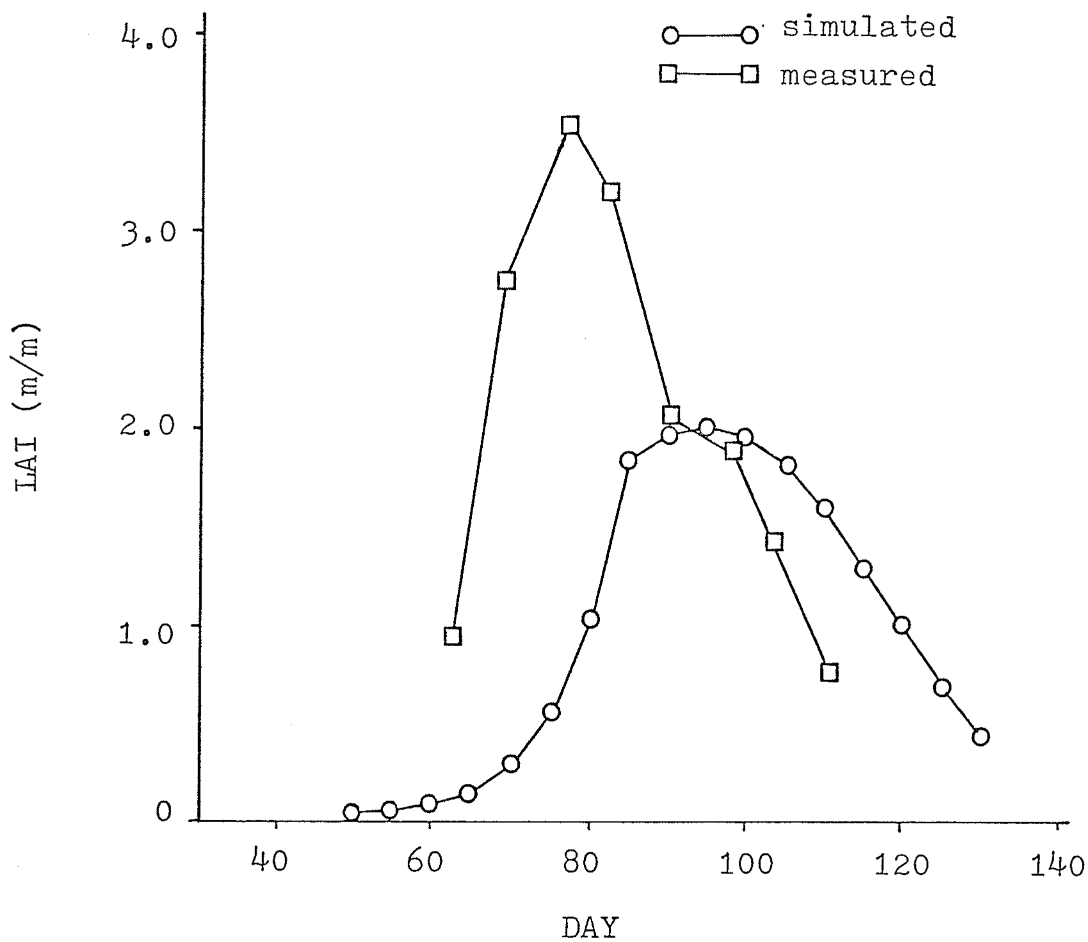

Figure 20: Comparison between simulated and measured daily leaf area index (LAI) for Glenlea, 1979. (DAY 0 is May 1).

result in lower predicted photosynthetic rates after heading and therefore lower grain yields.

5.2.2.2 Water Use Effeciency

While improving the prediction of leaf growth would improve the simulation of dry matter production, there is still the possibility of increased water use efficiency with increasing moisture stress. Field data and observations lead to the conclusion that the wheat crop at Glenlea during 1979 either did not experience moisture stress or was only mildly stressed. However the field data for Brandon 1979 indicate the crop may have been stressed. Dry matter production at both locations was similar but leaf area was much greater at Glenlea. Total water use (Table 4) was also greater at Glenlea. The sensitivity of leaf growth to moisture stress and the similarity in dry matter production at each location during 1979 indicates there may have been an increase in water use efficiency with increase in moisture stress. Rawson et al. (1977) found that wheat used water more efficiently when grown under moisture stress conditions. However, the adaptation to moisture stress was not persistent. When moisture conditions improved, water use efficiency decreased to the levels that existed before the plants were stressed. They concluded that wheat adapted to water stress and used water more efficiently during the vegetative period but there was little evidence to indicate that drought improved water use efficiency during grain production. Passioura (1977) found considerable variation in water use efficiency between wheat cultivars. Raschke (1976) states that water use efficiency is improved by stomatal closure. He concludes that CO_2 uptake (photosynthesis) is much less affected by stomatal closure than is water vapor loss (transpiration), particularly at large stomatal apertures. The ability of the wheat crop to withstand moisture stress is an area for improvement in the model.

5.2.2.3 Grain Yields

Predicted grain yields were higher in 1978 and lower in 1979 than the grain yields obtained from the plots (Table 5). The model underestimated total dry matter production but overestimated grain yield in 1978.

Therefore, the model was predicting a greater photosynthetic contribution to grain yield than actually occurred. Thorne (1966) states that 80% of assimilate produced after flowering contributes to grain yield. In the model, flowering was assumed to occur at the development stage of .5, i.e., when the crop had completed half its development. However if flowering occurs at a later stage, predicted grain yields would be lower. Also, improving the prediction of leaf area growth would result in decreased grain yields relative to total dry matter yields. Figures 18 to 20 show that leaf area index decreases from the maximum earlier than predicted by the model. Adjustment of the predicted LAI would result in lower simulated photosynthetic rates after flowering and therefore, a lower ratio of grain to dry matter yield. The grain yields obtained from the plots for 1978 were lower than for 1979. The higher rates of N fertilizer for 1979 compared to 1978 may have contributed to the yield difference. Another factor that may have contributed to the yield difference was temperature. The late seeding dates of 1979 resulted in the grain growth periods occurring later in the summer when temperatures were lower. Researchers have found increased yields with decreasing temperature mainly because of the increased duration of grain growth (Sofield et al, 1977). A review of the literature shows the complex nature of grain growth. To improve the model's prediction and simulation of grain growth and yield would be a difficult task.

5.2.2.4 Crop Development

Two methods of predicting the development stage of the crop were compared to the field observations. The model estimates development stage as a function of temperature only. The second model used was Robertson's (1968) biometeorological time scale which estimates development stage as a function of temperature and photoperiod. For 1978, the estimated number of days from planting to emergence (P-Emerg) and from planting to maturity (P-M) by both models was approximately equal to that observed in the field (Table 6). However, for 1979 both models underestimated the days for P-M (Table 7). The biometeorological time scale also underestimated the days for P-Emerg.

Table 5: Final grain yields for 1978 and 1979.

Location	Year	Grain Yield (g/m^2)	
		Model	Field
Glenlea	1978	435	352
	1979	377	433
Brandon	1978	409	325
plot 1	1979	262	382
plot 2		257	363

Table 6: Simulated and observed days from planting to emergence and planting to maturity for 1978.

Location	Planting	Planting to Emergence (DAYS)			Planting to Maturity (DAYS)		
	Day	Model	Biomet.*	Field	Model	Biomet.*	Field
Glenlea	May 23	9	8	7	87	89	90
Brandon	May 6	12	10	11	99	101	101

Table 7: Simulated and observed days from planting to emergence and planting to maturity for 1979.

Location	Planting	Planting to Emergence (DAYS)			Planting to Maturity (DAYS)		
	Day	Model	Biomet.*	Field	Model	Biomet.*	Field
Glenlea	June 9	10	7	8	90	88	98
Brandon plot 1	May 26	12	8	11	85	78	98
plot 2	June 2	10	7	10	82	79	91

*Robertson's Biometeorological Time Scale

Neither model considers the effects of moisture stress on phenological development. Mild stress may hasten plant development while severe stress may delay development (Angus and Moncur, 1977). Moisture stress may account for some of the differences between predicted and observed phenological development at Brandon for 1979 but probably not at Glenlea. Both models may not accurately predict the phenological response of Sinton wheat to the low temperatures and decreasing photoperiod that occur in the late summer and early fall. Riddel et al. (1958) found that that increasing daylength (photoperiod) accelerated development. Riddell and Griers (1958) found that one cultivar of their study was relatively insensitive, phenologically, to photoperiod and temperature when compared to a second cultivar. Decreasing temperature and photoperiod strongly delayed development of the second cultivar. Their work showed that there are varietal differences in response to photoperiod and temperature.

Chapter VI
SUMMARY AND CONCLUSIONS

Generally, the model did not accurately simulate the overall process of crop growth for the Canadian spring wheat cultivar Sinton. The model predicted stress conditions when field data indicated either stress did not exist or the crop as able to adapt to the stress.

The model did not accurately simulate the relationship between transpiration, dry matter production, seed yield and leaf area growth for Sinton wheat. The model underestimated dry matter production throughout the period of crop growth and did not accurately simulate leaf growth. Depending on moisture conditions the model; a) predicted seed yields to be greater than or lower than actual seed yields and b) overestimated water use. Also, the model probably overestimated the amount of water lost through soil evaporation. Under abnormal conditions, such as late seeding date and/or moisture stress, the model did not accurately simulate the development rate of Sinton wheat.

Suggested areas for improvement of the model are:

1) Adjustment of the model to accurately simulate leaf area production of Sinton wheat. This would probably result in increased predicted transpiration and dry matter production early in the growing season and also result in lower predicted seed yields.

2) Incorporate into the model the ability of Sinton wheat to adapt to moisture stress and/or to grow at lower soil water contents before stress conditions occur.

3) Improve the simulation of the soil temperature profile and the effects of soil temperature on root growth and functioning.

4) The method of simulating the development rate should be tested and adjusted to accurately predict phenological development of Sinton wheat. The effects of moisture stress on the phenological development of Sinton wheat should be studied and possibly included in the model.

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Appendix A

SOIL CHARACTERISTICS - BULK DENSITY, FIELD CAPACITY, WILTING POINT.

Soil characteristics - bulk density (BD - gm/cc), field capacity (FC - cm water/cm soil), wilting point (WP - cm water/cm soil) - for Brandon and Glenlea.

