

Evaluation of a Crop Simulation Model for Potatoes

by

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Randall R. Renwick

**A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University
of Manitoba in partial fulfillment of the requirements of the degree
of
Master of Arts**

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Abstract

A crop simulation model for the growth and development of the potato plant (*Solanum tuberosum* L.) was tested under Manitoba weather and soil conditions on irrigated and dryland sites near Carberry, Manitoba. At this location, both Russet Burbank and Shepody varieties were grown. Crop growth variables such as top and tuber dry matter production, leaf area index and gross yield were compared to field data collected during the growing seasons of 1996, 1997 and 1998. Simulated phenologic development and soil moisture were also compared to observed data for those same years.

SIMPOTATO is a weather driven model which requires daily rainfall, global radiation, and maximum and minimum air temperature. Soil physical properties such as field capacity and permanent wilting percentage were measured and used as input parameters for the model. Irrigation treatment amounts and fertilizer applications were field management information used to run the simulation model.

Simulations of leaf area, top green biomass and tuber dry weights were underestimated in both the maximum values reached and seasonal growth rate for each irrigation treatment for all three growing seasons for the Russet Burbank cultivar. Simulated total tuber yields were below measured values by 5 Tonnes/ha in the dryland treatment and 12.3 Tonnes/ha in the wettest treatment in 1996. In 1997 the dryland treatment simulated yield averaged 22.5 Tonnes/ha below measured yield while the wettest treatment was underestimated by 18.1 Tonnes/ha. For 1998, yields were underestimated by 11.7 and 11.1 Tonnes/ha for the respective treatments. Modeled soil moisture and crop water use agreed well with measured values for the 1998 season, while 1997 and 1996 results showed the model to be underestimating soil moisture.

Cultivar coefficients for the Shepody variety were not available so an evaluation of the model could not be performed for this variety. However, the crop measurements made during the 1997 and 1998 seasons were used to calibrate the simulation model for this cultivar. Yield, dry matter and leaf area simulations from this calibration procedure shows that the model overestimated yield and underestimated top biomass and leaf area. Improvements are needed in the model, particularly with estimation of leaf expansion rate, tuber growth rate and carbohydrate partitioning to tubers if the model is to be used under Manitoba conditions.

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Chapter 1 Introduction

Understanding the growth and yield potential of agricultural crops, in addition to satisfying scientific curiosity, has economic value. Much has been done to achieve these ends. The development of crop simulation models which estimate growth and development have been undertaken for many common agricultural crops. These are mechanistic models as they mathematically represent the life cycle of the plant. Simulation models are used to predict important aspects of plant growth and development such as dry matter accumulation (above and below ground), leaf area, physiological development and gross yield. These variables are estimated by quantifying the physiological processes within the plant in response to weather conditions, soil environments and management practices. The information obtained from simulation models is most commonly used for within-season crop management decisions, multi-year risk analysis for crop variety planning and yield forecasting for large areas (Ritchie, 1986).

Given the increasing importance of potato production in Manitoba in recent years (Manitoba Agriculture, 1995), it would be useful to be able to accurately estimate the yield of this crop in the Manitoba climate. This project was undertaken to evaluate the accuracy of the SIMPOTATO (Hodges, 1997; Hodges *et al.*, 1992), crop growth and development model for potatoes (*Solanum tuberosum* L.) within southern Manitoba's environment over the 1996, 1997 and 1998 growing seasons.

Potato production is largely dictated by the climate of an area and the physical and hydraulic properties of the soil at the site of production. These two kinds of information are used by the growth and development models to simulate the most important physiological processes within the plant. Before this model can be utilized in management or research applications in southern Manitoba, the validity of its output needs to be determined under representative environmental conditions. The SIMPOTATO model was developed and calibrated largely in the north-western United States in Washington and Oregon. This project is an evaluation of SIMPOTATO under weather and soil conditions at Carberry, Manitoba (49.90° N latitude, 99.35° W longitude) over three growing seasons. Simulations of daily top and tuber growth and total yield are compared to measured data from irrigated and dryland treatments. In each year (1996, 1997 and 1998), three irrigated and a non-irrigated moisture regime were used to evaluate the simulation model under a range of moisture conditions.

Chapter 2 Literature Review

Crop simulation models are based on fundamental relationships between the growth and development of the plant and its constituent parts, and the soil and atmospheric environment. These relationships are determined from experimental data in an attempt to summarize a crop's (and cultivar's) response to a complex environment. Multiple regression equations derived from these types of relationships are empirical models. In contrast, mechanistic models use a large number of equations to represent the plant's physiologic response to its environment (Hodges, 1991). Crop growth and development models are mechanistic models based on the empirically derived relationships. The accuracy of the relationships identified by the empirical models is limited by the variables measured within the study. Regression relationships assume that variables are independent and normally distributed. These assumptions however, are not always realistic and as a result error can be introduced into a simulation model at a basic level (Hodges, 1991). Careful selection and analysis of environmental variables is required so as not to misinterpret a crop's responses. A simulation model that can be applied in a diverse range of environments can be very useful as long as it is reasonably accurate. This success depends on the process of accurately identifying fundamental relationships between plant growth and the environment.

2.1 Crop Modeling and IBSNAT

In 1982 the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT, 1990) included crop simulation models in its program for international agrotechnology transfer. Two CERES (Crop Environment Research Synthesis) models, CERES-Wheat (Ritchie and Otter, 1985) and CERES-Maize (Jones and Kiniry, 1986) were the first simulation models to be included in this system. IBSNAT uses a standard format for input and output data. These models are written in the FORTRAN computer language and consist of many similar routines and subroutines that mimic common physiological processes. The SIMPOTATO model is based on the CERES-Maize model. Basic sub-routines that simulate carbohydrate production, root growth and water use have been borrowed from this model.

The IBSNAT standard file system allows for a common use and interchange of weather and cultivar-specific data so that a wide variety of crop models can be easily tested and applied (Ritchie and Godwin, 1997). The common exchange of site-specific data such as that for soil, management practices, and fertility is also supported by this standard.

2.2 Phenologic Modeling

An integral component of crop simulation models is the incorporation of the timing of crop growth processes, or phenology (Hodges, 1991). Phenology is the study of the changes between biological events or growth stages with respect to biotic and abiotic factors (Lieth, 1974). A knowledge of crop phenology is crucial as it greatly influences biomass accumulation and partitioning. Modeling crop phenology usually employs equations that predict the timing of biological stage from temperature, photoperiod and/or radiation. The equations used to estimate development rate of a crop from these environmental variables are derived using regression analysis from experimental data (Shaykewich, 1995). Daily minimum and maximum air temperatures are most commonly used to predict the duration of a plant phase which is reported in units of Thermal Time. Other common terms are Daily Thermal Time, Heat Units and Growing Degree Days. When photoperiod is used in addition to temperature for this purpose, the measure is commonly referred to as Photothermal Time.

Crop simulation models that use a minimum of input data, such as the CERES family of models, estimate the time required for a crop to pass through its development stages to maturity largely for the purposes of yield prediction. Simulated growth processes would inaccurately estimate the timing of actual crop growth without the incorporation of phenology (Hodges, 1991). The importance of predicting phenology is shown by the fact that a cereal crop subject to stress (thermal, moisture or nutrient) during flowering or grain filling can markedly decrease yield compared to stress incurred during vegetative

growth (Hodges, 1991). For the potato plant, yield can be significantly reduced if moisture stress occurs during the tuber bulking stage (Dawes *et al.*, 1983). If phenology can be accurately tracked, the effect of environmental stress on plant growth and yield can be more precisely estimated.

The use of the Growing Degree Day (GDD) is the most common approach to estimate plant development from temperature measurements. The simple GDD equations subtract the mean daily temperature (T_m) from an empirically derived base temperature (T_b) for a crop or variety to get the heat units for that day:

$$\text{GDD} = T_m - T_b \quad (2.1)$$

These daily values are accumulated over the growing season. The mean daily temperature is calculated by averaging the daily minimum and the daily maximum temperature. GDD equations assume development rate is a linear function of temperature above the base temperature and below an upper cut-off temperature (Kiniry and Keener, 1982). The base temperature is the temperature below which growth and development cease, and negative values are set to zero. This threshold is specific to each crop. Optimum temperatures at which various crops respond are also empirically derived. However, it is more difficult to quantify the upper cut-off temperature. Commonly, the curve for development rate is extrapolated to zero to estimate this upper value.

To avoid an underprediction of GDD, daily minimum temperatures below the base temperature are usually set to the base temperature (Shaykewich, 1995). However, when

temperatures are below the base temperature for a significant part of the day this method would result in an overprediction of development. A method to address this problem is to estimate the diurnal cycle of temperatures from the minimum and maximum daily temperatures using a sine curve. The area under the curve, above the base temperature, is used to represent the amount of useful heat available to the plant. Recalculating useful heat above the base temperature from this diurnal distribution results in a more accurate prediction of daily heat units than the simple GDD equation.

2.2.1 Development Rate

2.2.1.1 Effect of Temperature

The influence of temperature on the development of the potato plant has been studied by many scientists (Sands *et al.*, 1979). Emergence is always accelerated by high temperatures. Modeling development using units of thermal time has mainly focused on the timing of important events in the phasic development of crops like time to flowering and to maturity for the cereals and time to tuber initiation for potatoes. Thermal time is also useful in predicting developmental events like germination, tuber bulking and leaf growth duration (Ritchie and NeSmith, 1991).

2.2.1.2 Effect of Daylength and Light Intensity on Plant Development

Factors such as photoperiod and global radiation, when used with temperature, can improve the accuracy of simulating crop development. Light intensity largely determines photosynthetic potential and has some influence on the development of the potato plant (Bodlaender, 1963). These phenologic affects differ with variety and developmental stage. When global radiation values are high, tuber formation starts earlier, maximum stem length is reached earlier and plants tend to mature earlier (Bodlaender, 1963).

2.3 Growth and Yield

Changes in total dry weight of potato plants typically follow a sigmoidal curve throughout the growing season (Dawes *et al.*, 1983). Top dry weights commonly reach a maximum about mid-season and subsequently decline with the onset of senescence and the shift of photosynthate to growing tubers. Leaf dry weights largely follow this pattern of top growth as they are the most significant component in the above ground portion of the plant (haulm). Stem weights increase throughout the season in some varieties, or slowly decrease following the decline in leaf mass.

2.3.1 Effect of Daylength on Plant Growth

In the higher latitudes, which have long summer daylengths, long-day cultivars (*Solanum tuberosum*) are grown to achieve high yields. Optimal daylength for potato growth depends on temperature and cultivar (Manrique *et al.*, 1990). As the daylength decreases

in the higher latitudes late in the growing season, long day cultivars respond by partitioning more carbohydrate to the tubers (Manrique *et al.*, 1990; Bodlaender, 1963). The shorter the daylength, the greater the proportion of dry matter that is partitioned to tubers at the expense of the plant leaves and stems.

2.3.2 Moisture Stress and Tuber Growth

The amount of water available to the plant can directly affect yield. The potato is most sensitive to moisture stress during the time of tuber growth. Lis *et al.* (1964) report a reduction in tuber number with moisture stress during the tuber growth stage. Cultivars can also exhibit a different response to moisture stress which varies with developmental stage. Lynch and Tai (1989) studied the yield response to moisture stress for a number of common varieties of potato. The authors noted that tuber yield was generally effected more severely by stress during tuber growth than around the time of tuber initiation.

2.3.3 Root Growth

Root growth in the potato plant is rapid early in the growing season, and remains relatively constant for much of mid-season. Root dry weight decreases late in the season and coincides with leaf senescence. Gregory and Simmonds (1992) have summarized the results from other research as to the maximum depth of penetration of roots (Table 2.1).