Depth (cm)	Brandon 1978			Brandon 1979			Glenlea		
	BD	FC	WP	BD	FC	WP	BD	FC	WP
0-15	1.02	0.337	0.127	1.01	0.35	0.128	1.04	0.456	0.220
15-30	1.25	0.344	0.141	1.16	0.34	0.144	1.32	0.514	0.306
30-45	1.21	0.321	0.140	1.19	0.30	0.152	1.32	0.514	0.306
45-60	1.28	0.331	0.140	1.28	0.29	0.152	1.33	0.514	0.306
60-75	1.38	0.373	0.150	1.30	0.26	0.112	1.37	0.514	0.306
75-90	1.32	0.393	0.155	1.26	0.23	0.106	1.32	0.514	0.306
90-105	1.57	0.399	0.155	1.29	0.23	0.106	1.33	0.514	0.306
105-120	1.52	0.393	0.155	1.27	0.22	0.112	1.33	0.514	0.306
120-135	1.47	0.308	0.099	1.31	0.26	0.120	1.33	0.514	0.306

Appendix B

A PROGRAM VERSION OF ROBERTSON'S (1968) BIOMETEOROLOGICAL TIME SCALE

```
//SOILPHYS JOB '0526,SMPC,,T=10,L=4,I=30',H.CUTFORTH
/*TSO SOIL
// EXEC WATFIV
//GO.SYSIN DD *
$JOB WATFIV
C     ROBERTSON'S BIOMETEORLOGICAL TIME SCALE
      INTEGER SUMDAY,R,C,J(5),COL,N(40),NDAY,NLDATE
      REAL A(5,8),THETA,DELTA,DAYLEN,PHI,SIN,COS,ARCOS,SUMBIO,
     1BMTS,BIO,Y,B,D,E,TMAX,TMIN
      READ (5,55) ((A(R,C),C=1,8),R=1,5)
   99 SUMBIO=0.0
      SUMDAY=0
      BMTS=1.0
      COL=1
      R=1
      READ (5,1,END=444) (N(M),M=1,40)
    1 FORMAT (40A2)
      WRITE (6,2) (N(M),M=1,40)
    2 FORMAT (1H1, 40A2)
      READ 7,NDAY,NLDATE,PHI
    7 FORMAT (I3,1X,I3,1X,F5.0)
      WHILE(NDAY.LT.NLDATE) DO
         NDAY=NDAY+1
         READ (5,25) TMAX,TMIN
      END WHILE
      PRINT 35,NLDATE
   35 FORMAT (' ','PLANTING DATE=',I5,/,5X,'PE',4X,'EJ',4X,
     1'JH',4X,'HS',4X,'SR')
   10 READ (5,25) TMAX,TMIN
   25 FORMAT (13X,2F5.1)
      TMAX=TMAX*9./5.+32.
      TMIN=TMIN*9./5.+32.
      B=TMAX-A(R,4)
      D=TMIN-A(R,4)
      CONMAX=A(R,5)*B+A(R,6)*B*B
      CONMIN=A(R,7)*D+A(R,8)*D*D
      IF(CONMAX.LE.0.0) CONMAX=0.0
      IF(CONMIN.LE.0.0) CONMIN=0.0
      BIO=CONMAX+CONMIN
      SUMBIO=SUMBIO+BIO
      SUMDAY=SUMDAY+1
      NDAY=NDAY+1.0
      IF(SUMBIO.LT.1.0) GO TO 10
   30 J(COL)=SUMDAY
      Y = 0.0
      SUMBIO=0.0
      BMTS=BMTS+1.0
      IF(BMTS.GT.5.0) GO TO 40
C:
```

```
      R=R+1
   55 FORMAT (8E10.0)
   20 THETA = .01721 * NDAY
      DELTA = .3964 + 3.631 * SIN(THETA) - 22.97 * COS(THETA)+.03838*
     1SIN(2* THETA) - .3885 * COS(2*THETA)+.0759*SIN(3*THETA)-
     2.1587 * COS(3 * THETA)-.01021*COS(4*THETA)
      DELTA = DELTA / 57.2956
      DAYLEN = ARCOS((-.01454-SIN(PHI)*SIN(DELTA))/(COS(PHI)*COS(DELTA)))
      DAYLEN = DAYLEN * 7.639
      E=DAYLEN-A(R,1)
      B=TMAX-A(R,4)
      D=TMIN-A(R,4)
      CONDAY = A(R,2) * E + A(R,3) * E * E
      CONMAX = A(R,5) * B + A(R,6) * B * B
      IF(CONMAX.LT.0.)CONMAX= 0.0
      CONMIN = A(R,7) * D + A(R,8) * D * D
      IF(CONMIN.LT.0.) CONMIN = 0.0
      BIO = Y * CONDAY *(CONMAX + CONMIN)
      SUMBIO=SUMBIO+BIO
      Y=1.0
      IF(SUMBIO.GE.1.0) GO TO 50
         READ (5,25) TMAX,TMIN
         TMAX=TMAX*9./5.+32.
         TMIN=TMIN*9./5.+32.
         SUMDAY=SUMDAY+1
         NDAY=NDAY+1.0
         GO TO 20
   50    COL=COL+1
         GO TO 30
   40 PRINT 5,(J(COL),COL=1,5)
    5 FORMAT (' ',5I6)
      PRINT 12,NDAY
   12 FORMAT (' ','MATURITY DATE =',I5)
      WHILE(NDAY.LT.274)DO
      NDAY = NDAY + 1
      READ(5,25) TMAX, TMIN
      TMAX=TMAX*9./5.+32.
      TMIN=TMIN*9./5.+32.
      END WHILE
      GO TO 99
  444 STOP
      END
$ENTRY
   0.0E0     0.0E0      0.0E0   44.37E0  1.086E-2  -2.23E-4  9.732E-3 -2.267E-4
 8.413E0   1.005E0      0.0E0   23.64E0 -3.512E-3  5.026E-5  3.666E-4 -4.282E-6
 10.93E0 9.256E-1 -6.025E-2   42.65E0  2.958E-4    0.0E0  3.943E-4     0.0E0
 10.94E0   1.389E0 -8.191E-2   42.18E0  2.458E-4    0.0E0  3.109E-5     0.0E0
 24.38E0  -1.140E0      0.0E0   37.67E0  6.733E-5    0.0E0  3.442E-4     0.0E0
C:
```