Table 2.1 Root depth comparison of potato varieties with two other temperate crops

Crop	Soil	Cultivar	Rooting Depth (m)	Author(s)
Potatoes	Loamy sand	Vanessa	0.9	Asfary <i>et al.</i> (1983)
	Silty clay	Majestic	0.9	Durrant <i>et al.</i> (1973)
	Loamy sand	Russet Burbank	0.7	Lesczynski and Tanner (1976)
	Sandy loam	Record	0.8	Parker <i>et al.</i> (1989)
	Sandy loam	K. Edward	0.47	Steckel and Gray (1979)
		Majestic	0.55	
		M. Piper	0.5	
		P. Crown	0.6	
	Silty clay	Desiree	1.0	Stone (1982)
	Marine clay	Bintje	0.8-1.0	Vos and Groenwold (1986)
Wheat	Sandy loam	M. Huntsman	2.0	Gregory <i>et al.</i> (1978)
Field Beans	Sandy loam		0.8	Gregory (1988)

Table 2.1 indicates that the rooting depth of each potato crop never exceeds 1 m, even on deep soils. Not only is the rooting depth of potatoes shallower but a greater proportion of the root length (82%) is contained in the upper 30 cm when compared with winter wheat (73%).

Accurately simulating root depth is important because it determines the depth of soil from which plants get water and nutrients. This component of simulation models is one where improvements are needed. Jones *et al.* (1991) reported that no model considers the major physical properties of soils and crop characteristics affecting root growth. Crop models commonly simulate the downward growth of a root system at a predetermined rate. The rate, derived from experimental data, is often a function of environmental factors like soil temperature (Jones *et al.*, 1991). Borah and Milthorpe (1962) studied the effect of temperature on root growth and concluded that colder air temperatures lower maximum root biomass and slow the initial root growth.

2.3.4 Top Growth

Air temperature regulates the development of the plant and expansion growth of the leaves. Crop simulation models, therefore, utilize air temperature data to estimate leaf expansion. Because leaf expansion enables more solar radiation to be intercepted by the plant, Leaf Area Index (LAI) is calculated daily in these models. LAI is defined as the area of leaf surface per unit ground area, and is a measure of the photosynthetic system. A greater leaf area provides additional sites for the production of energy and for the synthesis and mobilization of carbohydrate. Monteith (1977) conducted experiments that quantified the relationship of global radiation to carbohydrate production for a number of crops in Britain (Figure 2.1).

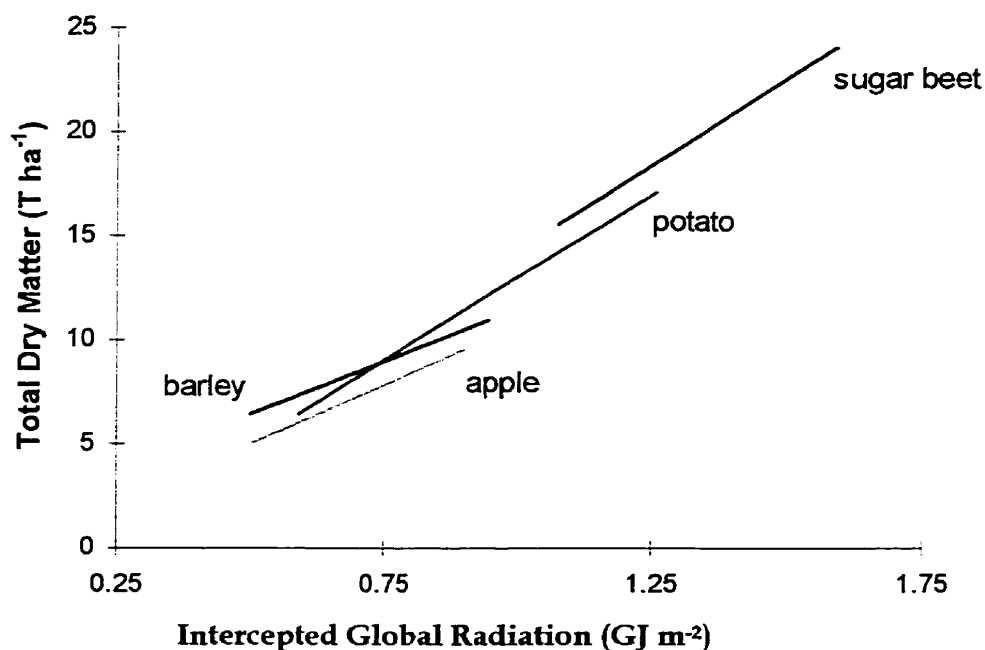


Figure 2.1 Relation between total dry matter at harvest and radiation intercepted by foliage throughout the growing season (Monteith, 1977)

Monteith termed the ratio of the energy output (carbohydrate) to energy input (global radiation) over the growing season the *efficiency of crop production*. Photosynthetic efficiency is not equivalent to the net assimilation rate, as light interception is a function of leaf area index (Monteith, 1977). Monteith (1977) found that 1.4 g of carbohydrate is formed per MJ of solar energy. However, because light interception is an exponential function of leaf area, variables such as net assimilation rate, relative growth rate and leaf area duration are appropriate indices of crop growth only when the leaf area index is small. Monteith (1977) notes that when shading of the leaves by other leaves becomes significant, net assimilation rate and relative growth rate decreases with time.

MacKerron and Waister (1985) indicate that experiments on different cultivars show that for most of the growing season there is a linear relationship between total dry matter and intercepted global radiation (Alberda, 1962; Sibma, 1970; Biscoe and Gallagher, 1977; Khurana and McLaren, 1982). The slope of this relationship, the conversion coefficient, varies with cultivar and season from 1.43 to 1.84 g MJ⁻¹ (MacKerron, 1983). To put this into perspective, during early July and under a clear sky, Carberry, Manitoba would receive no more than 30 MJ m⁻² of global radiation in one day.

Manrique and Kiniry (1990) studied the relationship between dry matter production and intercepted photosynthetically active radiation (IPAR) in the tropics, and found that this was a linear relationship from emergence through tuber enlargement. Specifically, Manrique and Kiniry (1990) found that 1.0 MJ of IPAR produced 2.3 g of dry mass in the potato plant.

Soil fertility also affects the growth of the component parts of the plant. Hodges (1997) reported that soil with a high nitrogen content tends to favor top growth in indeterminate cultivars (Russet Burbank) at the expense of growth in the tubers.

2.3.5 Tuber Growth

Tuber initiation requires a shift in carbohydrate sink priorities (sink strength) within the plant from tops to tubers. Few studies have identified the mechanisms controlling tuber initiation. It is assumed that this stage begins when assimilates begin to accumulate at the stolon tips (Moorby, 1978). Tuber dry matter accumulation is a sigmoidal function of time. The linear portion of this curve is referred to as tuber bulking, during which nearly all of the available photosynthate is allocated to the tubers. Evidence indicates that tuber sink strength influences the photosynthetic rate. Dwelle *et al.* (1980) found that with field-grown Russet Burbank potatoes the maximum photosynthetic rates at mid-season were close to double those during early growth. Ku *et al.* (1977) have similar results, where they found that maximum photosynthetic rate of tuberized plants was double that of non-tuberized ones.

2.3.5.1 Partitioning of Carbohydrates

The partitioning coefficient (PC) is the proportion of the plant tuber dry matter to total plant dry matter. This value increases from tuber initiation throughout the growth of the plant. Manrique *et al.* (1990) report the method for calculating this coefficient for a particular cultivar is:

$$PC = TGR / CGR \quad (2.2)$$

where TGR is the tuber growth rate, and is the difference between tuber biomass (per plant) at some day early in tuber growth and tuber biomass near the end of bulking, divided by the number of days between those measurements. CGR is the total crop growth rate and is the change in total plant biomass between the same period used for TGR divided by the number of days for the period. Between cultivars, great differences in the partitioning coefficient can exist. Because of these differences, the maximum rates of biomass accumulation for entire plants and tubers need to be quantified for each variety. These growth rates are obtained from experimental data under optimum conditions where soil moisture and fertility are not limiting factors. Maximum growth rates for each cultivar are used within simulation models to set the upper growth limit. Model simulation of plant growth then decreases as limiting factors become more pronounced.

2.3.6 Genetic Variables

Different cultivars can grow and develop differently within similar environments. Thus, genetic coefficients which describe specific cultivar characteristics are commonly utilized by crop models. Wide geographical applicability of mathematical crop models can be accomplished only if there is an understanding of the relationships between the genetically controlled characteristics of potato growth and development and the environment (Manrique *et al.*, 1990). For the most common cultivars, the relationship between environmental variables and the growth of major plant components such as leaf area, stem and branch elongation and tuber growth have been quantified. Presently however, genetic

variables are not well understood for the potato. Manrique *et al.* (1990) point out that this is largely because the experimental data needed to distinguish them are not generally available. Cultivars can respond differently to variables such as daily mean temperature, daily temperature range, light intensity, photoperiod and soil nitrogen content. In their paper, Manrique *et al.* (1990) propose a standard methodology in order to facilitate the collection of data required to calculate genetic variables for potato. Until the genetic coefficients for different potato cultivars are available, a simulation model that accurately predicts growth and yield under a wide range of environmental conditions may be unattainable.

2.4 Summary

The simple growing degree day, based on daily maximum and minimum temperatures, is commonly used in crop simulations. The thermal range for which each crop is sensitive is incorporated into each model. The developers of these models use optimum, minimum and maximum threshold temperatures to quantify this response based on their own research and that available from other experimental research. This information allows the models to be more flexible by accounting for decreased rates of development beyond the optimum temperature. This crop specific information is used to calculate the amount of useful heat available to the plant on a daily basis. The accurate simulation of vegetative and reproductive development is of particular importance as these can vary considerably between cultivars under different crop management and environmental conditions.

Although daily temperature is the primary variable for predicting crop development, photoperiod and solar radiation data are also used to improve the accuracy of prediction.

Moisture availability must be accurately estimated by the model, as it greatly affects yield. To do this, the model must realistically mimic the root growth processes of the plant as well as have accurate input data for initial soil moisture conditions at planting, and precipitation and irrigation data throughout the growth of the crop. Moisture stress has been found to decrease tuber number and yield, particularly if the stress occurs during the tuber bulking stage.

Simulating the development and growth of the potato is a difficult task, as one must consider the complexity of plant physiologic processes and their response to changing atmospheric conditions and the soil environment. In addition, cultivars have different growth responses to temperature, light intensity, daylength and moisture stress which need to be quantified. This is done in a simulation model by using coefficients to adjust cultivar growth rates for the plant, tubers and leaf expansion. More research is needed to characterize cultivar variability before simulation models can be successful in a wide range of environments.

Chapter 3 Description of the SIMPOTATO model

3.1 Outline of the Model

The SIMPOTATO model (Hodges, 1997; Hodges *et al.*, 1992) simulates the major growth processes of the potato plant. The model estimates growth and development for the average plant in the field. It assumes a block of soil that is variable with depth but horizontally homogeneous (Hodges *et al.*, 1992). This simulation model estimates growth and development processes from weather, soil and field management conditions. Soil moisture and fertility processes are simulated by the model and are used to calculate limiting factors for growth in the model. Like the other closely related crop growth simulation models, SIMPOTATO adopts the IBSNAT standard format for input and output data. These models are written in the FORTRAN computer language and consists of similar routines and subroutines that mimic common physiological processes. The input data needed for the model include: 1) daily weather data, 2) soil profile description, 3) crop management information and 4) cultivar specific genetic coefficients.

3.2 Model Input Variables and Parameters

3.2.1 Weather Variables

Daily weather inputs of the model include global radiation, maximum and minimum air temperature and precipitation. SIMPOTATO uses global radiation data primarily to simulate daily carbohydrate production. The model uses daily maximum and minimum temperature inputs to calculate accumulated heat units in order to simulate crop

development. This drives the progress of the crop through its lifecycle. The effects of daily air temperature on leaf area (expansion growth), soil temperature and root extension and maintenance respiration are calculated in the model.

Rainfall data is used in the model along with irrigation and initial soil moisture information to estimate crop moisture stress on a daily basis. Thresholds values for moisture stress are set in the model and vary with crop stage. If moisture stress occurs, this information is passed on to growth and partitioning subroutines in which it is used as a factor (between 0 and 1) to reduce net carbohydrate production and change storage and transfer of carbohydrates within the plant. The model can be run using weather data from planting date, but in order to estimate soil moisture storage, preplanting weather data can be used to calculate evaporation.

3.2.2 Soil Properties

The physical properties of the soil in which the crop grows greatly affects plant growth. The soil profile data, required by the model, includes information for each soil layer. These parameters are soil layer thickness, permanent wilting point (PWP), field capacity, saturated water content (porosity), weighting factor influencing root growth, bulk density, organic carbon concentration, soil ammonium, soil nitrate and pH. In addition, to estimate drainage from the profile a drainage rate coefficient is used, the model uses the U.S. Soil Conservation Service (SCS) curve number method for calculating runoff (USDA, 1972), soil surface albedo and a soil evaporation coefficient for Stage 1 energy-limited surface

evaporation (Ritchie, 1972). The annual average ambient air temperature and the annual amplitude in mean monthly air temperature are also used by the model to estimate mineralization of soil organic matter and soil root and surface residue.

3.2.3 Initial Conditions of the Experimental Plot

Measured initial soil moisture and soil fertility data at planting are used by the model in the budgeting of soil moisture and fertility throughout the growing season. This information, is used as a starting point for simulating plant moisture and nitrogen stress throughout the growing season. The fresh seed weight is also used within the model as it is the source of carbohydrate and moisture during early plant growth.

3.2.4 Crop Management Information

Management inputs include cultivar name, planting date, seed planting depth, plant population density, emergence date (optional), dates and amounts of water and nitrogen applications, oven dry weight of seed piece and length of sprouts on seed piece at planting. Plant density is represented by the number of mainstems per square meter.

3.3 Temperature and Thermal Time in SIMPOTATO

Thermal time in SIMPOTATO is calculated in the same way as thermal time in the CERES-Maize model. However, different optimum temperatures and different maximum and minimum thresholds are used to estimate the response of this crop to temperature. Daily thermal time (DTT) is calculated using two optimum temperatures of 17°C (DTT17) and 22°C (DTT22). Both thermal time variables use 5°C as the base temperature, while the upper cut-off temperature for DTT17 is 35°C and for DTT22 is 36°C. Daily thermal time calculations are accumulated for each growth stage. The simulated developmental stage of the crop progresses when particular thermal time accumulations are reached (section 3.4). DTT22 is used for calculating potential leaf and stem expansion and senescence, changes in stem length and appearance of new leaves and nodes. DTT17 is used for calculating percent dry matter in the tubers, the end of tuber growth, and root growth rate (Hodges, 1997). Soil thermal time (STT) is estimated from air temperature and is used for calculating root penetration into the soil, seed piece germination and emergence.

When daily minimum air temperatures are greater than 5°C and daily maximum temperatures are less than 35°C daily thermal time is calculated as follows:

$$TM = 0.4 T_{max} + 0.6 T_{min} \quad (3.1)$$

$$DTT = TM - T_{base} \quad (3.2)$$

where TM is the weighted daily mean temperature, T_{max} is the daily maximum temperature, T_{min} is the daily minimum temperature and DTT is daily thermal time.

In SIMPOTATO, thermal time is then calculated from a piece-wise linear function for optimum temperatures of 17 and 22C (on a 0 to 1 scale). Thermal time for DTT17 increases linearly from 0 at 5°C to 0.83 at 14°C and then to 1 at 17°C (Figure 3.1).

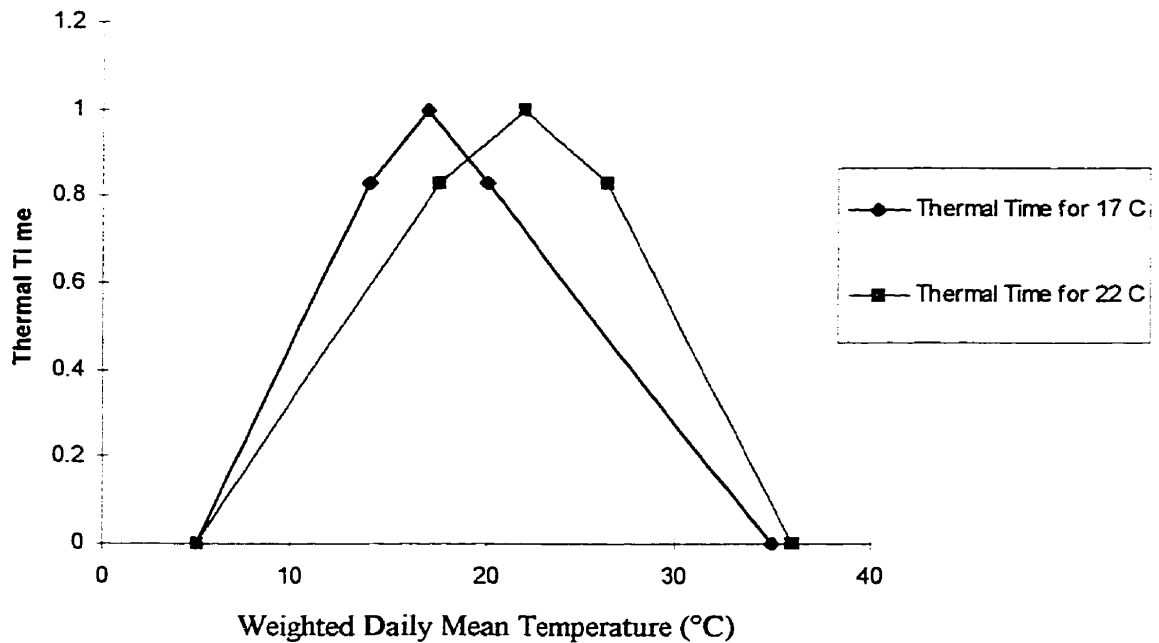


Figure 3.1 Thermal time as a function of weighted daily mean temperature

Thermal time then declines to 0.83 at 20°C and to 0 at 35°C. Thermal time for DTT22 increases linearly from 0 at 5°C to 0.83 at 17.5°C and then to 1 at 22°C. It then declines to 0.83 at 26.5°C and to 0 at 36°C.

When daily maximum temperature is greater than 34°C or daily minimum temperature is less than 5°C a more complex procedure is used to estimate useful heat. Eight

interpolations of air temperature (TTMP) are calculated using the three-hour temperature correction factor (TMFAC(I)) (Hodges and Evens, 1992).

$$\text{TMFAC}(I) = 0.931 + 0.114 \times I - 0.0703 \times I^2 + 0.0053 \times I^3 \quad (3.3)$$

Where $I = 1$ to 8.

$$\text{TTMP} = T_{\min} + \text{TMFAC}(I) \times (T_{\max} - T_{\min}) \quad (3.4)$$

For each value of TTMP, a three-hour value of thermal time (DTT) is calculated. If TTMP is between the base temperature and the upper cut-off temperature, DTT is calculated as follows:

$$\text{DTT} = \text{TTMP} - T_{\text{base}} \quad (3.5)$$

DTT is zero when TTMP is less than the base temperature or is greater than the upper cut-off temperature. The eight three-hour estimates of DTT are then summed to obtain the daily value of DTT.

Maximum soil thermal time occurs at 15°C. STT declines linearly as temperatures deviate from the optimum temperature at a rate of .0962 daily thermal units °C⁻¹. The maximum daily value is 1.

3.4 Development Events in SIMPOTATO

Flowering is not simulated in SIMPOTATO. The chief phenological events in SIMPOTATO are the beginning of tuber growth (tuber initiation) and the beginning of rapid tuber growth (bulking). These are predicted with the tuber induction variable

(TIND). TIND is accumulated daily over the growing season (planting to harvest) based on six genetic components that influence tuber growth. These components are mean temperature, temperature range, global radiation, photoperiod, modeled plant leaf area, and modeled plant nitrogen concentration. Before tuber initiation, TIND is reduced (decays) 15% each day before the next daily increment is added to it. Thus accumulated induction is lost during periods with conditions unfavorable for induction. After tuber initiation, the decay rate is 3%. Ten genetic coefficients (A1-A10 in the genetics file, Appendix A) are used to calculate the 6 components which influence tuber induction. The product of these components is used as a factor which limits tuber induction for specific cultivars. Tuber initiation is assumed to occur when the tuber induction variable accumulates 225 units and bulking when the variable accumulates 300 units. At present, the genetic coefficients used in calculating TIND are largely the same for all varieties. However, as greater understanding is acquired about how varieties differ in tuber induction response, there will be more differentiation between the coefficients used for varieties. Hodges (1997) noted that additional coefficients will be added to simulate other aspects of potato growth and development that are dependent on cultivar differences in characteristics such as specific leaf weight, tuber number, tuber quality, and disease resistance.

3.4.1 Phenology and Phasic Development in SIMPOTATO

Growth stages in this model are numbered using the same method as that used in CERES-Maize. Above ground growth from emergence through maturity comprise stages 1

through 4 and the time between the maturity of the previous years crop to emergence of the following years crop is separated into stages 5 through 7. A description of these growth stages is provided below.

Stage 5 is the period from maturity of the previous crop until the potato seed pieces are planted. During this period, only estimates of evaporation and soil processes are made. These calculations are made to estimate the available moisture in the soil at the date of planting. Both the beginning date of the simulation and the planting date are input from the management data file (Hodges, 1997).

Stage 6, planting to germination, occurs immediately after planting if sprout length is greater than zero. Otherwise germination is assumed to occur after 7.35 units of soil thermal time (STT) have accumulated (Hodges, 1997). The authors indicated that the soil moisture requirement for germination will be deleted from future versions of the model. Presently, germination does not occur if the soil water content above the lower limit of plant extractable water at seeding depth is below $0.02 \text{ (cm}^3 \text{ cm}^{-3}\text{)}$. The likely rationale for this decision is that soil moisture has relatively little effect on sprout growth as most of the moisture during early growth is provided by the mother tuber.

Stage 7 represents germination to emergence. Estimation of the length of this stage is problematic. Some important influences on emergence are seed piece storage conditions, harvest condition and maturity of the harvested tubers. SIMPOTATO is written to calculate the length of the period from germination to emergence. However, due to the

influence of these other variables on emergence, emergence date is usually treated as an data input to improve simulation accuracy if the data is available. If actual emergence date is not available, it is estimated by calculating sprout elongation from soil thermal time until sprout length is greater than the planting depth at which time emergence occurs (Hodges, 1997).

Stage 1 is the period from emergence to tuber initiation (period of vegetative growth).

This stage lasts until the variable for tuber induction accumulates 225 heat units. This measure, as described above, is the daily accumulation of the product of the six genetic tuber induction variables. During this stage, top growth and root growth are simulated.

The environmental variables used to estimate the duration of this stage are daily maximum and minimum air temperatures.

Stage 2 is the period from the beginning of tuber growth to the beginning of rapid tuber growth. Partitioning occurs between tops, roots, and tubers during this stage, but an increasing share of daily growth is allocated for tuber growth. Stage 2 ends when the induction variable reaches 300. Global radiation, photoperiod, plant nitrogen and LAI are used in addition to daily mean air temperature and daily temperature range to calculate the length of this stage.

Stage 3 is characterized by a period of dominant tuber growth (bulking) where potentially all available carbohydrate can be partitioned to tuber growth each day. Potato growth frequently ends when all the leaves die either because of senescence resulting from various

stresses (disease), frost or because of induced desiccation in preparation for harvest. The model uses harvest date as a final maturity date unless complete leaf senescence occurs earlier. At maturity (stage 4), the model ends the simulation. Stage 5 can be used to start another simulation if a multi-season rotation simulation is desired (Hodges, 1997).

3.5 Soil Moisture Calculations in SIMPOTATO

3.5.1 Initial Soil-Water Simulation

At the beginning of the simulation, SIMPOTATO calculates the initial amount of plant-extractable soil water (ESW) for each soil layer (L) using the equation:

$$ESW(L) = DUL(L) - LL(L) \quad (3.6)$$

Where DUL is the drained upper limit soil water content for each soil layer L ($\text{cm}^3 \text{cm}^{-3}$), and LL is the lower limit of plant extractable water for each soil layer L ($\text{cm}^3 \text{cm}^{-3}$).

The model then calculates the total soil water in the profile, total plant-extractable soil water in the profile, total soil water in the profile at the lower limit of plant-extractable water, total soil water in the profile at the drained upper limit and total soil water in the profile at saturation.