Appendix C

A MODIFIED VERSION OF VAN KEULEN'S (1975) CROP SIMULATION MODEL - PAPRAN

```
//SOILCSMP JOB '1163,HWCH,,T=2M,L=10,I=60',H.CUTFORTH
//*    CSMP WITH COSMOP PRE-PROCESSOR.
//CSMP  PROC OUTFILE=NULLFILE,OUTVOL=USER03,NOSET='&&NOSET',
//         SIZE=256K
//PRE EXEC PGM=COSMOP,REGION=150K
//STEPLIB DD DSN=MILLS.#0261.LIB,DISP=SHR
//FT05F001 DD DDNAME=SYSIN
//FT06F001 DD SYSOUT=A
//FT08F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1)),
//  DCB=(RECFM=FB,LRECL=80,BLKSIZE=6080),DISP=(NEW,PASS)
//CSMP1     EXEC PGM=DEJCSMP2,REGION=&SIZE
//COMPRINT DD SYSOUT=A
//FT01F001 DD DSN=*.PRE.FT08F001,DISP=(OLD,DELETE)
//FT02F001 DD SYSOUT=B,DCB=(RECFM=F,BLKSIZE=80)
//FT05F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1)),
//            DCB=(RECFM=FB,LRECL=80,BLKSIZE=4000)
//FT06F001 DD SYSOUT=A,DCB=(RECFM=FBA,LRECL=133,BLKSIZE=1330)
//FT07F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1)),
//            DCB=(RECFM=FB,LRECL=80,BLKSIZE=4000)
//FT13F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1)),
//            DCB=(RECFM=VS,LRECL=204,BLKSIZE=208)
//FT14F001 DD UNIT=SYSDA,SPACE=(CYL,(1,1)),
//            DCB=(RECFM=VS,LRECL=204,BLKSIZE=208)
//FT15F001 DD DSN=&OUTFILE,UNIT=DISK,VOL=SER=&OUTVOL,
//            DISP=(MOD,KEEP),SPACE=(CYL,(1,1))
//STEPLIB  DD DSN=SYS4.CSMP.LOADM,DISP=SHR
//SYSLIB   DD DSN=SYS4.CSMP.LOADM,DISP=SHR
//         DD DSN=SYS2.FORTLIB,DISP=SHR
//SYSLIN   DD UNIT=SYSDA,SPACE=(CYL,(1,1)),DCB=BLKSIZE=3200,
//            DISP=(MOD,PASS)
//SYSLINK  DD DISP=(MOD,PASS),VOL=REF=*.SYSLIN,DSN=*.SYSLIN
//         DD DSN=SYS4.CSMP.SYMBM(CTLCDS),DISP=SHR
//SYSLMOD  DD UNIT=SYSDA,SPACE=(CYL,(1,1,1)),DSN=&NOSET(DEJEXE),
//            DISP=(MOD,PASS)
//SYSPRINT DD SYSOUT=A
//SYSUT1   DD UNIT=DISK,SPACE=(CYL,(1,1))
//       PEND
//  EXEC CSMP,SIZE=300K
//PRE.SYSIN DD *
C:
```

```
******************************************************************************
*                                                                            *
*                                   PAPRAN                                   *
*                                 ------------                               *
*        PRODUCTION OF ANNUAL PASTURES LIMITED BY RAIN AND NITROGEN          *
*** WARNING ***** THIS MODEL IS STILL IN AN EXPERIMENTAL PHASE ,MARCH 1976 *****
*                                                                            *
*          DEPARTMENT OF  THEORETICAL PRODUCTION ECOLOGY                     *
*                    AGRICULTURAL UNIVERSITY,WAGENINGEN                      *
*                                                                            *
******************************************************************************
*                                                                            *
*                              INPUT DIMENSIONS                              *
*                                                                            *
*     TEMPERATURE               DEGREE C                                     *
*     WINDSPEED           IN    M/S             SET    C06=1.                *
*     WINDSPEED           IN    MILE/H          SET    C06=.445              *
*     WINDSPEED           IN    KM/DAY          SET    C06=.0116             *
*     WINDSPEED           IN    KM/H            SET    C06=.278              *
*     RADIATION                 CAL/CM**2.DAY                                *
*     HOURS OF SUNSHINE         H/DAY                                        *
*     RAINFALL            IN    MM/DAY          SET    C09=1.157E-5          *
*     RAINFALL            IN    IN/DAY          SET    C09=29.388E-5         *
*                                                                            *
*     IN CASE NO RADIATION IS AVAILABLE,PUT IN HOURS OF SUNSHINE             *
*     RADIATION INPUT, SET SWRASU=1.   HOURS OF SUNSHINE INPUT, SET SWRASU=0. *
*     IN CASE NO DEW POINT TEMPERATURE IS AVAILABLE,PUT IN RELATIVE HUMIDITY *
*     DEW POINT TEMPERATURE TWICE A DAY     SET    SWDPRH=-1.                *
*     DEW POINT TEMPERATURE ONCE A DAY      SET    SWDPRH=0.                 *
*     RELATIVE HUMIDITY                     SET    SWDPRH=1.                 *
*                                                                            *
******************************************************************************
*                                                                            Q
*                        INTERNAL BASIC DIMENSIONS USED                      *
*                                                                            *
*     LENGTH                    M   (METER)                                  *
*     TIME                      S   (SECOND)                                 *
*     MASS                      KG  (KILOGRAM)                               Q
*     ENERGY                    J   (JOULE)                                  *
*     TEMPERATURE               C   (CENTIGRADE)                             *
*     PRESSURE                  PA  (PASCAL)                                 Q
*                                                                            *
******************************************************************************
*                                                                            *
*                           OUTPUT DIMENSIONS USED                           *
*                                                                            *
*     MOISTURE                          MM                                   *
*     PRODUCTION                        KG/HA                                *
*     EVAPORATION AND TRANSPIRATION     MM/DAY                               *
*                                                                            *
******************************************************************************

C:
```

```
*                           LIST OF VARIABLES
*                           -----------------

* A      = RUN OFF FACTOR
* ADBIOM = DEATH BIOMASS ATTACHED TO PLANTS,KG/M**2
* AEPER  = RATIO OF ACTUAL AND POTENTIAL EVAPOTRANSPIRATION
* AEVAP  = ACTUAL RATE OF EVAPORATION,MM/S
* AGR    = ACTUAL GROWTH RATE
* ALPHA  =  REDUCTION FACTOR FOR TRANSPIRATION
* ALPHAT = PROPORTIONALITY FACTOR AS FUNCTION OF LAI AND RADIATION INTENSITY
* ALPHT  =
* APTRAN = ACTUAL POTENTIAL TRANSPIRATION,CORRECTED FOR DEVELOPMENT STAGE,MM/S
* ATB    = RELATION BETWEEN SOIL COVER AND RUN OFF COEFFICIENT
* AW     = AVAILABLE AMOUNT OF WATER IN SOIL COMPARTMENT,MM
*
* B      = SURFACE STORAGE CAPACITY,MM
* BIOM   = TOTAL AMOUNT OF VEGETATION,KG/M**2
*
* C01    = CONSTANT TEMPERATURE,K=273.+C
* C02    = CONVERSION FACTOR TIME,=86400. S/DAY
* C03    = CONVERSION FACTOR TIME,=365 DAY/YEAR
* C04    = CONVERSION FACTOR TIME,=3600. S/HR
* C05    = CONVERSION FACTOR ENERGY,=4.1868 CAL/J
* C06    = CONVERSION FACTOR VELOCITY,=.278 (M/S)/(KM/HR)
* C07    = CONVERSION FACTOR PRESSURE,=133.322 PA/MM HG
* C09    = CONVERSION FACTOR RATE  ,=1.157E-5, (MM/S)/(MM/DAY)
* C14    = CONVERSION FACTOR LENGTH,=100. CM/M
* C15    = CONVERSION FACTOR AREA,=10000. CM**2/M**2
* CONFS  = CONVERSION EFFICIENCY, 0.75
* CSRR   = CURRENT SHOOT/ROOT RATIO I.E.DIVISION OF NEW MATERIAL BETWEEN
*          ABOVE AND BELOW GROUND PARTS
* CSRRT  = CSRR AS A FUNCTION OF DVS
*
* DAY    = SIMULATION DAY
* DAYL   = EFFECTIVE DAYLENGTH,S
* DAYLT  = EFFECTIVE DAYLENGTH AS FUNCTION OF DAYY AND LATITUDE,HR
* DAYY   = DAYNUMBER,DAYY=1. IS FIRST OF JANUARI
* DBIOM  = DEAD BIOMASS(KG/M**2
* DCAUSE = INDICATOR FOR DYING,1-NITROGEN SHORTAGE,2-WATER SHORTAGE,3-SENESCENC
* DDRM   = DBIOM,KG/HA
* DELT   = TIME INTERVAL OF INTEGRATION,S
* DELTA  = SLOPE OF SATURATED VAPOR PRESSURE CURVE AT AIR TEMPERATURE
* DGRCL  = DAILY TOTAL GLOBAL RADIATION WITH CLEAR SKY,J/M**2
* DGROV  = DAILY TOTAL GLOBAL RADIATION WITH OVERCAST SKY,J/M**2
* DGRRT  = GROWTH RATE OF THE ROOTS UNDER OPTIMAL CONDITIONS,MM/S
* DPT    = AVERAGE DEW POINT TEMPERATURE,C
* DPTA   = AVERAGE DEW POINT TEMPERATURE AT DAYTIME,C
* DPTT   = DPT AS A FUNCTION OF DAY,C
C:
```

```
*  DPT2   = DEW POINT TEMPERATURE AT 2 IN THE AFTERNOON,C
*  DPT8   = DEW POINT TEMPERATURE AT 8 IN THE MORNING,C
*  DP2T   = DPT2 AS A FUNCTION OF DAY,C
*  DP8T   = DPT8 AS A FUNCTION OF DAY,C
*  DRF..  = INITIAL DRYNESS FACTOR OF CONSECUTIVE COMPARTMENTS AS A FRACTION
*           OF MOISTURE CONTENT AT WILTINGPOINT
*  DTGAS  = HOURLY TOTALS OF GROSS ASSIMILATION AS A FUNCTION OF RADIATION
*           INTENSITY AND LAI,KG CH2O/M**2
*  DTMPA  = AIR TEMPERATURE 10 DAYS AGO,C
*  DTR.   = DAILY TOTAL RADIATION,J/M**2
*  DTRT   = DTR AS A FUNCTION OF DAY,CAL/CM**2.DAY
*  DVR.   = RATE OF DEVELOPMENT,/S
*  DVRT.  = RELATION BETWEEN DEVELOPMENT RATE AND TEMPERATURE
*  DVS    = DEVELOPMENT STAGE OF THE VEGETATION AS A FRACTION,DVS=1. IS RIPENESS
*
*  EA     = CONTRIBUTION OF DRYING POWER OF THE ATMOSPHERE TO EVAPORATIVE
*           DEMAND,J/M**2.S
*  EAVT   = AVERAGE TEMPERATURE AT DAYTIME,C
*  EB..   = CUMULATIVE ER..
*  EDPTFT = RELATION BETWEEN SOIL MOISTURE AND EFFECTIVINESS OF ROOTS
*  ELWR   = OUTGOING LONG WAVE RADIATION AT DAYTIME,J/CM**2.S
*  ENGR   = RATE OF EMPTYING OF TEMPERATURESUM WHEN NO SEEDS ARE GERMINATING,C/S
*  ENGRS  = SWITCH PARAMETER TO INDICATE END OF GROWING SEASON
*  ER..   = EVAPORATION RATE,MM/S
*  ERLB   = EFFECTIVE ROOTING LENGTH,M
*  EVAP   = PENMAN EVAPORATION,MM/S
*  EVAPO  = EVAP,MM/DAY
*
*  FCL.   = FRACTION OF THE DAY THAT IS CLEAR
*  FDAYY  = FIRST DAY OF SIMULATION,1 JANUARY IS DAY 1
*  FLDCP  = FIELD CAPACITY SOIL,DM**3/M**3
*  FLTRT  = RELATION BETWEEN LAI AND FRACTION OF ENERGY REACHING THE SOIL
*           SURFACE CALCULATED ACCORDING TO INTERCEPTION =1.-EXP(-.5*LAI)
*           THIS HOLDS FOR SPHERICAL LEAF DISTRIBUTIONS
*  FOV    = FRACTION OF THE DAY THAT IS OVERCAST
*  FRLT   = FRACTION OF LIGHT TRANSMITTED THROUGH VEGETATION
*
*  GAMMA  = PSYCHROMETER CONSTANT,PA  (65.328)
*  GMD    = DAY OF GERMINATION OF THE CROP
*  GROWTR = GROWTH RATE SHOOT,KG/M**2.S
*  GRRT   = GROWTH RATE OF THE ROOT,M/S
*  GRRWT  = GROWTH RATE ROOT,KG/M**2.S
*  GRS    = GROWTH RATE OF THE SEEDS,KG/M**2.S
*
*  HNOT   = NET RADIATION,J/M**2.S
*  HRAD   = RADIATION INTENSITY,CAL/CM**2.HR
*  HZERO  = ENERGY AVAILABLE FOR EVAPORATION,J/M**2.S
*
C:
```

```
*  IBIOM  = INITIAL AMOUNT OF BIOMASS PRESENT AFTER ESTABLISHMENT,KG/M**2
*  INFR   = RATE OF INFILTRATION,MM/S
*  IRTD   = INITIAL ROOTING DEPTH,M
*  IRWT   = INITIAL ROOT WEIGHT,KG/M**2
*  ITAG.  = STATUS VARIABLE USED IN TWOVAR FUNCTION
*
*  LAI    = LEAF AREA INDEX,M**2/M**2
*  LAI.TB = SET OF Z-VALUES IN TWOVAR FUNCTION
*  LAGRTR = RATE OF LEAF AREA GROWTH,M**2/M**2.S
*  LAT.TB = SET OF Z-VALUES IN TWOVAR FUNCTION
*  LBIOM  = LIVING BIOMASS ,KG/M**2 (= VBIOM)
*  LDRM   = LBIOM,KG/HA
*  LFARR  = LEAF AREA RATIO,M**2/KG
*  LFARRT = RELATION BETWEEN LEAF AREA RATIO AND TEMPERATURE
*  LFI    = INITIAL LEAF AREA,M**2/M**2
*  LFOV   = LIMITED FOV
*  LHVAP  = HEAT OF VAPORISATION OF WATER,.1*J/MM  (247.02)
*  LMBIOM = LIMITING BIOMASS TO BE CONSIDERED,KG/M**2
*  LRF    = FACTOR ACCOUNTING FOR LOCAL RUN-OFF/RUN-ON,NEG.IS ON RUN-OFF AREA
*  LRNON  = EFFECT OF LOCAL RUN-OFF/RUN-ON SITUATIONS
*  LWR    = OUTGOING LONG WAVE RADIATION,J/M**2.S
*
*  MAINT  = LOSS BY MAINTENANCE RESPIRATION,KG/S
*  MAW..  = MAXIMUM AVAILABLE WATER  IN COMPARTMENT, MM
*  MAXBIO =
*  MNT    = MINIMUM TEMPERATURE,C
*  MNTT   = MNT AS A FUNCTION OF DAY
*  MRESF  = MAINTENANCE RESPIRATION FACTOR,PERC/S  (2.31E-7)
*  MW     = MAXIMUM WATER CONTENT IN SOIL COMPARTMENT,MM
*  MWRTD  = MAXIMUM AMOUNT OF WATER TO BE STORED IN ROOTED DEPTH,MM
*  MXRTD  = MAXIMUM DEPTH OF ROOTING,M
*  MXT    = MAXIMUM TEMPERATURE,C
*  MXTT   = MXT AS A FUNCTION OF DAY
*  MW..   = MAXIMUM AMOUNT OF WATER IN A COMPARTMENT, MM
*
*
*  PDTGAS = POTENTIAL DAILY GROSS ASSIMILATION,KG CH2O/M**2
*  PDTGR  = POTENTIAL DAILY GROWTH,KG/M**2
*  PEVAP  = POTENTIAL EVAPORATION AS A FUNCTION OF SOIL COVER,MM/S
*  PLBIOM = LIVING BIOMASS 1 TIME STEP AGO,KG/M**2
*  PROP   = PROPORTIONALITY FACTOR FOR DIVISION OF SOIL WATER EVAPORATION OVER
*           VARIOUS COMPARTMENTS
*  PTRAN  = POTENTIAL TRANSPIRATION RATE,MM/S
*  PTRANS = PTRAN,MM/DAY
*  PUSHD  = VARIABLE TO KILL THE VEGETATION AFTER DROUGHT PERIOD
*  PUSHG  = VARIABLE TO INITIALISE BIOMASS AT MOMENT OF ESTABLISMENT
*  PUSHS  = VARIABLE TO START THE FILLING OF THE TENPERATURE SUM FOR GERMINATION
*
C:
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*  RA     = RESISTANCE TO WATER VAPOUR DIFFUSION FROM THE LEAF TO THE ATM.,S/M
*  RADT   = TOTAL DAILY VISIBLE RADIATION AS A FUNCTION OF LATITUDE AND DAY OF
*           THE YEAR,J/M**2
*  RAIN   = RAIN INTENSITY,MM/S
*  RAINTB = RAIN AS A FUNCTION OF DAY,MM/DAY
*  RAWR.. = RELATIVE AMOUNT OF WATER AVAILABLE FOR THE ROOTS
*  RCST   = RATE OF CHANGE OF SOIL TEMPERATURE,C/S
*  RDNG   = RATE OF DYING OF BIOMASS,KG/M**2.S
*  RDNGB  = RATE OF DYING OF BIOMASS,KG/M**2.S
*  RDRD   = RELATIVE DEATH RATE CAUSED BY COMPLETION OF DEVELOPMENT,/S
*  RDRDT  = RDRD AS A FUNCTION OF DVS
*  RDR    = RELATIVE DEATH RATE ,/S
*  RDRW   = RELATIVE DEATH RATE AS A RESULT OF WATER SHORTAGE,/S
*  RDRWD  = RELATIVE DEATH RATE TO EITHER WATER SHORTAGE OR SENESCENCE
*  RDRWT  = RDRW AS A FUNCTION OF RWRB8
*  REDFD  = REDUCTION FACTOR FOR EVAPORATION DUE TO DRYING OF THE SOIL
*  REDFDT = RELATION BETWEEN FRACTION OF POTENTIAL EVAPORATION AND DIMENSIONLESS
*           WATER CONTENT IN TOP COMPARTMENT
*  REDTTB = RFRGT AS A FUNCTION OF TS
*  REFCF  = REFLECTION COEFFICIENT OF WATER   (.05)
*  REFT   = REFERENCE TEMPERATURE FOR RESPIRATION, 25C
*  RELH   = RELATIVE HUMIDITY FRACTION
*  RELHT  = RELH AS A FUNCTION OF DAY
*  RFDVS  = REDUCTION FACTOR FOR TRANSPIRATION
*  RFDVST = RFDVS AS A FUNCTION OF DVS
*  RFRGT  = RELATIVE GROWTH RATE OF ROOTS  AS AFFECTED BY TEMPERATURE
*  RHOCP  = VOLUMETRIC HEAT CAPACITY OF THE AIR,J/M**3.C  (1195.48)
*  RLBIOM =
*  ROSPT  = RELATION BETWEEN SALT CONCENTRATION (KG/M**2.MM) AND REDUCTION IN
*           TRANSPIRATION DUE TO OSMOTIC PRESSURE,USDA-HANDBOOK 60.
*  RRNOFF = RATE OF RUNOFF ,MM/S
*  RS     = STOMATAL RESISTANCE,S/M
*  RTD    = ROOTING DEPTH,M
*  RTL..  = ROOTING LENGTH,M
*  RTWGHT = WEIGHT OF THE ROOTS,KG/M**2
*  RWFB.. = RATE OF WATER FLOW AT THE BOTTOM OF THE COMP.,MM/S
*  RWRB.. = RELATIVE AMOUNT OF WATER AVAILABLE IN THE ROOTING ZONE
*
*  SDAY   = DAY OF SEEDING
*  SDWT   = WEIGHT OF THE SEED,KG/M**2
*  SEEDW  = SEED WEIGHT, KG/HA
*  SLOP   = DELTA FOR DAYTIME
*  STDAY  = FIRST DAY OF SIMULATION,=1
*  SUN    = SUNSHINE,S
*  SUNTB  = SUN AS A FUNCTION OF DAY,HR/DAY
*  SVPA   = AVERAGE SATURATED VAPOR PRESSURE IN THE AIR,PA
*  SVPAM  = SATURATED VAPOR PRESSURE IN THE AIR AT DAYTIME,PA
*  SW     = AMOUNT OF AVAILABLE WATER IN UPPER 10 CM OF SOIL
C:
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*  SWDPRH = SWITCH PARAMETER,-1=DEW POINT TEMP.TWICE A DAY,0=DEW POINT TEMP.
*           ONCE A DAY,1=RELATIVE HUMIDITY INPUT
*  SWP..  = SWITCH PARAMETER,=1 IF THE ROOT FRONT IS IN A COMPARTMENT WITH
*           MOISTURE CONTENT ABOVE WILTING POINT,OTHERWISE =0
*  SWPB.. = CUMULATIVE SUM OF SWP..
*  SWRASU = SWITCH PARAMETER,0=HOURS OF SUNSHINE,1=RADIATION INPUT
*
*  TAU2   = DELAY TIME,S
*  TCK    = THICKNESS OF CONSECUTIVE COMPARTMENTS,M
*  TDB    = TOTAL DEPTH AT THE BOTTOM OF THE COMPARTMENT,M
*  TDRAIN = WATER LOST BY DEEP DRAINAGE BELOW DEPTH OF 1.80M
*  TDRWT  = TOTAL DRY WEIGHT,KG/M**2
*  TEC    = TEMPERATURE EFFECT ON ROOT CONDUCTIVITY
*  TECT   = RELATION BETWEEN SOIL TEMPERATURE AND ROOT CONDUCTIVITY,HERE USED
*           AS A FACTOR TO REDUCE POTENTIAL TRANSPIRATION.TABLE IS DERIVED FROM
*           MAIZE MEASUREMENTS IN PHOTOSROOM (72)
*           ALL TEMPERATURES ARE DECREASED BY 15 DEGREES
*  TEFR   = TEMPERATURE EFFECT ON RESPIRATION
*  TEVAP  = TOTAL SURFACE EVAPORATION,MM
*  TGRWTH = TOTAL GROWTH RATE,KG/M**2.S
*  TMPA   = AVERAGE DAILY AIR TEMPERATURE,C
*  TMPSUM = TEMPERATURE SUM FROM THE ONSET OF GERMINATION,C
*  TMPSMI = TEMPERATURE SUM INITIAL,C
*  TOTINF = TOTAL AMOUNT OF WATER INFILTRATED,MM
*  TOTRAN = ACCUMULATED TRANSPIRATION OVER GROWING SEASON,MM
*  TPEVAP = TOTAL POTENTIAL EVAPOTRANSPIRATION,MM
*  TR..   = TRANSPIRATION RATE,MM/S
*  TRAIN  = TOTAL SEASONAL RAINFALL,MM
*  TRAN   = ACTUAL RATE OF TRANSPIRATION,MM/S
*  TRANS  = TRAN,MM/DAY
*  TRB..  = CUMULATIVE SUM OF TRR..,MM/S
*  TRPMM  = POTENTIAL TRANSPIRATION RATE PER M ROOT LENGTH IN WET SOIL,MM/M
*  TRR    =
*  TS     = AVERAGE SOIL TEMPERATURE,C
*  TSI    = INITIAL VALUE OF SOIL TEMPERATURE,C
*  TSUMG  = TEMPERATURE SUM NEEDED FOR GERMINATION,C  (150.)
*
*  VPA.   = AVERAGE VAPOR PRESSURE IN THE AIR,PA
*
*  W      = TOTAL AMOUNT OF WATER IN SOIL COMPARTMENT,MM
*  WCLIM  = LOWEST WATER CONTENT THAT CAN BE REACHED IN A SOIL COMPARTMENT,IS
*           EQUIVALENT TO AIR DRY,DM**3/M**3
*  WCPR   = DIMENSIONLESS WATER CONTENT IN TOP COMPARTMENT
*  WLTPT  = WILTING POINT SOIL,DM**3/M**3
*  WRED   = REDUCTION FACTOR FOR WATER UPTAKE
*  WREDT  = RELATION BETWEEN AVAILABLE WATER IN THE SOIL AND THE REDUCTION IN
*           WATER UPTAKE,RESULTING IN A REDUCED TRANSPIRATION
*  WSA    = WSR AT DAYTIME,M/S
C:
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*  WSR    = MEASURED WINDSPEED,M/S
*  WSTB   = WSR AS A FUNCTION OF DAY,M/S
*  WTOT   = TOTAL AMOUNT OF WATER IN THE PROFILE,MM
*  WUSEFF = WATER USE EFFICIENCY IN KG DRY MATTER PER MM WATER TRANSPIRED

********************************************************************************
*                                                                              *
TITLE SIMULATION OF PRODUCTION OF ANUAL PASTURES LIMITED BY RAIN AND NITROGEN
/      EXTERNAL AND
INITIAL

PROCEDURE TSI,MW1,MW2,MW3,MW4,MW5,MW6,MW7,MW8,IW1,IW2,IW3,IW4,IW5,    ...
          IW6,IW7,IW8,LFI,IRWT=INPRO(STDAY)
      TSI = 5.*(AFGEN(MXTT,STDAY)+AFGEN(MNTT,STDAY))
      MW'1,8'=FLDCP'1,8'*TCK'1,8'
*     IW'1,8'=DRF'1,8'*WLTPT*TCK'1,8'
      IW'1,8'=FLDCP'1,8'*TCK'1,8'
      MAW'1,8'=MW'1,8'-TCK'1,8'*WLTPT'1,8'
      IRWT=IBIOM
      LFI=13.3*IBIOM
      WCLIM'1,8'=WLTPT'1,8'*.333
ENDPRO

STORAGE LAT1TB(10),RADT(10),LAI1TB(6),ALPHT(6)
STORAGE LAI2TB(6),DTGAS(6)
FIXED ITAG1,ITAG2,ITAG4
       SINLAT = SIN(50./180. * 3.1416)
       COSLAT = COS(50./180. * 3.1416)

DYNAMIC

*                              TIMER VARIABLES

      DAY=AINT(STDAY+TIME/C02)
      DAYY = AMOD(DAY+FDAYY,C03)

************************ SECTION 2 ***********************************

C:
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*                                  WEATHER
*                                 RADIATION
PROCEDURE DTR,TMPA,RAIN,DAYL=WEATHR(DAY,DAYY)
      SUN=C04*AFGEN(SUNTB,DAY)
*     DAYL=C04*TWOVAR(DAYLT1,9,LAT2TB,DAYLT,LAT,DAYY,ITAG3)
      DEC = -6.2832 * 23.4/360.* COS(6.2832 * (DAYY + 10.)/365.)
      DAYL = ACOS(.2079 - (SINLAT * SIN(DEC))/(COSLAT * COS(DEC)))   ...
             * 24./3.1416 * C04
      FCL1=SUN/DAYL
      DTR2=C05*C15/C02*AFGEN(DTRT,DAY)
      DGRCL=2.*C05*C15/C02*TWOVAR(RADT1,10,LAT1TB,RADT,LAT,DAYY,ITAG1)
      DGROV = 0.2*DGRCL
      FCL2= (DTR2-DGROV)/(DGRCL-DGROV+NOT(DGRCL-DGROV))
      FCL=INSW(SWRASU-.5,FCL1,FCL2)
      LFOV=LIMIT(0.,1.,1.-FCL)
      DTR1=FCL*DGRCL+LFOV*DGROV
      DTR=INSW(SWRASU-.5,DTR1,DTR2)

*                                TEMPERATURE

      MNT = AFGEN(MNTT,DAY)
      MXT = AFGEN(MXTT,DAY)
      TMPA = (MNT+MXT)/2.

*                                 WINDSPEED

      WSR=C06*AFGEN(WSTB,DAY)

*                                  HUMIDITY

      DPT=(5./9.)*(AFGEN(DPTT,DAY)-32.)
      SVPA=C07*4.58*EXP(17.4*TMPA/(TMPA+239.))
      VPA3=SVPA*AFGEN(RELHT,DAY)
      VPA2=C07*4.58*EXP(17.4*DPT/(DPT+239.))
      DPTA=.5*(AFGEN(DP8T,DAY)+AFGEN(DP2T,DAY))
      VPA1=C07*4.58*EXP(17.4*DPTA/(DPTA+239.))
      VPA=FCNSW(SWDPRH,VPA1,VPA2,VPA3)

*                                  RAINFALL

      RAIN=C09*AFGEN(RAINTB,DAY)
ENDPRO