Daily changes in soil moisture throughout the growing season are calculated. These include calculations for the redistribution of water due to irrigation, precipitation and drainage and calculations for potential evapotranspiration, soil evaporation and plant

evaporation (transpiration). If irrigation and/or precipitation occur on a day, the amount of irrigation and rainfall are summed in the variable PRECIP. Calculations are made for runoff, water that infiltrates and drainage from a soil layer. Runoff is calculated by the U.S. Soil Conservation Service (SCS) curve number method (USDA, 1972). Initially, a weighting factor used to determine runoff is calculated for each soil layer and is a proportional to the ratio of the cumulative depth of the soil profile and the depth of rooting (Jones *et al.*, 1986).

$$WX = 1.016 \times (1 - \exp(-4.16 \times \text{CUMDEP} / \text{DEPMAX})) \quad (3.7)$$

$$\text{WF(L)} = WX - XX \quad (3.8)$$

Where XX is equal to zero in the surface soil layer and in other layers is equal to the value of WX in the layer above, and CUMDEP is the cumulative depth of the soil profile (cm) and DEPMAX is set equal to the depth of rooting. A temporary variable (R2) is then calculated using the weighted sum (weighted for soil depth by the factor WF(L)) of the relative amount of plant-extractable soil water (ESW(L)) in the profile and the drainage coefficient (SCS curve number) is calculated (Jones *et al.*, 1986).

$$R2 = \text{SMX} \times (1 - \text{SUM}) \quad (3.9)$$

No runoff occurs if precipitation is less than 2% of R2.

$$\text{PB} = \text{PRECIP} - 0.2 \times R2 \quad (3.10)$$

Where PB is a temporary runoff variable. If runoff occurs, then it is calculated as follows:

$$\text{RUNOFF} = \text{PB} \times \text{PB} / (\text{PRECIP} + 0.8 \times R2) \quad (3.11)$$

Potential infiltration into the soil layer (PINF) is calculated:

$$\text{PINF} = \text{PRECIP} - \text{RUNOFF} \quad (3.12)$$

3.5.2 Potential Evapotranspiration and Evaporation from Soil

Simulated Potential evapotranspiration is a function of mean temperature during the daylight hours (when both soil and plant evaporation are greatest), global radiation and integrated crop-soil albedo (Jones *et al*, 1986). If the daily maximum temperature is between 5 and 35°C potential evapotranspiration is calculated as follows:

$$\text{PET} = (\text{SOLRAD} \times (0.004876 - 0.004374 \times \text{ALBEDO}) \times (\text{TD} + 29)) \times 1.1 \quad (3.13)$$

Where SOLRAD is global radiation in langleys per day, ALBEDO is the integrated crop-soil albedo and TD is the weighted mean daily temperature estimated for daylight hours. For daily maximum temperatures above 35°C PET increases at an increasing rate, and for maximum temperature below 5°C PET decreases at an increasing rate.

The potential rate of soil evaporation (EOS) is calculated using PET and leaf area index (LAI). When LAI is less than 1.0 the equation is:

$$\text{EOS} = \text{PET} \times (1 - 0.43 \times \text{LAI}) \quad (3.14)$$

If LAI is greater than 1.0:

$$\text{EOS} = \text{PET} / 1.1 \times \text{EXP} (-0.4 \times \text{LAI}) \quad (3.15)$$

Actual soil evaporation is now calculated according to the method of Ritchie (1972), which is based on two stages of soil evaporation. During stage 1, actual soil evaporation

(ES) is limited to energy available for evaporation at the soil surface. This stage continues until a soil-dependent upper limit of stage 1 evaporation (U) specified in the input soil file is reached. Soil evaporation then enters stage 2, in which ES is a declining function of time since the beginning of stage 2. The variables SUMES1 and SUMES2 are the sums of ES in stages 1 and 2, respectively, and they are used to determine which stage of soil evaporation is occurring on a day (Jones *et al*, 1986).

At the start of the simulation SIMPOTATO calculates the amount of extractable soil water (SWR) for the uppermost soil layer (layer 1) in the subroutine SOILRI using the equation:

$$SWR = (SW(1) - LL(1)) / (DUL(1) - LL(1)) \quad (3.16)$$

Where SW(1) is the soil water content of layer 1 ($\text{cm}^3 \text{cm}^{-3}$), LL(1) is the lower limit of plant extractable water for layer 1 ($\text{cm}^3 \text{cm}^{-3}$), DUL(1) is the drained upper limit soil water content for soil layer 1 ($\text{cm}^3 \text{cm}^{-3}$). SWR is used to initialize the cumulative stage 2 soil evaporation variable (SUMES2, mm). If SWR is less than 0.9 then:

$$SUMES2 = 25 - 27.8 \times SWR \quad (3.17)$$

After the cumulative stage 1 soil evaporation variable (SUMES1) equals the parameter for upper limit of stage 1 evaporation, the time after the beginning of stage 2 evaporation (T, days) is calculated using the following equation:

$$T = (SUMES2 / 3.5)^2 \quad (3.18)$$

If the relative soil water content in the top soil layer (SWR) is not less than 0.9, SUMES2 and T are set to 0 and the cumulative stage 1 soil evaporation is calculated:

$$\text{SUMES1} = 100 - 100 \times \text{SWRV} \quad (3.19)$$

A limit on the amount of soil water that can be evaporated is calculated as a fraction of the lower limit soil water content (SWEF) using the equation:

$$\text{SWEF} = 0.9 - 0.00038 \times (\text{DLAYR}(1) - 30)^2 \quad (3.20)$$

Where DLAYR(1) is the thickness of soil layer 1 (top layer).

If rainfall and/or irrigation occur on a day and infiltration into the upper layer is greater than or equal to SUMES1, SUMES1 is set back to zero. If infiltration is less than SUMES1, SUMES1 is updated by subtracting the amount that infiltrated.

Whenever SUMES1 is less than the upper limit of stage 1 evaporation (U) which is specified in the soil input file, SUMES1 is updated daily according to the following equations (Jones *et al.*, 1986):

$$\text{SUMES1} = \text{SUMES1} + \text{EOS} \quad (3.21)$$

If the new value of SUMES1 is less than or equal to U, then actual soil evaporation equals potential soil evaporation:

$$\text{ES} = \text{EOS} \quad (3.22)$$

If the new value of SUMES1 exceeds U, then,

$$\text{ES} = \text{EOS} - 0.4 \times (\text{SUMES1} - \text{U}) \quad (3.23)$$

Where SUMES1 is the new value of SUMES1. When this occurs, SUMES2 is calculated as follows:

$$\text{SUMES2} = 0.6 \times (\text{SUMES1} - U) \quad (3.24)$$

And the time after stage 2 evaporation begins (T) is calculated (see equation 3.18). As the soil continues to dry during stage 2 evaporation, T increases by 1 each day, and actual soil evaporation (ES) is calculated as follows:

$$\text{ES} = 3.5 \times T^{0.5} - \text{SUMES2} \quad (3.25)$$

If rainfall and/or irrigation wet the soil surface slightly but WINF is less than SUMES2, actual soil evaporation is the minimum of either potential soil evaporation, $0.8 \times$ infiltration, or actual soil evaporation + infiltration.

3.5.3 Root Growth and Water Uptake

Root growth and water uptake are calculated for each soil layer in order to update volumetric soil water. The first calculation is the conversion of the daily growth of the root system (GRORT, g plant⁻¹) to root length (RLNEW, cm of root per cm² of soil surface area).

$$\text{RLNEW} = \text{GRORT} \times 0.80 \times \text{PLANTS} \quad (3.26)$$

Where PLANTS is plant population (plants m⁻²).

A zero-to-unity root length density factor for root growth is calculated for each layer (RLDF(L)). This factor is calculated using the soil water deficit factor for root growth in

that layer (SWDF) and a root growth weighting factor (WR(L)) for soil depth (read from soil parameter file).

$$RLDF(L) = SWDF \times WR(L) \quad (3.27)$$

For a layer, SWDR is 1.0 unless the volumetric soil water (SW(L)) decline below 0.25 of the plant-extractable soil water for that layer (ESW(L)). In which case,

$$SWDR = 4 \times (SW(L) - LL(L)) / ESW(L) \quad (3.28)$$

Rooting depth is also updated daily. Calculations for increased daily root depth are made using air temperature, soil profile water content and soil water in the deepest layer. New root depth is added to the previous days depth, plus the product of the daily accumulation of growing degree days and minimum of either: 1) the soil water deficit factor for photosynthesis and transpiration (SWDF1), or 2) the soil water deficit factor for deepest layer in which roots are growing (SWDF).

The amount of water removed from the profile is the minimum of: 1) the total potential root water uptake for all layers (RWU(L)), or 2) potential transpiration (EP1). The maximum rate of water uptake per unit root length (RWUMX) was defined in subroutine SOILRI as 0.03 cm³ per cm of root (Jones *et al.*, 1986). However, potential root water uptake per unit root length may be limited by soil water content. Root water uptake per soil layer is the product of the depth of the layer (cm) and the root length density factor (RLV(L)) from the soil input file. Potential root water uptake from the profile (TRWU) is calculated by summing RWU(L) for all soil layers. IF transpiration (EP1) is less than or equal to TRWU, the zero-to-unity water use factor (WUF) is calculated (Jones *et al.*, 1986).

$$WUF = EP1 / TRWU \quad (3.29)$$

The water use factor is then used to reduce root water uptake throughout the soil profile to the rate of transpiration.

$$RWU(L) = RWU(L) \times WUF \quad (3.30)$$

This method allows either EP1 or the summation of all RWU(L) to limit transpiration.

Actual soil water in each layer after the day's transpiration (SW(L)) is updated.

$$SW(L) = SW(L) - RWU(L) / DLAYR(L) \quad (3.31)$$

The total soil water in the profile (TSW) is calculated by summing (SW(L) * DLAYR(L)) for all soil layers.

Total plant-extractable soil water for the profile is the difference between total soil water in the profile and the amount of water in the profile when all layers are at the lower limit of plant-extractable water.

Two zero-to-unity soil water deficit factors are calculated. The less sensitive (SWDF1) is used to reduce simulated photosynthesis when transpiration exceeds total root water uptake.

$$SWDF1 = TRWU / EP1 \quad (3.32)$$

The more sensitive factor (SWDF2) affects plant cell expansion and is less than 1.0 whenever TRWU / EP1 is less than 1.5.

$$SWDF2 = 0.67 \times TRWU / EP1 \quad (3.33)$$

Whenever $EP1$ is greater than $TRWU$, transpiration (expressed in mm) is set equal to $TRWU$, and total evapotranspiration (ET) is recalculated.

$$ET = ES + EP \quad (3.34)$$

3.6 Carbohydrate Production and Partitioning

The major physiologic processes simulated at daily intervals are net photosynthesis, root nitrogen uptake, carbohydrate and nitrogen partitioning, tuber solids content, nitrogen stress, and leaf area expansion and senescence. These processes vary with plant development stage and development rates. **SIMPOTATO** version 6.1 divides the haulm (above-ground plant) into stems and leaves, but does not consider branching.

3.6.1 Daily Photosynthesis, Growth Rate and Dry Matter Production

Dry matter accumulation ($\text{g m}^{-2} \text{ day}^{-1}$) is a multiplicative function of the following: proportion of total global radiation intercepted by the plant surface ($\text{MJ m}^{-2} \text{ day}^{-1}$), potential crop growth rate ($\text{g MJ}^{-1} \text{ day}^{-1}$), a moisture stress reduction factor, and the change in phasic development of the plant which is dictated by the temperature dependent function that estimates physiological activity.

Calculations to determine daily net photosynthesis are made from estimates of potential dry matter production and environmental stress factors. LAI and incoming global radiation are first used to calculate intercepted global radiation which is then converted to

photosynthetically active radiation (PAR) MJ m^{-2} . PAR is assumed to be 50% of net solar radiation. Net daily photosynthesis is reduced by the most limiting of the water, nitrogen, and temperature stresses. Similar to both the CERES-wheat and CERES-maize models, a temperature stress factor (PRFT) is calculated to correct net photosynthesis for temperatures above or below the optimum temperature of 20°C :

$$\text{PRFT} = 1.35 - 0.0035 (\text{TM} - 20)^2 \quad (3.35)$$

Where TM is weighted daily mean temperature ($^{\circ}\text{C}$). If PRFT is less than zero it is set to zero. As TM deviates from 20°C , net photosynthesis is reduced at an increasing rate.

Two nitrogen stress variables are calculated in SIMPOTATO (NDEF1 and NDEF2).

NDEF1 is used to calculate nitrogen stress effects on photosynthesis, while NDEF2 is used to calculate effects on leaf growth.

$$\text{NDEF1} = 1.0 - ((\text{TCNP} - \text{TANC}) / (\text{TCNP} - \text{TMNC})) 0.6 \quad (3.36)$$

$$\text{NDEF2} = 1.0 - ((\text{TCNP} - \text{TANC}) / (\text{TCNP} - \text{TMNC})) 0.75 \quad (3.37)$$

Where TCNP is the leaf critical nitrogen concentration (g of N / g of dry weight), TANC is the leaf actual nitrogen concentration (g of N / g of dry weight), and TMNC is the leaf minimum nitrogen concentration (g of N / g of dry weight). The critical and minimum nitrogen concentration levels vary with plant development stage. From plant emergence to the beginning of rapid tuber growth the critical nitrogen concentration level used is 7% per gram of dry weight, and the minimum level is 6% per gram of dry weight. After tuber bulking, these levels reduce to 6% and 5% respectively. The nitrogen deficit factors (NDEF1, NDEF2) equal 1.0 when the leaf actual nitrogen concentration equals the leaf

critical nitrogen concentration, and these factors decreases linearly to zero as the leaf actual nitrogen concentration decreases from the critical to minimum concentration level.

Potential dry matter production (PCARB) is estimated in grams per plant using the following equation:

$$\text{PCARB} = 4.0 \times \text{PAR} / \text{PLANTS} (1. - \text{EXP} (- 0.55 \times \text{LAI})) \quad (3.38)$$

Where PAR is MJ m⁻² and PLANTS is plants m⁻². This equation shows that the value used to describe the rate at which global radiation traveling through the potato canopy is reduced due to scattering and absorption (extinction coefficient) is 0.55. In this equation, 4 g of biomass is produced per MJ of intercepted PAR. Other factors also influence potential net photosynthesis. Before tuber initiation the photosynthetic efficiency is assumed to be 4 g carbohydrate m⁻² MJ⁻¹. However, photosynthetic efficiency rate (PCF) increases after tuberization. At this time SIMPOTATO assumes a PCF value of 5 g carbohydrate m⁻² MJ⁻¹.

According to Dwelle (1985), the photosynthesis rate in the potato is also limited by tuber sink strength so the daily calculation of net photosynthesis (CARBO) is done after the effects of nitrogen, temperature and water stresses on organ growth and partitioning are calculated. The nitrogen (NDEF1), temperature (PRFT) and water (SWDF1) stress factors are used to make a preliminary estimate of daily net photosynthesis in grams of carbohydrate per plant. Daily carbohydrate production (CARBO) is the product of potential dry matter production (PCARB) and the smallest of the three stress factor values

for each day. The smallest stress factor (between 0 and 1) will be the factor which is most limiting to plant growth.

At tuber initiation the model assumes that the leaf critical nitrogen concentration is 7% of dry weight, the stem critical nitrogen concentration is 4.6% of dry weight. The optimum ratio of daily leaf growth to daily stem growth is 4. In a nitrogen limiting condition the model processes a number of steps to reduce nitrogen demand until the available nitrogen meets demand. These steps are: 1) use any available nitrogen from the seed reserve, 2) if leaf nitrogen is above the leaf critical nitrogen concentration then the surplus is removed for new growth, 3) if leaf, stem or tuber nitrogen is more than the minimum, then these are reduced to the minimum and the surplus becomes available, 4) shift growth from leaves to stems and tubers according to a set nitrogen:carbon ratio and 5) remove carbon from leaves to free more nitrogen for tuber growth.

3.6.2 Leaf Growth and Senescence

Potential leaf area expansion (PLAG, $\text{cm}^2 \text{ plant}^{-1}$) is calculated from daily thermal time and a plant genetic coefficient for leaf expansion ($G2$, $\text{cm}^2 \text{ plant}^{-1}$):

$$\text{PLAG} = G2 \times \text{DTT} \quad (3.39)$$

The top dry weight needed for this leaf growth is calculated daily from the variable PLAG and the specific leaf weight.

Leaf senescence due to normal aging is calculated for each growth stage. The ratio of top weight (leaf + stem weight) to leaf area should increase with age as the proportion of stems and branches increases. Hodges (1997) observed that experimental field data at Hermiston (1988)¹ and Prosser (1989)² confirm this trend. Following tuber bulking, senescence increases in the plant as it progresses through stage 3. After senescence due to aging is calculated leaf and stem weights are adjusted for senescence. Senesced stem weight and half of senesced leaf weight is added to the dead leaf total and the other half of the senesced leaf weight is added to the daily net photosynthesis to account for remobilization of carbohydrates.

Leaf senescence due to normal aging (SLAN, cm² plant⁻¹) is calculated in the absence of plant stress. Specific leaf weight, the ratio of leaf dry weight to plant leaf area is set to a constant value (0.005 g carbohydrate per cm² of leaf area). Some varieties will have a different specific leaf weight and plant nitrogen concentration which may also affect senescence, but this is not considered in the model. Hodges (1997) observed that of the two cultivars Hilite and Russet Burbank, the Hilite has the higher leaf density.

From emergence to tuber bulking senescence increases:

$$\text{SLAN} = \text{CUMDTT} \times \text{PLA} / 10000 \quad (3.40)$$

where SLAN is senescence (cm² plant⁻¹), CUMDTT is accumulated daily thermal time and PLA is plant leaf area.

¹ Hermiston Research Station, USDA-ARS, Hermiston, Oregon, 1988

² Prosser Research Station, USDA-ARS, Prosser, Washington, 1989

After bulking, senescence increases as the plant progresses through stage 3 as indicated by increasing values of the variable XSTAGE (values 1, 2 or 3):

$$SLAN = PLA / (500 \times 3 / XSTAGE) \quad (3.41)$$

During stage 3, stem senescence (STLOSS, g plant⁻¹) is also calculated as a fraction of senesced leaf area using equation 3.41. This is calculated to a maximum of the estimated plant stem weight.

$$STLOSS = SLAN \times 0.2 \times 0.0050 \quad (3.42)$$

At maturity (stage 4) a greater senesced leaf area is calculated using equation 3.43.

$$SLAN = PLA / (500 / XSTAGE) \quad (3.43)$$

Effects of water nitrogen and cold temperature stresses on leaf senescence are calculated. If nitrogen or water stress exists, the stress factors (NDEF2 and SWDF1) are used to calculate additional leaf loss. Top kill caused by frost is simulated by having increasing leaf kill from 0°C down to -7°C. The leaf senescence factor due to low temperatures (SLFT) is calculated using the equation:

$$SLFT = 1 - 0.02 \times T_{min}^2 \quad (3.44)$$

After senescence due to aging is calculated, leaf and stem weights are adjusted for senescence. Senesced stem weight and half of senesced leaf weight is added to the dead leaf pool (DEADLF, g of carbohydrate plant⁻¹) and half of the senesced leaf weight is added to CARBO to account for remobilization of carbohydrates. All nitrogen is assumed to be remobilized.

3.6.3 Root Growth

Simulation of root growth is made during the vegetative growth stage of the plant. It is during this stage that leaf, stem and root growth occur. In the model, daily and accumulated thermal time (optimum 17°C) are used to calculate growth rate which is used to simulate potential daily root growth (GRORT g carbohydrate plant⁻¹). After net daily photosynthesis is calculated (actual daily carbohydrate input), partitioning of new photosynthate to leaves, stems and roots is simulated. With the onset of tuber initiation, less photosynthate is partitioned to roots, stems and leaves and an increasing amount goes into tuber growth. As with top and tuber weights, root weight is incremented by the amount of daily growth. Prior to tuber initiation root growth is constant even if the plant is subject to moisture or fertility stresses. During the tuber bulking stage, nearly all available carbohydrate collects in the tubers. Root and leaf growth essentially stops at the end of tuber bulking. Root growth is reduced at this stage to 10% of the daily total plant biomass production (Hodges, 1997).

3.6.4 Tuber Growth

Since temperature affects the growth of the tuber, a temperature limitation factor on partitioning to tubers (ETGT) is calculated during tuber growth stages (Figure 3.2).

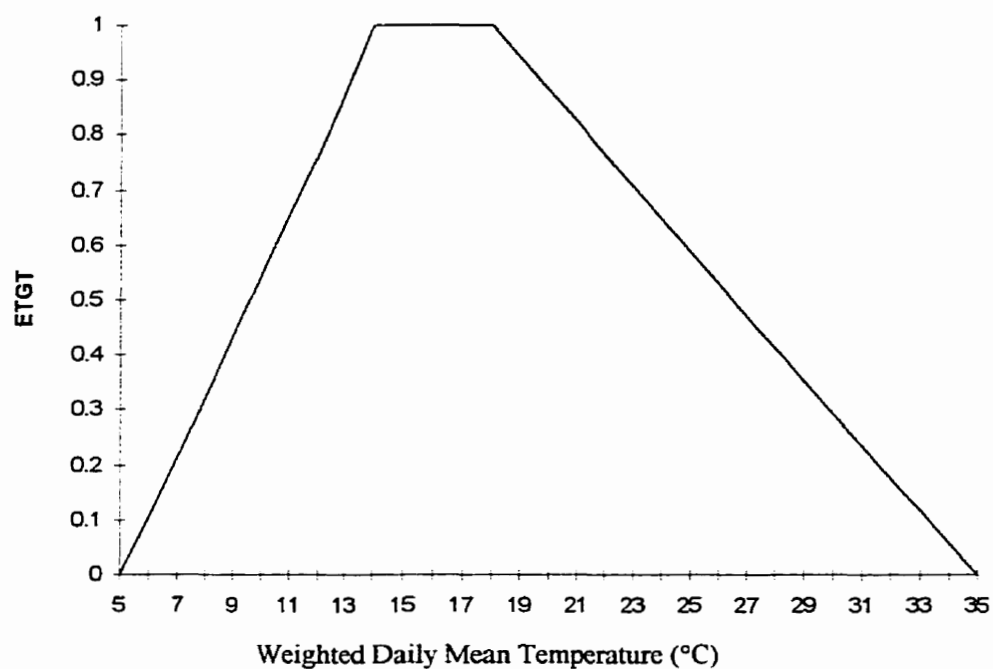


Figure 3.2 Temperature limitation factor on partitioning to tubers

Figure 3.2 shows that maximum potential tuber growth is greatest with daily mean temperatures between 14°C to 18°C. This figure also indicates that tuber growth is more sensitive in the range of 5 to 14°C compared to the range from 18 to 35°C.

Percent dry matter in the tubers and fresh tuber weight is simulated from daily thermal time. Percent dry matter in the tubers is initiated at 12% and then increases or decreases daily during the tuber growth period based on daily thermal time. SIMPOTATO makes no distinctions between initial percent dry matter for different cultivars in rate of change or in response to environment. Hodges (1997) notes that the Russet Burbank cultivar tends to have a higher percent dry matter than some other varieties. However, he suggests that

other variables may also effect percent dry matter, and the understanding of the process is inadequate at this time to be used for modeling.

Another important simulated growth variable is the potential maximum tuber growth (TUBMAX, g of carbohydrate plant⁻¹). TUBMAX is calculated from the minimum of a temperature limitation factor (ETGT) or a tuber partitioning factor representing the fraction of daily net growth potentially going into tuber growth (PARTUB) multiplied by a genetic coefficient for rate of tuber growth (G3).

An initial estimate of tuber growth is made from TUBMAX and the genetic coefficient for tuber growth (G1):

$$\text{GROTUB} = \text{G1} \times \text{TUBMAX} \quad (3.45)$$

For indeterminate cultivars such as Russet-Burbank, this initial estimate of tuber growth will be 0.0 until the model calculates how much of the available carbohydrate (CARBO plus carbohydrate from the seed piece and released from leaf senescence) will be needed for leaf growth. For determinant cultivars the model assumes tuber growth to have priority over top growth. In this case tuber growth is limited by photosynthesis and the degree of tuberization (Hodges, 1997).

Carbohydrate potentially available from the seed piece is used as a source. The seed piece can provide up to 1.5 g per plant per day if needed until it is all used (Hodges, 1997).

The changed weight of the seed piece is calculated after the model determines whether carbohydrate from the seed piece will be needed to support growth.