      TRAIN = INTGRL(0.,RAIN)

*                     CALCULATION OF PENMAN EVAPORATION

      TPEVAP = INTGRL(0.,EVAP)
PROCEDURE EVAP=EPRO(DTR)
      DELTA = 17.4*SVPA*(1.-TMPA/(TMPA+239.))/(TMPA+239.)
      LWR=1.178E-7*C05*C15/C02*(TMPA+C01)**4*(.58-.00779*SQRT(VPA))* ...
          (1.-.9*LFOV)
      HZERO = DTR*(1.-REFCF)-LWR
      EA=.35*C15/(C07*C02)*(SVPA-VPA)*(.5+.54*WSR)*LHVAP
      EVAP =(HZERO*DELTA/GAMMA+EA)/(1.+DELTA/GAMMA) *1./(LHVAP*C15)
ENDPRO

************************ SECTION 3 **********************************

*                            SOIL WATER SECTION

      TOTINF = INTGRL(0.,INFR)
      INFR=RAIN
*      INFR = RAIN-RRNOFF+LRNON
*      RRNOFF = AMAX1(0.,A*(RAIN-B))
*      A = AFGEN(ATB,BIOM)
*      LRNON = LRF*RAIN
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C:

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      TDRAIN = INTGRL(0.,RWFB8)
      RWFB1=AMAX1(0.,INFR-(MW1-W1)/DELT)
      RWFB'2,8'=AMAX1(0.,RWFB'1,7'-(MW'2,8'-W'2,8')/DELT)
      W1=IW1+INTGRL(0.,INFR-RWFB1-TRR1-ER1)
      W'2,8'=IW'2,8'+INTGRL(0.,RWFB'1,7'                                ...
             -RWFB'2,8'-TRR'2,8'-ER'2,8')

      WTOT=SUM1(W'1,8')
     WTOT7=SUM1(W'1,7')

*                              TRANSPIRATION

      TOTRAN = INTGRL(0.,TRAN)
      TRAN=SUM1(TRR'1,8')
 PROCEDURE APTRAN,TRR1,TRR2,TRR3,TRR4,TRR5,TRR6,TRR7,TRR8,RTL1,RTL2,   ...
          RTL3,RTL4,RTL5,RTL6,RTL7,RTL8,TDB1,TDB2,TDB3,TDB4,TDB5,      ...
          TDB6,TDB7,TDB8,AW1,AW2,AW3,AW4,AW5,AW6,AW7,AW8=PTRPRO(LAI,   ...
          EVAP,DVS)
      AW'1,8'=AMAX1(0.,W'1,8'-TCK'1,8'*WLTPT'1,8')
      TDB1=TCK1
      TDB'2,8'=TDB'1,7'+TCK'2,8'
      RTL1=LIMIT(0.,TCK1,RTD)
      RTL'2,8'=LIMIT(0.,TCK'2,8',RTD-TDB'1,7')
      ERLB1=RTL1*AFGEN(EDPTFT,AW1/MAW1)
      ERLB'2,8'=ERLB'1,7'+RTL'2,8'*AFGEN(EDPTFT,AW'2,8'/MAW'2,8')
      HRAD = DTR*C04*C02/(C05*C15*DAYL)
      ALPHA=TWOVAR(ALPHT1,6,LAI1TB,ALPHT,LAI,HRAD,ITAG2)
      WSA=1.333*WSR
      EAVT = MXT-0.25*(MXT-MNT)
      SVPAM=C07*4.58*EXP(17.4*EAVT/(EAVT+239.))
      SLOP =17.4*SVPAM*(1.-EAVT/(EAVT+239.))/(EAVT+239.)
      RA=3.04E-3*SQRT(C02*C14)*SQRT(1./WSA)+20./WSA*AMIN1(1.,LAI)
      ELWR=1.178E-7*C05*C15/C02*(EAVT+C01)**4*(.58-.00779*SQRT(VPA))*...
           (1.-.9*LFOV)*DAYL/C02
      HNOT = 0.75*DTR-ELWR
      CC = 1./(SLOP +(RA+RS)/RA*GAMMA)
      PTRAN=CC*((1.-EXP(-.5*LAI))*HNOT*SLOP +ALPHA*LAI*RHOCP/RA*        ...
            (SVPAM-VPA)*DAYL/C02)/(LHVAP*C15)
      APTRAN = PTRAN*AFGEN(RFDVST,DVS)
      TRPMM = APTRAN/(ERLB8+NOT(ERLB8))
      TRR'1,8'=TRPMM*RTL'1,8'*AFGEN(TECT,TS)*AFGEN(WREDT,AW'1,8'        ...
               /MAW'1,8')
 ENDPRO

*                               EVAPORATION

      TEVAP = INTGRL(0.,EB8)
 PROCEDURE EB8,ER1,ER2,ER3,ER4,ER5,ER6,ER7,ER8=EVAPRO(LAI)
      VAR1=AMAX1(W1/TCK1-WCLIM1,0.)*EXP(-PROP*(0.+.5*TCK1))
      VAR'2,8'=AMAX1(W'2,8'/TCK'2,8'-WCLIM'2,8',0.)*EXP(-PROP*          ...
              (TDB'1,7'+.5*TCK'2,8'))
      SUM8=SUMX(VAR'1,8',TCK'1,8')
      PEVAP = .9*EVAP*AFGEN(FLTRT,LAI)
      WCPR = (W1/TCK1-WCLIM1)/(FLDCP1-WCLIM1)
      AEVAP = PEVAP * AFGEN(REDFDT,WCPR)
      ER'1,8'=AMIN1((W'1,8'-WCLIM'1,8'*TCK'1,8')/DELT,AEVAP*TCK'1,8'*...
              VAR'1,8'/(SUM8+NOT(SUM8)))
      EB8=SUM1(ER'1,8')
      AEPER = (TRAN+EB8)/(PEVAP+PTRAN+NOT(PEVAP+PTRAN))
 ENDPRO

*                            SOIL TEMPERATURE

      TS = 0.1*INTGRL(TSI,(TMPA-DTMPA)/DELT)
      DTMPA = DELAY(20,10.*C02,TMPA)+INSW(TIME-10.*C02,0.1*TSI,0.)


************************ SECTION 4 ************************************

C:
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*                             GROWTH OF THE CROP

*                                 GERMINATION

      TMPSUM = INTGRL(TMPSMI,(TS/DELT-ENGR-TMPSUM*PUSHD/DELT)*PUSHS)
      ENGR = INSW(TSUMG-TMPSUM,0.,INSW(SW,TS/DELT,0.))
      SW = AMAX1(W1-WLTPT1*TCK1,W2-WLTPT2*TCK2,W3-WLTPT3*TCK3)
      PUSHG =AND(TMPSUM-TSUMG,LMBIOM-LBIOM)*INSW(TIME-180.*C02,1.,0.)
      PUSHS=STEP(SDAY)

      GMD=INSW(DAY-300.,1.,0.)*INTGRL(0.,DAY*PUSHG/DELT-GMD*PUSHD/DELT)

*                       GROWTH OF STANDING VEGETATION

      LBIOM = INTGRL(0.,GROWTR+IBIOM*PUSHG/DELT-LBIOM*PUSHD/DELT-RDNGB)
PROCEDURE GROWTR,CSRR,WUSEFF,AGR,TGRWTH,GRS=GRPRO(LAI,DVS)
      PDTGAS=DAYL/(C04*C02*C15)*TWOVAR(DTGAS1 ,6,LAI2TB,DTGAS,LAI,    ...
            HRAD,ITAG4)*INSW(TMPA-5.,0.,INSW(TMPA-10.,(TMPA-5.)/5.,1.))
      TEFR = 2**((TMPA-REFT)/10.)
      MAINT = TDRWT*MRESF*TEFR
      CSRR = AFGEN(CSRRT,DVS)
      PDTGR = (PDTGAS-MAINT)*CONFS
      WUSEFF = PDTGR/(PTRAN+NOT(PTRAN))
      TGRWTH = TRAN*WUSEFF
      AGR=TGRWTH*X
      GRS=INSW(DVS-.5,0.,.8*AGR)
      GROWTR=AGR*CSRR-GRS
ENDPRO
      TDRWT= LBIOM+RTWGHT+SDWT

*                           *      DEAD BIOMASS

      DBIOM = INTGRL(0.,RDNGB+LBIOM*PUSHD/DELT)
      ADBIOM=INTGRL(0.,RDNGB-ADBIOM*PUSHD/DELT)
      RDNGB= RDR*LBIOM*(1.-PUSHD)
      RDR=AMAX1(RDRWD,RDRN)
      RDRWD=AMAX1(RDRW,RDRD)
      RDRW =1./C02*AFGEN(RDRWT,RWRB8)
*     MWRTD = RTD*(FLDCP-WLTPT)+NOT(RTD)
      MWRTD = INSW(RTD-.08,RTD*(FLDCP3-WLTPT3)+NOT(RTD),   ...
              .08*(FLDCP3-WLTPL3)+(RTD-.08)*(FLDCP4-WLTPT4))
      RDRD =1./C02*AFGEN(RDRDT,DVS)
      PUSHD =AND(PLBIOM-LMBIOM,LMBIOM-LBIOM)*INSW(TIME-85.*C02,1.,0.)
      PLBIOM =DELAY(10,DELT,LBIOM)
      LMBIOM =.2*MAXBIO
      RDRN =.3*(1.-SQRT(1.-Z*Z))/C02
      Z=1.-X
      X=1.
      RWRB8=SUM1(RAWR'1,8')
      RAWR'1,8'=RTL'1,8'/TCK'1,8'*AW'1,8'/MWRTD

      MAXBIO=INTGRL(IBIOM,RLBIOM)
      RLBIOM=AMAX1(0.,(LBIOM-PLBIOM)/DELT)

*                                LEAF AREA INDEX

      LAI= INTGRL(0.,LAGRTR+LFI*PUSHG/DELT-LAI*PUSHD/DELT-RDNGB*LAI/ ...
           (LBIOM+NOT(LBIOM)))
      LAGRTR = GROWTR*LFARR
      LFARR = AFGEN(LFARRT,TMPA)

*                       DEVELOPMENT OF THE VEGETATION

      DVS = INTGRL(0.,DVR-DVS*PUSHD/DELT)
      DVR =1./C02*AFGEN(DVRT ,TMPA)*INSW(LBIOM-IBIOM,0.,1.)*          ...
        (1.-PUSHD)*INSW(DVS-1.,1.,0.)

*                                 ROOT GROWTH
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C:

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      RTWGHT = INTGRL(0.,AGR*(1.-CSRR)+IRWT*PUSHG/DELT-RTWGHT*PUSHD/ ...
               DELT)

      RTD = INTGRL(0.,GRRT+IRTD*PUSHG/DELT-RTD*PUSHD/DELT)
      GRRT = SWPB8*DGRRT*RFRGT*2.                                ...
             *INSW(RTD-MXRTD,1.,0.)*INSW(DVS-.5,1.,0.)
      SWPB8=SUM1(SWP'1,8')
      SWP1=FCNSW(AW1,0.,0.,AND(RTD,TDB1-RTD))
      SWP'2,8'=FCNSW(AW'2,8',0.,0.,AND(RTD-TDB'1,7',TDB'2,8'-RTD))
      RFRGT = AFGEN(REDTTB,TS)

*                                   SEED GROWTH

      SDWT=INTGRL(0.,GRS)

*********************** SECTION 5 ************************************

*                                 OUTPUT AND RUN CONTROL

      ENGRS = AND(TIME-120.*C02,LMBIOM-LBIOM)
*     ENGRS = NOR(85.0*C02-TIME,1.0-DVS)
FINISH ENGRS=0.5,DVS=1.0

PROCEDURE EVAPO,PTRANS,TRANS,LDRM,DDRM,DRM,DCAUSE,         ...
          SEEDW=UITPRO(RDRN)
      EVAPO=C02*EVAP
      PTRANS=C02*PTRAN
      TRANS=C02*TRAN
      LDRM=C15*LBIOM
      DDRM=C15*DBIOM
      DRM=C15*BIOM
      SEEDW=C15*SDWT
      DCAUSE = INSW(RDRWD - RDRN, 1., INSW(RDRD - RDRW, 2., 3.))
ENDPRO
PRINT W'1,8',WTOT7,TRAIN,TPEVAP,TEVAP,TOTRAN,TRANS,DVS,WUSEFF,LAI,...
  RTD,GROWTR,RTWGHT,SEEDW,LDRM,DDRM,AGR,TGRWTH,RDNGB,DCAUSE,ENGR...
   ,GMD,DAY,PUSHG,PUSHD,RWRB8,RDR,RDRWD,RDRW,RDNGB,DVR,SW,...
     TMPSUM,EB8
METHOD RECT
TIMER FINTIM=21168000., PRDEL=432000.,DELT=86400., OUTDEL=432000.
PRTPLT WTOT(0.,1000.,DAY)
PRTPLT DRM(0., 10000.,DAY,DAYY)
PRTPLT LAI(0.,6.,DAY)
PRTPLT TS(0.,30.,DAY)
PRTPLT SEEDW(0.,6000.,DAY)
********************* SECTION 6 *************************************
*                        PARAMETERS AND FUNCTIONS
*                           CONSTANTS
INCON ITAG1 = 0, ITAG2 = 0,  ITAG4 = 0
*  TOTAL DAILY VISIBLE RADIATION (CAL/CM**2) AS A FUNCTION OF LATITUDE
*            AND DAY OF THE YEAR
FUNCTION RADT1 = 0.,340.,  15.,343.,  46.,360.,  74.,369.,         ...
             105.,364., 130.,349., 166.,337., 196.,342., 227.,357.,...
             258.,368., 288.,365., 319.,349., 349.,337., 365.,340.
FUNCTION RADT2 = 0.,295.,  15.,299.,  46.,332.,  74.,359.,         ...
             105.,375., 135.,377., 166.,374., 196.,375., 227.,377.,...
             258.,369., 288.,345., 319.,311., 349.,291., 365.,294
FUNCTION RADT3 = 0.,243.,  15.,249.,  46.,293.,  74.,337.,         ...
             105.,375., 135.,394., 166.,400., 196.,399., 227.,386,...
             258.,357., 288.,313., 319.,264., 349.,239., 365.,241.
FUNCTION RADT4 = 0.,185.,  15.,191.,  46.,245.,  74.,303.,         ...
             105.,363., 135.,400., 166.,417., 196.,411., 227.,384.,...
             258.,333., 288.,270., 319.,210., 349.,179., 365.,183.
FUNCTION RADT5 = 0.,124.,  15.,131.,  46.,190.,  74., 260.,        ...
             105.,339., 135.,396., 166.,422., 196.,413., 227.,369.,...
             258.,298., 288.,220., 319.,151., 349.,117., 365.,122.
FUNCTION RADT6 = 0., 67.,  15.,73.,   46.,131.,  74.,207.,         ...
             105.,304., 135.,380., 166.,418., 196.,405., 227.,344.,...
             258.,254., 288.,163., 319., 92., 349.,61.,  365.,66.
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FUNCTION RADT7 = 0., 18.,  15., 22.,  46., 72.,  74.,149.,       ...
                 105.,260., 135.,356., 166.,408., 196.,389., 227.,309.,...
                 258.,201., 288.,103., 319., 37., 349., 14., 365., 17.
FUNCTION RADT8 = 0.,  0.,  15.,  0.,  46., 20.,  74., 89.,          ...
                 105.,209., 135.,331., 166.,408., 196.,380., 227.,269.,...
                 258.,142., 288., 45., 319.,  2., 349.,  0., 365., 0.
FUNCTION RADT9 = 0.,  0.,             46.,  0.,  74., 28.,          ...
                 105.,162., 135.,334., 166.,424., 196.,380., 227.,248.,...
                 258., 81., 288.,  3., 319.,  0.,            365.,0.
FUNCTION RADT10 = 0.,0.,                                      74.,0.,...