Initial Carbohydrate Partitioning (stage 1) is divided between leaf, stem, and root growth. The potential growth for each of these three plant parts is calculated using thermal time and genetic coefficients. The daily total potential growth is the sum of these three calculations. This total is compared to estimated net daily photosynthesis (CARBO). If total potential growth is greater than CARBO, then it is compared to potentially available carbohydrate (CARBO plus that carbohydrate available from the seed). If CARBO is greater than potential growth, photosynthetic rates are assumed to be sink limited so CARBO is reduced. If potential growth is greater than available carbohydrate then leaf, stem, and root growth are each reduced so that the ratio of leaf plus stem potential growth to root potential growth remains unchanged. If potential growth is greater than CARBO but less than available carbohydrate then the amount of stored carbohydrate in the seed is reduced by the difference between potential growth and available carbohydrate (Hodges, 1997). This is the amount of growth that will occur unless nitrogen is limiting.

3.6.4.1 Tuber Growth Rate

Calculations for the tuber growth rate after initiation are made separately for determinate and indeterminate varieties. For determinate varieties, the fraction of daily net growth going to tuber growth (PARTUB) is used. The tuber growth rate increases as PARTUB increases. PARTUB is calculated from the degree of tuber induction (TIND). Before

tuber initiation PARTUB is zero. It increases linearly with TIND to 1.0 during tuber bulking when potentially all available carbohydrate and nitrogen may be partitioned to new tuber growth. For indeterminate varieties, tuber growth is initially set to zero, and if daily net carbohydrate production is greater than that required for top and root growth then tubers will grow. Tubers will then absorb available nitrogen before haulm and so may reduce top growth if nitrogen is limiting and daily carbohydrate production is sufficient (Hodges, 1997).

Chapter 4 Methods and Materials

Evaluation of the crop simulation model was undertaken by conducting field experiments during the spring and summer of 1996, 1997 and 1998. Important crop growth and development characteristics were measured. The experiment was conducted four km north of Carberry, Manitoba at the Manitoba Crop Diversification Centre (MCDC).

Figure 4.1 illustrates the regional and local position of MCDC, and the approximate plot location for each of the three trial years.

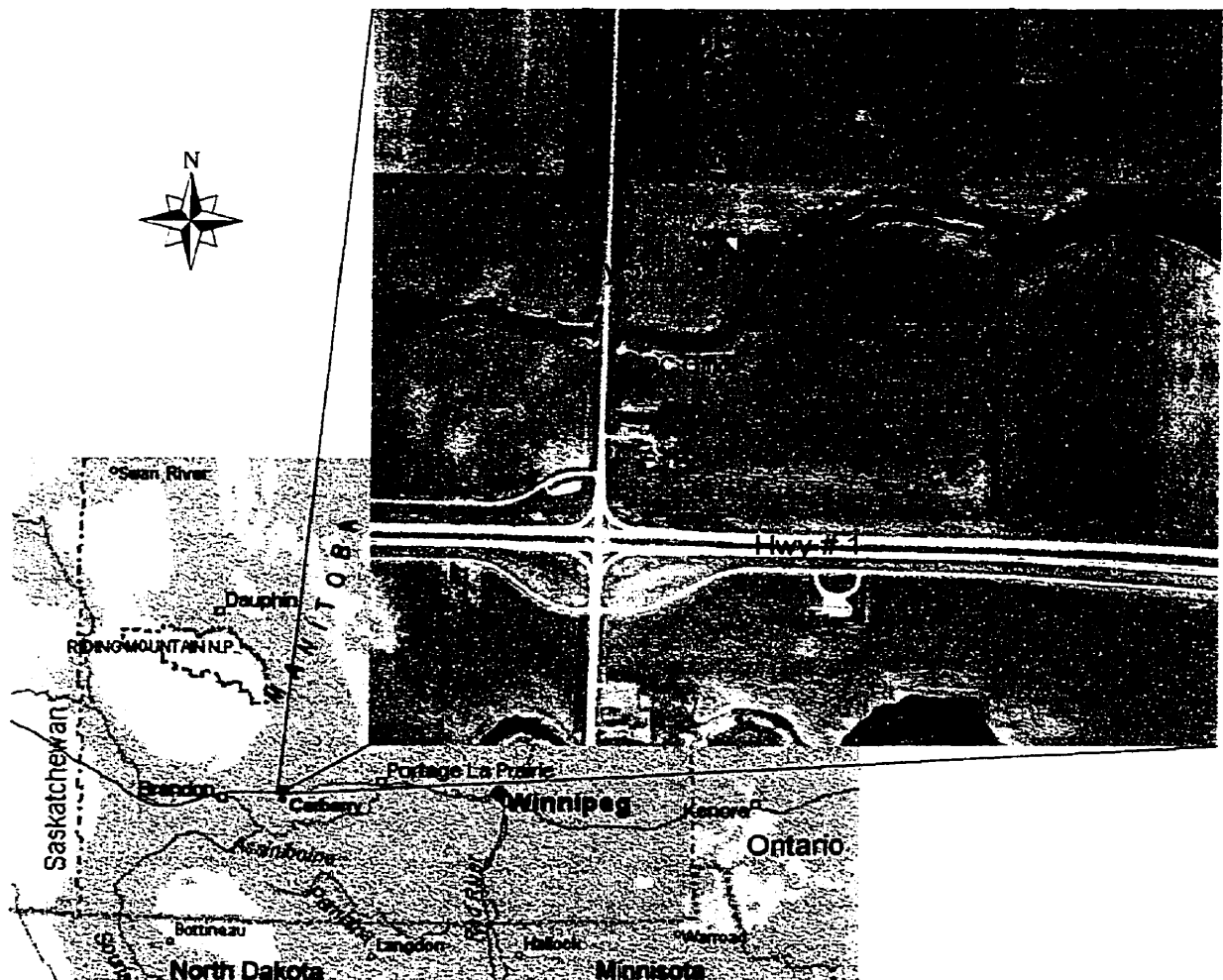


Figure 4.1 Manitoba Crop Diversification Centre and regional map

MCDC provided necessary equipment and labor to plant, irrigate, fertilize and manage pests and diseases. The 1996, 1997 and 1998 trials were laid out in a split-plot design with four complete blocks. The size of the experiment for each trial-year was 60 m by 120 m. Main plot treatments were varieties (Shepody and Russet Burbank). Sub-plot treatments were separated into four moisture treatments, A, B, C and D. To illustrate this layout the 1997 experiment plan is provided (Figure 4.2). The 1996 and 1998 plot maps are provided in Appendix B.

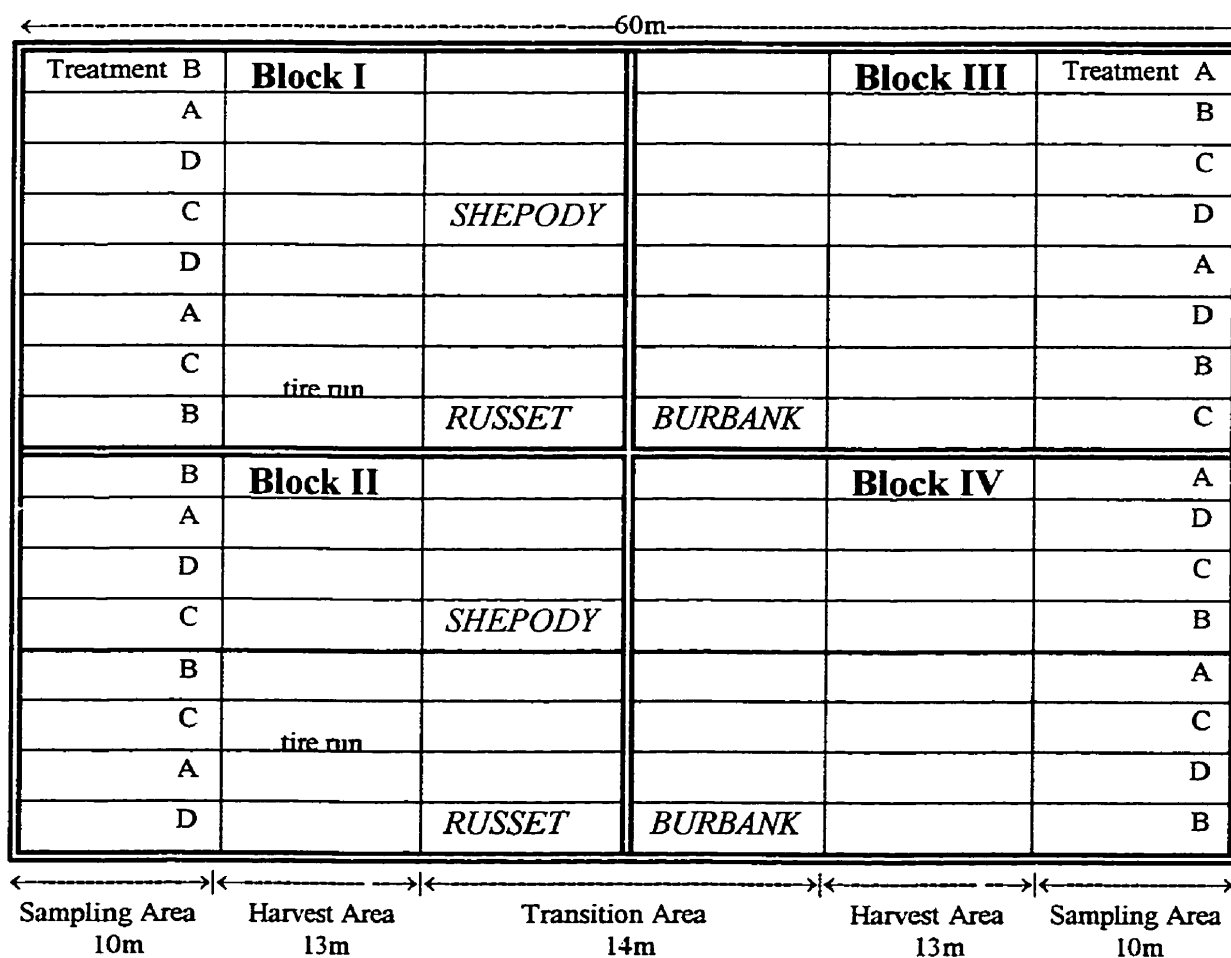


Figure 4.2 MCDC potato trials, Carberry, 1997

The locations of the sub-plot treatments were randomly selected in each of the trial years. Treatment A was irrigated when 25% of the plant-available water in the root zone was depleted. Available soil moisture was determined using soil moisture and root depth measurements (section 4.1.1). Treatment B was irrigated when 45% of the available water was depleted, and C was irrigated at 65%. Treatment D received rain only and no irrigation. Treatments A, B and C were irrigated to field capacity moisture content (100%) when the treatments averaged at or below their specified available soil moisture threshold. Figure 4.3 shows the irrigation of selected treatments by the irrigation system at MCDC. The movement of the irrigation lateral was in a East-West direction across the experimental plot.

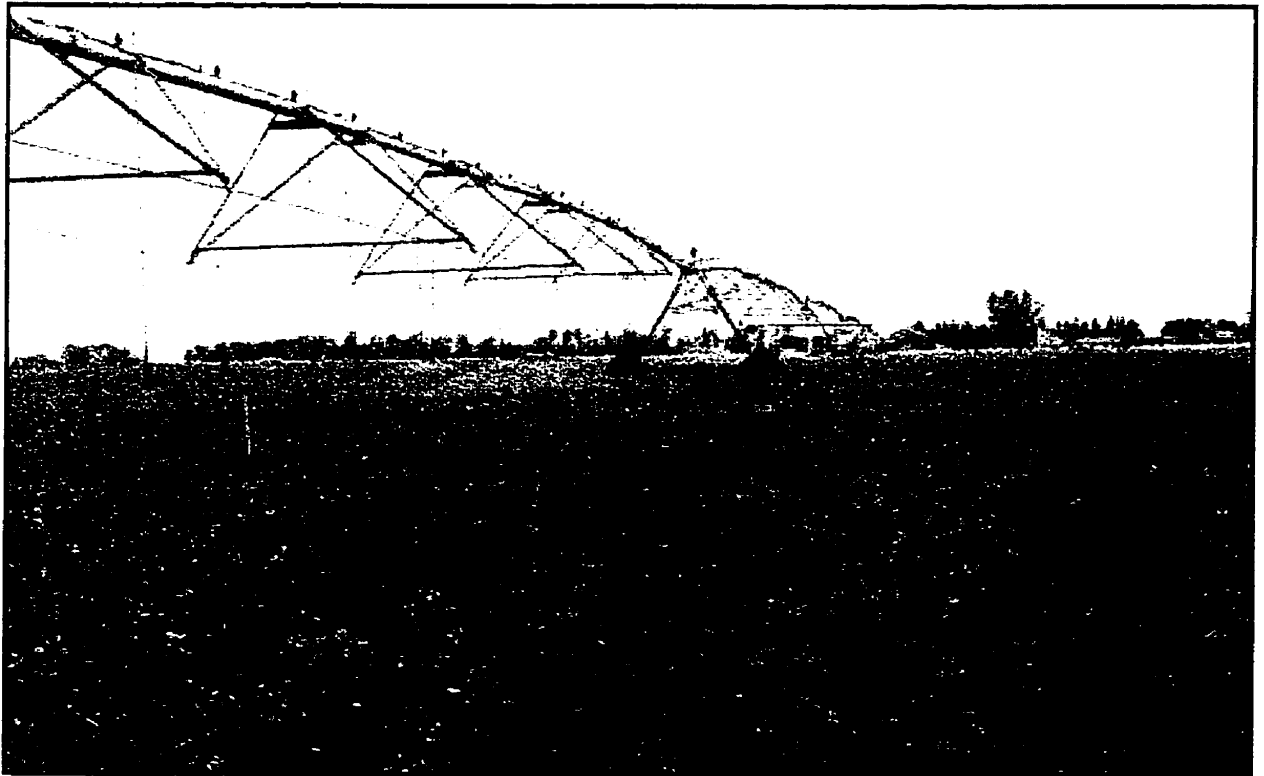


Figure 4.3 Irrigating the experimental plot, Carberry

Important field season information for the three trial years is provided in Table 4.1.

Table 4.1 Field season information

Year	Seeding Date	Crop Desiccation Date	Average Seed Piece Mass (g)
1996	May 13	September 20	60
1997	May 20	September 19	60
1998	May 20-21	September 18	Russet 61 Shepody 65

The trials in 1996, 1997 and 1998 used a 95 cm row spacing and within-row seed piece spacing of 31 cm for Shepody and 38 cm for Russet Burbank. Fertilizers were applied to meet or exceed recommendations for irrigated processing potatoes (Platford *et al.*, 1994). This resulted in the fertilizer applications described in Table 4.2. All pests were effectively controlled.

Table 4.2 Rates, method and time of fertilizer applications

Year	Fertilizer Regime
1996	155 kg ha ⁻¹ of N as granular urea incorporated prior to planting
	45 kg ha ⁻¹ of N applied with the irrigation system
1997	80 kg ha ⁻¹ of N as granular urea incorporated prior to planting
	56 kg ha ⁻¹ of N as urea broadcast (prior to 1st hilling)
1998	170 kg ha ⁻¹ of N as granular urea incorporated prior to planting
	50 kg ha ⁻¹ of P ₂ O ₅ and 25 kg ha ⁻¹ K ₂ O incorporated prior to planting

The field experiment for evaluating SIMPOTATO was structured so that the primary data input requirements of the simulation model were met and that the field measurements made were ones that would allow for comparison of important model estimates.

The field data collected for the growth and development of a potato crop are presented in this section along with a description of the methods and rationale used. These measurements include gross yield, observations of biomass growth in tubers and the above ground part of the plant (haulm) throughout the growing season. The necessary daily weather inputs used in the model were collected at the experiment site. Global radiation, air temperature and precipitation were measured and logged by an automated weather station at 15 minute intervals. SIMPOTATO also estimates crop water use and available soil moisture. Comparisons of estimated water use by the crop and actual soil moisture availability were also made.

4.1 Measurements

4.1.1 Soil Characteristics and Soil Moisture

Soil particle size distribution for the top 15 cm of the Ramada soil was found to be 31% sand, 45% silt and 24% clay (loam).³ Below this depth sand becomes a more important component of the soil. Soil measurements were made for successive 15 cm thick layers from the soil surface to a depth of 60 cm, below which was the final segment (30 cm) down to 90 cm. Sand was often encountered in the deepest layer of the soil at MCDC. Measurements of depth to sand for the experimental plot in 1997 were made by Tomaszewicz.⁴ Out of eight 1997 sampling sites, sand was encountered between 88 and 120 cm at five sites, and the other three sites had no sand to at least 120 cm. At the 1998 experimental plot, four of twelve evenly spaced sites revealed sand at less than 90 cm.

³ Melanie Head, 1998, personal communication

Information on depth to sand for the 1996 trial location was not available, but very likely similar variability existed within the soil at this location as with that at the 1997 and 1998 locations. Such variability is not conducive to accurately measuring crop water use, and is a source of error within model simulation results as well as error in the soil moisture measurements used to evaluate the model.

Throughout each of the experimental seasons, soil moisture contents were measured weekly and sometimes twice weekly using a neutron probe (Campbell Pacific Nuclear Corp.) for every moisture treatment for every block.⁵ Water use by the crop was calculated from these results, and irrigation water applied to compensate for the deficit in water use over precipitation. Probe calibration was performed during May in each of the three growing seasons at the same time sampling was performed to assess the field capacity of the Ramada soil (described below). The calibration procedure involved collecting neutron readings with the probe at specific soil depths (Figure 4.4), and graphing these readings with the measured soil moisture at the corresponding depths.

⁴ Dale Tomaszewicz, 1997, personal communication

⁵ Trade names are provided for the benefit of the reader and do not imply endorsement by the author

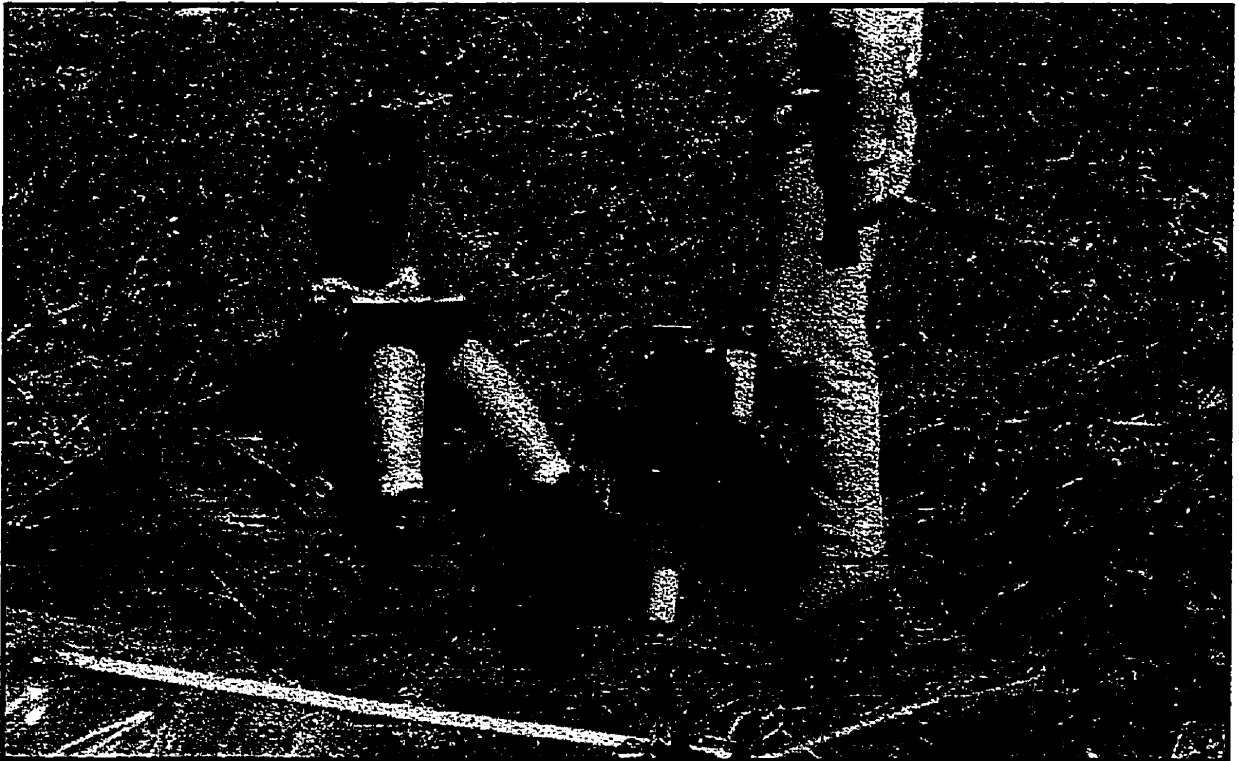


Figure 4.4 Neutron probe calibration

In order to develop a calibration curve which works within the range of soil moistures to which a crop of potatoes is subject during growth, other sites were used for calibration. These sites included sandier soils (1998), other non-field capacity sites on and near the experimental plot (1996, 1997, 1998), and a nearby site which had a forage crop (1997). This calibration resulted in two linear equations that were used to estimate soil moisture. Because of the loss of the emitted (fast) neutrons from the soil surface, a regression curves was used to estimate volumetric soil moisture from neutron counts for the uppermost soil layer (0 to 15 cm), while another equation was used for all of the lower soil layers (15 to 90 cm). Table 4.3 lists the calibration equations used in each of the trial years.

Table 4.3 Neutron calibration curves used for each trial year

Year	Depth (cm)	Equation
1996	0 to 15	$\theta = 0.0041 CP^{\frac{1}{2}}M - 1.5195$
	15 to 30	$\theta = 0.0046 CP^{\frac{1}{2}}M - 12.606$
1997	0 to 15	$\theta = 0.0031 CP^{\frac{1}{2}}M + 10.736$ (4.1)
	15 to 30	$\theta = 0.0048 CP^{\frac{1}{2}}M - 13.41$ (4.2)
1998	0 to 15	$\theta = 0.0041 CP^{\frac{1}{2}}M - 1.5195$ (4.3)
	15 to 30	$\theta = 0.0046 CP^{\frac{1}{2}}M - 12.606$ (4.4)

where θ is volumetric soil moisture and $CP^{\frac{1}{2}}M$ is the neutron count per half minute.

Equations 4.3 and 4.4 are a combination of the 1997 and 1998 calibration data collected, and were used for estimating soil moisture throughout the 1998 field season. Equations 4.1 and 4.2 were obtained from data collected in the spring of 1997 and used for the 1997 experiment. Although no regression curves were available for the 1996 field season, neutron readings were taken. Growing season soil moisture was estimated for 1996 using the 1998 equations.

4.1.1.1 General Soil Characteristics

Soil profile properties are used in the soil water, nitrogen and root growth sections of the crop model. A number of soil parameters are used in the model because of their influence on various processes of soil water availability. These soil properties are read into the model at the start of the simulation, and include constants like bare soil albedo, upper limit of stage 1 soil evaporation, soil drainage constant and Soil Conservation Society of America (SCS) runoff curve.

The values of the soil properties used to run SIMPOTATO for the Ramada soil are provided in Table 4.4.

Table 4.4 Ramada soil constants

Soil Property	Value
Bare Soil Albedo	0.14
Upper limit of stage 1 soil evaporation (mm)	6
Soil Drainage Constant (fraction drained per day)	0.3
SCS Runoff Curve (from SCS tables)	0.4

Measurement of soil pH was conducted using procedures outlined by Peech (1965).

4.1.1.2 Physical Properties of the Ramada Soil

The field capacity of a soil and the permanent wilting point are primary parameters required to determine the amount of water available to the plant. Field capacity is the soil moisture content after equilibrium with deep drainage. The permanent wilting point is that soil moisture content at and below which no moisture is available to the plant. The method used to assess the field capacity of the Ramada soil prior to planting is as follows. Eight evenly distributed sites were selected on the experimental plot. Each site consisted of approximately 1.5 × 1.5 m of reasonable level ground bordered by soil that was mounded up to a height of 15 to 20 cm. These sites were flooded with about 10 cm of water, covered with plastic to prevent evaporation and left to allow percolation into the soil. After about three days the soil was assumed to have drained to field capacity and soil samples were taken for measurement of bulk density and moisture content. Four replicate holes were augured at each of the eight sites to attempt to account for the variability of the soil (Figure 4.5).