                 105.,154., 135.,339., 166.,428., 196.,393., 227.,252.,...
                 258., 40., 288.,  0.,                       365.,0.
TABLE LAT1TB(1-10) = 0., 10., 20., 30., 40., 50., 60., 70., 80., 90.
FUNCTION REDFDT = 0.,.075, .05,.1, .1,.2, .2,.45, .25,.7,          ...
                 .4,.85, .5,.95, 1.,1.
CONSTANT GAMMA = 65.328
CONSTANT LHVAP = 247.02
CONSTANT REFCF = .05
CONSTANT REFT = 25.
CONSTANT RHOCP = 1195.48
CONSTANT STDAY = 0.
CONSTANT TMPSMI = 0.
CONSTANT C01 = 273.
CONSTANT C02 = 86400.
CONSTANT C03 = 365.
CONSTANT C04 = 3600.
CONSTANT C05 = 4.1868
CONSTANT C06 = .278
CONSTANT C07 = 133.322
CONSTANT C09 = 1.157E-5
CONSTANT C14 = 100.
CONSTANT C15 = 10000.
************************************************************************
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*  THE FOLLOWING FUNCTIONS AND PARAMETERS ARE DIFFERENT FOR DIFFERENT
*  CROPS, SOILS, LOCATIONS AND WEATHER CONDITIONS
*                            CROP
*  PROPORTIONALITY FACTOR ALPHA AS A FUNCTION OF LAI AND RADIATION
FUNCTION ALPHT1 = 0.,1., 100.,1.
FUNCTION ALPHT2 = 0.,1., 100.,1.
FUNCTION ALPHT3 =(  0.,.0  ),( 10.,.6  ),( 15.,.66 ),( 20.,.715),    ...
                 ( 25.,.76 ),( 30.,.795),( 35.,.835),( 40.,.87 ),    ...
                 ( 45.,.91 ),( 50.,.94 ),( 60.,.97 ),(100.,1.  )
FUNCTION ALPHT4 =(  0.,.0  ),( 10.,.425),( 15.,.515),( 20.,.585),    ...
                 ( 25.,.64 ),( 30.,.68 ),( 35.,.715),( 40.,.745),    ...
                 ( 45.,.77 ),( 50.,.795),( 60.,.845),(100.,.875)
FUNCTION ALPHT5 =(  0.,.0  ),( 10.,.39 ),( 15.,.455),( 20.,.505),    ...
                 ( 25.,.545),( 30.,.58 ),( 35.,.61 ),( 40.,.635),    ...
                 ( 45.,.66 ),( 50.,.685),( 60.,.74 ),(100.,.775)
FUNCTION ALPHT6 =(  0.,.0  ),( 10.,.35 ),( 15.,.41 ),( 20.,.45 ),    ...
                 ( 25.,.485),( 30.,.51 ),( 35.,.53 ),( 40.,.55 ),    ...
                 ( 45.,.565),( 50.,.585),( 60.,.61 ),(100.,.65 )
TABLE LAI1TB(1-6)= 0. , 0.2, 2.0, 3.5, 5.0, 10.0

*  HOURLY TOTALS OF GROSS ASSIMILATION IN KG CH2O/HA AS A FUNCTION OF
*  RADIATION INTENSITY AND LEAF AREA INDEX (WHEAT)

FUNCTION DTGAS1 =( 0., 0.  ),(100.,0.  )
FUNCTION DTGAS2 =( 0., 0.  ),( 5., 1.25),(10., 2.  ),(15., 2.5 ),    ...
                 (20., 3.  ),(25., 3.25),(30., 3.5 ),(40., 3.75),    ...
                 (50., 4.  ),(60., 4.25),(65., 4.3 ),(75., 4.5 )
FUNCTION DTGAS3 =( 0., 0.  ),( 5., 5.  ),(10., 9.5 ),(15.,12.5 ),    ...
                 (20.,15.  ),(25.,16.25),(30.,17.5 ),(40.,20.5 ),    ...
                 (50.,23.75),(60.,26.25),(65.,27.75),(75.,28.5 )
FUNCTION DTGAS4 =( 0., 0.  ),( 5., 6.25),(10.,10.75),(15.,14.75),    ...
                 (20.,17.5 ),(25.,20.  ),(30.,22.25),(40.,26.5 ),    ...
                 (50.,30.  ),(60.,33.75),(65.,35.  ),(75.,36.  )
FUNCTION DTGAS5 =( 0., 0.  ),( 5., 6.5 ),(10.,11.5 ),(15.,15.75),    ...
                 (20.,18.75),(25.,21.75),(30.,24.25),(40.,29.5 ),    ...
                 (50.,34.25),(60.,37.5 ),(65.,39.5 ),(75.,41.  )
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FUNCTION DTGAS6 =( 0., 0.  ),( 5., 8.75),(10.,16.25),(15.,22.75),    ...
                 (20.,28.75),(25.,33.75),(30.,38.  ),(40.,43.25),    ...
                 (50.,45.  ),(60.,46.25),(65.,47.5 ),(75.,50.  )
TABLE LAI2TB(1-6)= 0. , 0.2, 2.0, 3.5, 5.0, 10.0

FUNCTION EDPTFT = 0.,.15,.15,.6,.3,.8,.5,1.,1.,1.
FUNCTION RDRWT = -0.25,0.10, 0.,0.10, .1,.015, .25,.005,1.,0.005
FUNCTION RFDVST = 0.,1.,.9,1.,1.,0.,1.1,0.
FUNCTION WREDT = 0.,0.,.1,.30,.15,.45,.3,.7,.5,.975,.75,1.,1.,1.
FUNCTION CSRRT= 0.,0.3,0.1,0.4,0.25,0.5,0.5,0.65,0.75,0.75,1.,0.975, ...
      1.1,0.975
FUNCTION DVRT = 0.,0., 3.75,0.,  16.,0.01,  25.,0.0175, 40.,0.02
FUNCTION FLTRT = 0.,1.,0.5,.705,1.,0.496,1.5,0.384,2.,0.248,3.,0.134,...
        5.,0.03,8.,0.004,10.,0.001,15.,0.0001
FUNCTION LFARRT = 5.,11.5,10.,12.5,15.,13.0,20.,14.0,25.,15.0,30.,13.2
FUNCTION REDTTB = 5.,.8,10.,.9,15.,1.,20.,.97,25.,.97,30.,.97,50.,.97
FUNCTION TECT = 0.,0.06, 3.,0.29, 10.,0.85,                          ...
                              16.,0.94,20.,1.,31.,0.87,40.,0.6,50.,0.3
FUNCTION ROSPT=0.,1., 2.8E-1,1., 5.6E-1,.2, 1.12,0., 7.0,0.
FUNCTION MFRTT= 0.,.012, .5,.012, 3.,.005, 5.,.005

PARAMETER MRESF=2.31E-7
PARAMETER RS=159.84
PARAMETER CONFS=.75
PARAMETER DGRRT=.000000139
PARAMETER FDAYY=273.
PARAMETER IBIOM=.00503
PARAMETER IRTD=.101
PARAMETER TSUMG = 135.
PARAMETER TAU2=172800.
PARAMETER CF = 350.E-4
PARAMETER SDAY=864000.

*                                    SOIL

FUNCTION ATB=0.,0.,         10000.,0.
*          SET AT 0., HERE TO PREVENT THE OCCURENCE OF RUN OFF

PARAMETER B = 5.785E-5
PARAMETER DRF1=0.5,DRF2=0.75,DRF3=0.8,DRF4=0.9,DRF5=1.0,DRF6=1.0
PARAMETER DRF7=1.0,DRF8=1.2
PARAMETER FLDCP=230.
PARAMETER LRF = 0.
PARAMETER MXRTD=1.8
PARAMETER PROP=15.
PARAMETER TCK1=.02,TCK2=.03,TCK3=.05,TCK4=.2,TCK5=.3,TCK6=.3
PARAMETER TCK7=.3,TCK8=.6
PARAMETER WLTPT = 75.

*                                  WEATHER

FUNCTION WSTB=0.,5.0,365.,5.0
FUNCTION MNTT=0.,10.,365.,10.
FUNCTION MXTT=0.,20.,365.,20.
FUNCTION DP8T=0.,10.,365.,10.
FUNCTION DP2T=0.,10.,365.,10.
FUNCTION DPTT=0.,10., 365.,10.0
FUNCTION DTRT=0.,100., 365.,100.
FUNCTION SUNTB=0.,10.,365.,10.
FUNCTION RELHT=0.,.50, 365.,.50
FUNCTION RAINTB=0.,1.0,365.,1.0

PARAMETER SWDPRH=-1.
PARAMETER SWRASU=0.

*                                  LOCATION

PARAMETER LAT=0

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PARAMETER LAT=50.
PARAMETER FDAYY=121.
FUNCTION MXTT=                          ...
            0., 6.5,     1., 0.5,     2., 1.0,     3., 3.5,     4., 6.5,...
            5., 7.0,     6., 3.0,     7., 4.5,     8., 4.5,     9., 2.5,...
           10., 4.5,    11.,13.0,    12.,10.6,    13.,10.5,    14.,15.0,...
           15.,25.0,    16.,18.5,    17., 7.0,    18.,10.0,    19.,11.5,...
           20.,16.5,    21.,17.5,    22.,14.5,    23.,21.0,    24.,19.0,...
           25.,19.5,    26.,22.5,    27.,26.5,    28.,18.5,    29.,10.5,...
           30.,14.0,    31.,15.0,    32.,19.5,    33.,22.0,    34.,17.5,...
           35.,20.0,    36.,22.5,    37.,16.0,    38.,22.5,    39.,21.5,...
           40.,22.5,    41.,23.5,    42.,27.0,    43.,33.5,    44.,27.5,...
           45.,23.0,    46.,21.0,    47.,24.5,    48.,25.0,    49.,21.0,...
           50.,21.5,    51.,11.5,    52.,18.5,    53.,22.0,    54.,24.5,...
           55.,26.5,    56.,24.0,    57.,28.0,    58.,25.0,    59.,30.0,...
           60.,29.0,    61.,29.0,    62.,29.0,    63.,26.0,    64.,29.0,...
           65.,27.0,    66.,28.0,    67.,24.0,    68.,31.0,    69.,33.0,...
           70.,33.0,    71.,30.0,    72.,31.0,    73.,29.0,    74.,28.0,...
           75.,28.0,    76.,24.0,    77.,29.0,    78.,29.0,    79.,28.0,...
           80.,32.0,    81.,29.0,    82.,30.0,    83.,25.0,    84.,27.0,...
           85.,23.0,    86.,22.0,    87.,26.0,    88.,30.0,    89.,27.0,...
           90.,21.0,    91.,24.0,    92.,29.0,    93.,24.0,    94.,22.0,...
           95.,22.0,    96.,22.0,    97.,25.0,    98.,24.0,    99.,23.0,...
          100.,22.0,   101.,22.0,   102.,25.0,   103.,25.0,   104.,13.0,...
          105.,17.0,   106.,21.0,   107.,21.0,   108.,27.0,   109.,29.0,...
          110.,29.0,   111.,29.0,   112.,20.0,   113.,21.0,   114.,13.0,...
          115.,22.0,   116.,21.0,   117.,23.0,   118.,25.0,   119.,25.0,...
          120.,20.0,   121.,21.0,   122.,27.0,   123.,23.0,   124.,14.0,...
          125.,16.0,   126.,25.0,   127.,24.0,   128.,15.0,   129.,16.5,...
          130.,22.0,   131.,19.0,   132.,15.0,   133.,19.0,   134.,15.0,...
          135.,14.0,   136.,21.5,   137.,24.0,   138.,31.0,   139.,21.5,...
          140.,14.0,   141.,25.0,   142.,17.0,   143.,18.0,   144.,17.0,...
          145.,20.0,   146.,21.0,   147.,21.5,   148.,25.5,   149.,15.0,...
          150.,11.5,   151.,17.5,   152.,17.0,   153., 0.0,   154., 0.0
FUNCTION MNTT=                          ...
            0.,-1.0,     1.,-2.0,     2.,-3.5,     3.,-3.5,     4.,-2.0,...
            5.,-1.0,     6., 1.0,     7.,-1.0,     8.,-1.5,     9.,-0.5,...
           10.,-1.0,    11.,-1.0,    12., 1.5,    13., 4.0,    14., 2.0,...
           15.,10.5,    16.,14.6,    17., 1.5,    18.,-1.0,    19., 0.0,...
           20., 2.0,    21., 6.5,    22., 6.0,    23., 9.0,    24.,12.0,...
           25., 7.0,    26., 2.0,    27.,16.0,    28.,11.5,    29., 7.0,...
           30., 5.0,    31., 8.0,    32., 6.0,    33., 7.0,    34., 7.0,...
           35.,11.5,    36.,14.5,    37., 3.5,    38., 2.0,    39., 7.0,...
           40., 4.0,    41., 2.5,    42.,10.5,    43.,16.0,    44.,14.0,...
           45.,16.5,    46., 5.0,    47., 6.0,    48., 9.5,    49.,14.0,...
           50.,13.5,    51., 6.5,    52., 4.0,    53., 4.0,    54., 9.5,...
           55.,17.5,    56., 8.0,    57., 9.0,    58.,14.0,    59.,12.0,...
           60.,13.0,    61.,13.0,    62.,13.0,    63.,13.0,    64., 9.0,...
           65.,14.0,    66.,16.0,    67.,13.0,    68.,13.0,    69.,14.0,...
           70.,13.0,    71.,17.0,    72.,19.0,    73.,16.0,    74.,12.0,...
           75.,12.0,    76., 7.0,    77., 8.0,    78.,14.0,    79.,13.0,...
           80.,15.0,    81.,18.0,    82.,11.0,    83.,20.0,    84.,13.0,...
           85.,16.0,    86., 7.0,    87., 8.0,    88.,13.0,    89.,14.0,...
           90.,15.0,    91., 5.0,    92.,11.0,    93.,13.0,    94., 7.0,...
           95.,12.0,    96., 9.0,    97., 7.0,    98., 6.0,    99., 9.0,...
          100.,12.0,   101., 7.0,   102., 5.0,   103., 5.0,   104., 4.0,...
          105., 0.0,   106., 1.0,   107., 6.0,   108.,11.0,   109., 9.0,...
          110.,11.0,   111.,11.0,   112.,14.0,   113.,16.0,   114., 9.0,...
          115., 7.0,   116., 5.0,   117., 5.0,   118., 5.0,   119.,10.0,...
          120.,11.0,   121., 3.0,   122., 8.0,   123.,15.0,   124.,11.0,...
          125., 8.0,   126.,15.0,   127., 9.0,   128., 7.0,   129., 2.0,...
          130., 5.5,   131., 8.0,   132., 7.0,   133., 8.0,   134., 7.0,...
          135., 4.5,   136.,-1.5,   137., 7.5,   138., 6.5,   139.,17.0,...
          140., 5.0,   141., 7.0,   142., 4.0,   143., 0.0,   144.,-0.5,...
          145.,-0.5,   146., 3.0,   147., 4.0,   148., 5.5,   149., 7.5,...
          150., 4.0,   151., 3.5,   152., 0.0,   153., 0.0,   154., 0.0
FUNCTION RAINTB=                        ...
            0.,0.20,     1.,0.00,     2.,0.00,     3.,0.00,     4.,0.08,...
            5.,0.31,     6.,0.08,     7.,0.00,     8.,0.00,     9.,0.00,...
           10.,0.33,    11.,0.06,    12.,0.00,    13.,0.00,    14.,0.00,...
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          15.,0.08,  16.,0.00,  17.,0.00,  18.,0.00,  19.,0.00,...
          20.,0.40,  21.,0.01,  22.,0.04,  23.,0.00,  24.,0.00,...
          25.,0.00,  26.,0.00,  27.,4.17,  28.,0.95,  29.,0.83,...
          30.,0.24,  31.,0.03,  32.,0.00,  33.,0.10,  34.,0.02,...
          35.,0.00,  36.,0.00,  37.,0.19,  38.,0.00,  39.,0.00,...
          40.,0.00,  41.,0.00,  42.,0.00,  43.,0.00,  44.,0.00,...
          45.,0.04,  46.,0.01,  47.,0.00,  48.,0.01,  49.,0.00,...
          50.,0.94,  51.,0.00,  52.,0.00,  53.,0.00,  54.,0.00,...
          55.,0.00,  56.,0.00,  57.,0.55,  58.,0.00,  59.,0.00,...
          60.,0.00,  61.,0.00,  62.,0.00,  63.,0.05,  64.,0.00,...
          65.,0.00,  66.,0.00,  67.,0.00,  68.,0.00,  69.,0.00,...
          70.,0.00,  71.,0.00,  72.,0.00,  73.,0.15,  74.,0.03,...
          75.,0.30,  76.,0.00,  77.,0.00,  78.,0.00,  79.,0.10,...
          80.,0.00,  81.,0.00,  82.,0.00,  83.,0.36,  84.,0.00,...
          85.,0.00,  86.,0.00,  87.,0.00,  88.,0.00,  89.,0.40,...
          90.,0.00,  91.,0.00,  92.,0.30,  93.,0.10,  94.,0.45,...
          95.,0.00,  96.,0.00,  97.,0.00,  98.,0.00,  99.,0.03,...
         100.,0.00, 101.,0.00, 102.,0.00, 103.,0.13, 104.,0.13,...
         105.,0.00, 106.,0.00, 107.,0.00, 108.,0.00, 109.,0.00,...
         110.,0.00, 111.,0.00, 112.,0.55, 113.,0.45, 114.,0.13,...
         115.,0.00, 116.,0.00, 117.,0.00, 118.,0.00, 119.,0.13,...
         120.,0.00, 121.,0.00, 122.,0.25, 123.,0.65, 124.,0.00,...
         125.,0.00, 126.,0.00, 127.,0.00, 128.,0.00, 129.,0.00,...
         130.,0.00, 131.,0.17, 132.,0.00, 133.,0.15, 134.,0.00,...
         135.,0.00, 136.,0.00, 137.,0.00, 138.,0.00, 139.,0.00,...
         140.,0.00, 141.,0.00, 142.,0.00, 143.,0.00, 144.,0.00,...
         145.,0.00, 146.,0.00, 147.,0.00, 148.,0.00, 149.,0.00,...
         150.,0.00, 151.,0.00, 152.,0.00, 153.,0.00, 154.,0.00
FUNCTION DPTT=           ...
          0.,36.0,   1.,30.5,   2.,25.5,   3.,28.5,   4.,32.0,...
          5.,32.5,   6.,38.0,   7.,35.0,   8.,32.0,   9.,33.5,...
         10.,32.5,  11.,36.0,  12.,35.0,  13.,41.0,  14.,36.0,...
         15.,46.0,  16.,60.0,  17.,35.0,  18.,32.0,  19.,38.0,...
         20.,40.0,  21.,44.5,  22.,43.0,  23.,45.5,  24.,48.5,...
         25.,51.0,  26.,50.0,  27.,53.5,  28.,54.0,  29.,46.5,...
         30.,41.5,  31.,47.0,  32.,48.5,  33.,54.0,  34.,46.0,...
         35.,54.0,  36.,57.0,  37.,47.0,  38.,47.0,  39.,54.0,...
         40.,51.0,  41.,46.0,  42.,55.0,  43.,58.0,  44.,57.0,...
         45.,57.0,  46.,51.0,  47.,49.5,  48.,55.5,  49.,55.0,...
         50.,59.5,  51.,46.0,  52.,45.0,  53.,48.0,  54.,55.0,...
         55.,63.0,  56.,57.0,  57.,63.0,  58.,60.0,  59.,60.0,...
         60.,59.5,  61.,60.0,  62.,62.0,  63.,61.0,  64.,60.0,...
         65.,60.0,  66.,62.0,  67.,62.0,  68.,62.0,  69.,77.0,...
         70.,65.0,  71.,66.0,  72.,67.0,  73.,64.5,  74.,57.0,...
         75.,52.0,  76.,55.0,  77.,55.0,  78.,58.0,  79.,65.0,...
         80.,65.5,  81.,66.0,  82.,55.0,  83.,67.0,  84.,60.5,...
         85.,63.5,  86.,53.0,  87.,55.0,  88.,61.0,  89.,63.0,...
         90.,58.5,  91.,52.0,  92.,56.5,  93.,59.0,  94.,55.0,...
         95.,59.0,  96.,58.0,  97.,61.0,  98.,60.0,  99.,55.0,...
        100.,63.0, 101.,54.0, 102.,44.0, 103.,60.0, 104.,41.0,...
        105.,45.0, 106.,42.5, 107.,50.0, 108.,59.0, 109.,55.0,...
        110.,54.5, 111.,57.0, 112.,60.5, 113.,63.5, 114.,50.0,...
        115.,50.0, 116.,45.0, 117.,52.0, 118.,50.5, 119.,60.0,...
        120.,58.0, 121.,41.0, 122.,59.0, 123.,63.5, 124.,50.5,...
        125.,52.0, 126.,59.0, 127.,49.0, 128.,43.0, 129.,43.0,...
        130.,47.0, 131.,48.0, 132.,46.0, 133.,52.0, 134.,45.0,...
        135.,44.5, 136.,38.5, 137.,44.0, 138.,49.0, 139.,54.0,...
        140.,39.0, 141.,43.0, 142.,43.0, 143.,36.0, 144.,40.0,...
        145.,44.0, 146.,41.5, 147.,41.0, 148.,42.0, 149.,51.0,...
        150.,39.5, 151.,43.5, 152.,35.5, 153., 0.0, 154., 0.0
FUNCTION WSTB=           ...
          0.,17.7,   1.,23.2,   2.,17.1,   3., 4.9,   4., 7.2,...
          5.,10.6,   6., 9.7,   7.,16.3,   8.,12.6,   9.,15.1,...
         10.,16.4,  11., 9.3,  12.,10.9,  13., 9.8,  14., 8.5,...
         15.,19.7,  16.,19.6,  17.,13.5,  18., 9.5,  19., 6.4,...
         20.,11.0,  21., 9.4,  22., 3.7,  23.,11.1,  24.,14.8,...
         25.,10.5,  26., 4.5,  27., 8.8,  28.,12.3,  29.,17.5,...
         30., 8.9,  31.,11.4,  32., 6.5,  33., 9.4,  34., 7.8,...
         35.,13.1,  36.,14.0,  37., 8.9,  38., 5.9,  39., 8.5,...
         40., 9.2,  41., 5.5,  42.,16.1,  43.,22.4,  44., 9.3,...
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                  45., 9.6,  46., 7.7,  47., 5.7,  48.,11.6,  49.,10.0,...
                  50.,14.3,  51.,11.3,  52., 6.6,  53.,11.3,  54.,17.1,...
                  55.,11.5,  56.,10.6,  57., 6.7,  58.,11.7,  59., 7.1,...
                  60., 7.3,  61., 9.1,  62., 9.1,  63., 6.4,  64., 6.5,...
                  65., 6.9,  66.,18.0,  67.,11.0,  68., 8.4,  69., 7.6,...
                  70., 6.0,  71., 9.7,  72., 5.0,  73., 9.0,  74.,15.3,...
                  75., 8.0,  76., 5.4,  77.,10.5,  78., 7.2,  79., 4.6,...
                  80.,10.5,  81., 9.5,  82., 9.3,  83., 4.7,  84., 5.8,...
                  85., 7.4,  86., 4.8,  87., 8.0,  88.,11.3,  89., 7.0,...
                  90., 7.8,  91., 6.8,  92.,13.9,  93., 8.7,  94., 5.6,...
                  95., 5.8,  96., 5.1,  97., 7.7,  98., 8.4,  99., 6.6,...
                 100.,10.0, 101., 7.1, 102.,13.3, 103.,12.6, 104.,11.5,...
                 105., 4.0, 106., 4.6, 107., 4.6, 108., 5.3, 109., 4.0,...
                 110., 5.5, 111., 5.9, 112., 4.9, 113.,13.8, 114.,10.0,...
                 115., 8.3, 116., 5.1, 117., 5.3, 118., 9.2, 119., 6.6,...
                 120., 9.5, 121., 7.9, 122., 7.9, 123.,12.1, 124., 5.6,...
                 125., 6.2, 126., 8.9, 127.,14.8, 128., 7.5, 129., 6.0,...
                 130., 9.5, 131., 9.9, 132., 9.1, 133., 9.6, 134.,10.7,...
                 135., 8.9, 136.,10.0, 137., 8.4, 138.,11.8, 139.,15.1,...
                 140., 6.5, 141.,13.0, 142.,11.9, 143., 7.0, 144., 5.4,...
                 145., 7.2, 146.,10.0, 147., 8.1, 148., 9.0, 149., 5.6,...
                 150., 7.5, 151.,12.8, 152., 8.0, 153., 0.0, 154., 0.0
 FUNCTION DTRT=                           ...
               0.,350.0,   1.,350.0,   2.,350.0,   3.,350.0,   4.,350.0,...
               5.,350.0,   6.,350.0,   7.,350.0,   8.,350.0,   9.,350.0,...
              10.,350.0,  11.,350.0,  12.,350.0,  13.,350.0,  14.,350.0,...
              15.,350.0,  16.,350.0,  17.,350.0,  18.,350.0,  19.,350.0,...
              20.,350.0,  21.,350.0,  22.,350.0,  23.,350.0,  24.,350.0,...
              25.,350.0,  26.,350.0,  27.,350.0,  28.,500.0,  29.,500.0,...
              30.,500.0,  31.,393.3,  32.,533.8,  33.,801.7,  34.,620.0,...
              35.,393.3,  36.,533.8,  37.,558.2,  38.,801.7,  39.,423.3,...
              40.,685.5,  41.,704.3,  42.,764.2,  43.,672.4,  44.,393.3,...
              45.,767.9,  46.,769.8,  47.,760.5,  48.,805.4,  49.,340.9,...
              50.,374.6,  51.,247.2,  52.,805.4,  53.,767.9,  54.,782.9,...
              55.,659.3,  56.,773.6,  57.,561.9,  58.,605.0,  59.,741.7,...
              60.,717.4,  61.,535.7,  62.,552.5,  63.,608.7,  64.,721.1,...
              65.,655.6,  66.,683.7,  67.,449.5,  68.,693.0,  69.,739.8,...
              70.,711.8,  71.,693.0,  72.,487.0,  73.,496.4,  74.,674.3,...
              75.,655.6,  76.,702.4,  77.,724.9,  78.,524.4,  79.,561.9,...
              80.,674.3,  81.,649.9,  82.,702.4,  83.,322.2,  84.,608.7,...
              85.,580.6,  86.,661.2,  87.,736.1,  88.,693.0,  89.,430.8,...
              90.,533.8,  91.,664.9,  92.,590.0,  93.,627.5,  94.,402.7,...
              95.,599.4,  96.,655.6,  97.,346.5,  98.,739.8,  99.,646.2,...
             100.,502.0, 101.,721.1, 102.,646.2, 103.,580.6, 104.,535.7,...
             105.,556.3, 106.,655.6, 107.,505.7, 108.,500.1, 109.,646.2,...
             110.,612.5, 111.,575.0, 112.,149.8, 113.,249.1, 114.,187.3,...
             115.,575.0, 116.,623.7, 117.,561.9, 118.,605.0, 119.,440.2,...
             120.,445.8, 121.,533.8, 122.,309.1, 123.,237.9, 124.,187.3,...
             125.,282.8, 126.,322.2, 127.,515.1, 128.,490.7, 129.,477.6,...
             130.,473.9, 131.,275.3, 132.,256.6, 133.,453.3, 134.,333.4,...
             135.,309.1, 136.,324.0, 137.,488.9, 138.,481.4, 139.,342.8,...
             140.,237.9, 141.,453.3, 142.,324.0, 143.,421.4, 144.,239.7,...
             145.,430.8, 146.,528.2, 147.,455.1, 148.,355.9, 149.,239.7,...
             150.,352.1, 151.,314.7, 152.,281.0, 153.,   0.0, 154.,   0.0
PARAMETER C06=.445
*     WSTB IN MILES/HOUR
PARAMETER SWDPRH=0.
*     INPUT DEW POINT TEMPERATURE ONCE A DAY
PARAMETER SWRASU=1.
*     INPUT RADIATION
PARAMETER C09=29.388E-5
*     RAINTB IN INCHES/DAY
FUNCTION DVRT=0.,0., 5.,0., 22.5,0.0180, 30.,0.0250, 45.,0.03
FUNCTION CSRRT=0.,.3, .1,.4, .2,.6, .3,.8, .5,.975, .6,1., 1.,1.,    ...
               1.1,.975
FUNCTION RDRDT=0.,0., .3,.0, .31,.01, 1.0,.1, 1.1,.1
FUNCTION RDRWT = -0.25,0.10, 0.,0.10, .1,.015, .25,.000, 1.,.000
PARAMETER DRF1=1.68, DRF2=1.68, DRF3=1.68, DRF4=1.68, DRF5=1.68
PARAMETER DRF6=1.68, DRF7=1.68, DRF8=1.68
PARAMETER WLTPT1=176., WLTPT2=176., WLTPT3=176., WLTPT4=245.
```