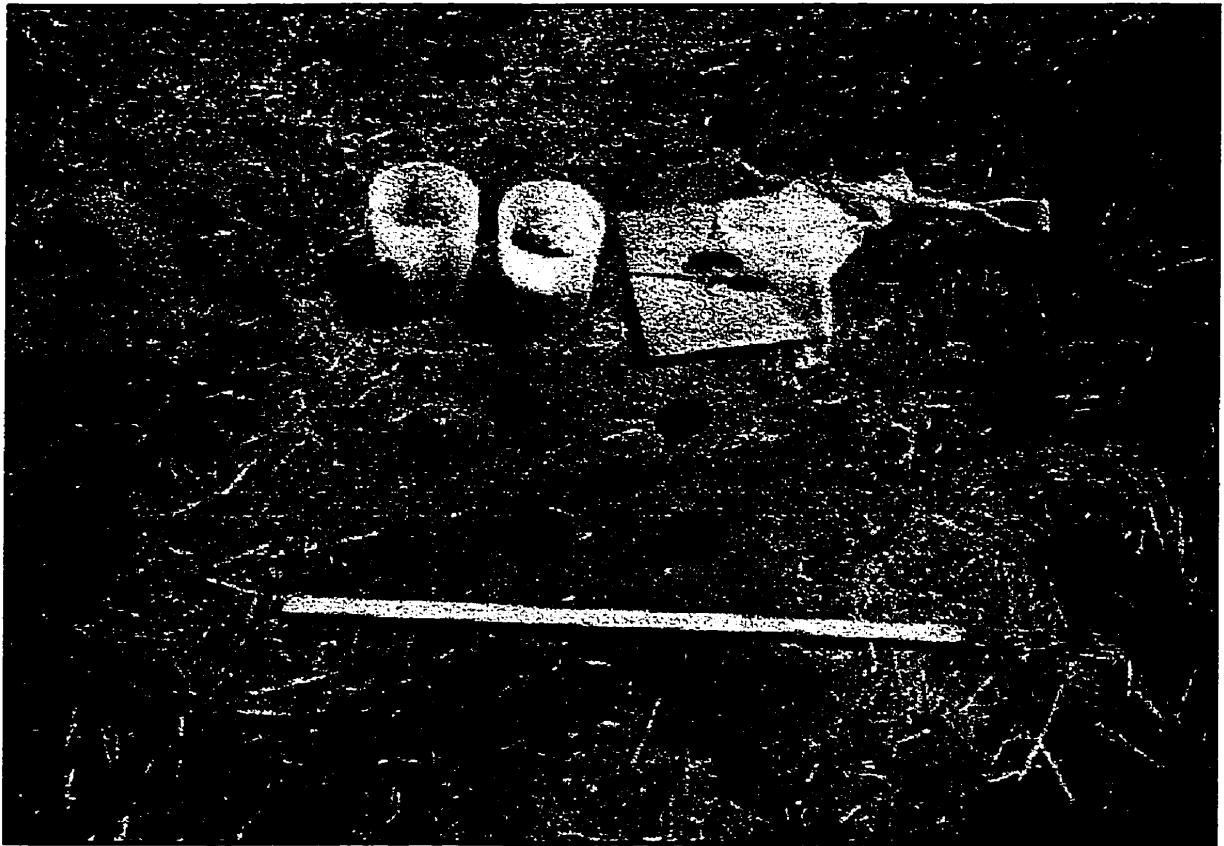


Figure 4.5 Characterizing the physical properties of the soil at the experimental site

A total of 32 holes in all were dug on the plot in each trial year. The diameter of each of these holes ranged between 11.4 and 11.8 cm. This makes the size of these samples large enough to minimize the error associated with measuring the hole diameter for calculating bulk density. The soil profile of each replicate was divided into 5 segments. These segments are 0 to 15 cm, 15 to 30 cm, 30 to 45 cm, 45 to 60 cm and 60 to 90 cm. This provided a vertical characterization of the Ramada soil.

The soil was removed from each hole for each of the five depth layers and weighed. The depth of the samples was measured for each segment. Using the hole diameter and segment sample depth, the volume of each sample was calculated.

$$\text{Volume} = 3.14 \times (\text{diameter of hole} / 2)^2 \times \text{depth of the segment sample} \quad (4.5)$$

A soil sample of 350 to 450 g was taken from each of the depth segments for calculation of gravimetric moisture content (GWC, equation 4.6).

$$\text{GWC \%} = \frac{\text{mass of wet soil sample} - \text{mass of oven dry soil sample}}{\text{mass of oven dry soil sample}} \times 100 \quad (4.6)$$

Using the GWC of the subsample, the oven dry mass of the entire segment sample was calculated (equation 4.7).

$$\frac{\text{oven dry mass of total segment sample}}{\text{segment sample}} = \frac{\text{total wet mass}}{1 + (\text{GWC} / 100)} \quad (4.7)$$

The bulk density (BD) for each profile segment was then calculated (equation 4.8).

$$\text{BD} = \frac{\text{oven dry mass of segment sample}}{\text{volume of the sample}} \quad (4.8)$$

Volumetric moisture content can then determined from GWC and BD.

$$\theta = \text{GWC} \times \text{BD} \quad (4.9)$$

The drained upper limit of moisture available to the plant is required by the model. The average depth of the segments used to determine field capacity corresponds to the depths for which readings were taken by the neutron probes. For example, neutron probe readings were taken at the 37.5 cm depth to estimate soil moisture for the 30 to 45 cm depth segment.

The lower limit of extractable water (permanent wilting point) was estimated for each depth segment using a pressure membrane apparatus to determine the 15 atmosphere percentage. The 15 atmosphere percentage has been found to be closely related to the

permanent wilting percentage (Lehane and Staple, 1960). For this determination, composite samples for each of the five depths were made using the four replicate holes dug in the field capacity test. This was done for each of the eight field capacity sites to gain representative permanent wilting point values for the experimental plot. These eight different composite soil profiles were used to determine the 15 atmosphere percentage for each layer using a pressure membrane apparatus. The 40 samples were placed into the apparatus and subjected to 15 atmospheres of pressure exerted by nitrogen gas (Figure 4.6).

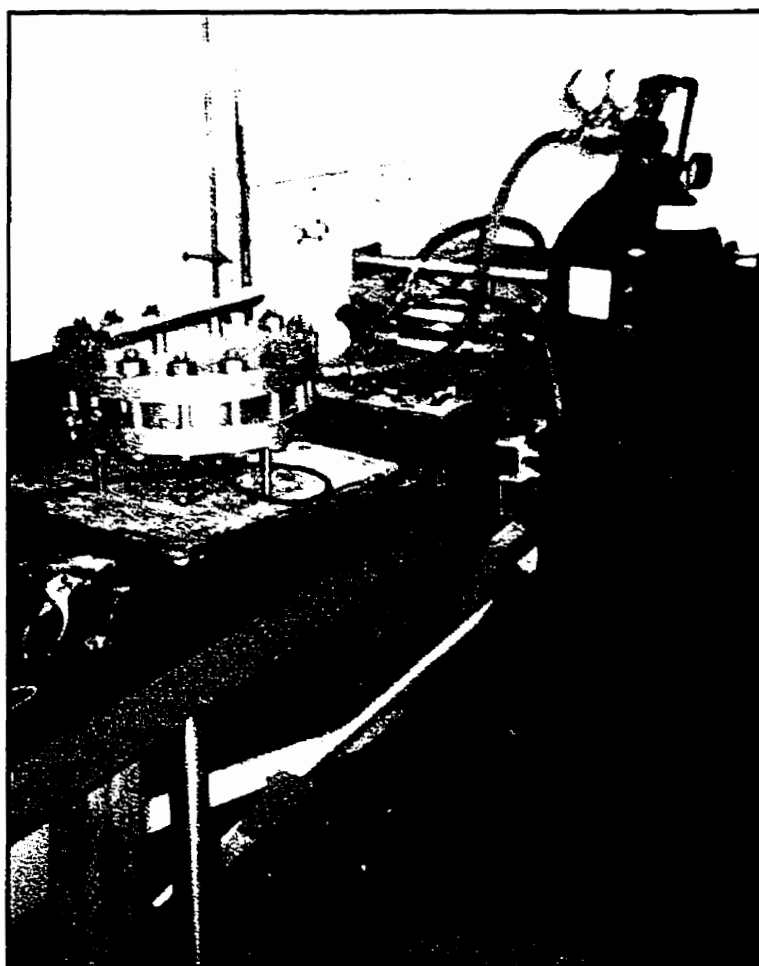


Figure 4.6 Pressure membrane apparatus

After the samples equilibrated, i.e. outflow ceased, they were dried to calculate gravimetric moisture content. Using the average bulk density values for each of the five depth segments determined earlier, volumetric moisture percentage was calculated for the samples. This percentage was used as model input data for the lower limit of available water to plant roots.

Field capacity and permanent wilting percentage data measured for the three growing seasons are given in Table 4.5.

Table 4.5 Average field capacity and permanent wilting percentage of five Ramada soil depths for 1996, 1997 and 1998

Year	Depth (cm)	Field Capacity (% by Volume)	Permanent wilting Percentage (% by Volume)
1996	0 to 15	34.23	12.0
	15 to 30	35.13	12.0
	30 to 45	36.21	10.0
	45 to 60	36.51	10.0
	60 to 90	36.81	8.0
1997	0 to 15	34.38	16.51
	15 to 30	34.73	17.86
	30 to 45	34.45	20.24
	45 to 60	33.72	18.46
	60 to 90	25.44	14.95
1998	0 to 15	34.59	18.01
	15 to 30	35.02	17.81
	30 to 45	35.42	18.74
	45 to 60	36.41	16.54
	60 to 90	32.65	19.31

4.1.2 Weather Data

Daily measurements of rainfall, maximum and minimum temperature and global radiation were taken from planting to harvest for each year. The data was collected at the research site using an Adcon automated meteorological station (Geotech Environmental Services)⁶. Summary climate data is provided (Table 4.6) for the three growing seasons.

Table 4.6 Summary of climatic data for the 1996, 1997 and 1998 growing seasons

Year	Parameter	Max Daily Temperature (°C)	Min Daily Temperature (°C)	Global Radiation (MJ m ⁻² day ⁻¹)	Precipitation (mm)
1996	Average	22.7	9.0	15.8	-
	Minimum	9.8	-5.6	2.6	-
	Maximum	34.7	19.1	39.6	-
	Total	-	-	2080.1	267
1997	Average	23.7	9.2	21.7	-
	Minimum	9.0	-4.0	0.5	-
	Maximum	34.2	18.5	33.2	-
	Total	-	-	2706.9	203
1998	Average	23.1	9.8	19.8	-
	Minimum	9.2	-1.4	1.3	-
	Maximum	33.4	19.3	31.8	-
	Total	-	-	2487.4	435

In addition, net radiation data collected at Environment Canada's automated weather station at MCDC was also used.⁷ Net radiation is the difference between radiation gained from the sun and the atmosphere and that lost by reflection, transmission and emission (Monteith, 1965). This climatological station is a permanent site and was located

⁶ Trade names are provided for the benefit of the reader and do not imply endorsement by the author

⁷ Environment Canada, Atmospheric Environment Service, automated station

approximately 30 m west of the 1996 plot location, approximately 100 m north of the 1997 location and 400 m WNW location of the 1998 experimental plot.

Since there were 26 days after planting in which there was no global radiation data available for 1997, the net radiation data from the AES station was used with the solar radiation data collected over the plant canopy. The relationship between the two measured radiation data between June 16 and September 20, 1997 was found to be a linear one with an r^2 of .92, a Root Mean Square Error of $1.84 \text{ MJ m}^{-2} \text{ day}^{-1}$ and is described by the regression equation:

$$\text{Global Radiation} = 3.37249 + 1.53074 \times \text{Net Radiation} \quad (4.10)$$

where Solar and Net Radiation are in units of $\text{MJ m}^{-2} \text{ day}^{-1}$.

To identify if there are biases, the regression residuals can be graphed with either the dependent or independent variables. Figure 4.7 is such a residual plot and reveals two model biases: 1) estimates are poorer when daily net radiation values are low, and 2) late season estimates have a greater scatter around the regression line, while early season predictions are underestimated until Net Radiation exceeds $14 \text{ MJ m}^{-2} \text{ day}^{-1}$.