C:

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PARAMETER WLTPT5=245., WLTPT6=245., WLTPT7=245., WLTPT8=245.
PARAMETER FLDCP1=456., FLDCP2=456., FLDCP3=456., FLDCP4=514.
PARAMETER FLDCP5=514., FLDCP6=514., FLDCP7=514., FLDCP8=514.
PARAMETER IRTD=.081
PARAMETER PROP=25.
FUNCTION RDRDT = 0.,0.005, 0.90,0.005, 1.,0.10,1.1,0.1
FUNCTION REDFDT= 0.,.075, .1,.1, .2,.2, .3,.4, ...
                   .4,.6,  .45,.75,  .5,.95,  1.,1.
PARAMETER TCK1=.01,TCK2=.02,TCK3=.05,TCK4=.12,TCK5=.25,TCK6=.3
PARAMETER TCK7=.45,TCK8=.6
PARAMETER SDAY=3456000.
PARAMETER TSUMG=120.
FUNCTION RDRDT=0.,.005,.5,.005,.6,.017,.7,.032,.8,.05,.9,.071,...
                 1.,.1,1.1,.1
PARAMETER PROP=10.
TITLE GLENLEA,MAN. SEEDING JUNE 9 1979, IBIOM=.0044
PARAMETER IBIOM=.0044
END
**********************************************************************
STOP
      REAL FUNCTION TWOVAR(KXY,NZ,ZTAB, IXY,Z,X,ITAG)
      COMMON D(64), KC(8000)
      DIMENSION ZTAB(2), IXY(50)
      IF(ITAG.NE.0) GO TO 9
      ITAG = 2
      IXY(1) = KXY
      DO 5 I = 2,NZ
      IKC = IXY(I - 1) - 1
   5  IXY(I) = MRIGHT(MLEFT(KC(IKC),18),18) + 5
   9  I = ITAG
  10  IF(Z - ZTAB(I))12,18,11
  11  IF(I.EQ.NZ)GO TO 20
      I = I + 1
      GO TO 10
  12  IF(Z - ZTAB(I-1))13,17,20
  13  IF(I.EQ.2) GO TO 20
      I=I-1
      GO TO 12
  17  TWOVAR = AFGEN(IXY(I - 1),X)
      GO TO 22
  18  TWOVAR = AFGEN(IXY(I),X)
      GO TO 22
  20  ZVAL = (Z - ZTAB(I - 1))/(ZTAB(I) -ZTAB(I - 1))
      TWOVAR = (1. - ZVAL)* AFGEN(IXY(I - 1),X) + ZVAL * AFGEN(IXY(I),X)
  22  ITAG = 1
      RETURN
      END
ENDJOB
```

C: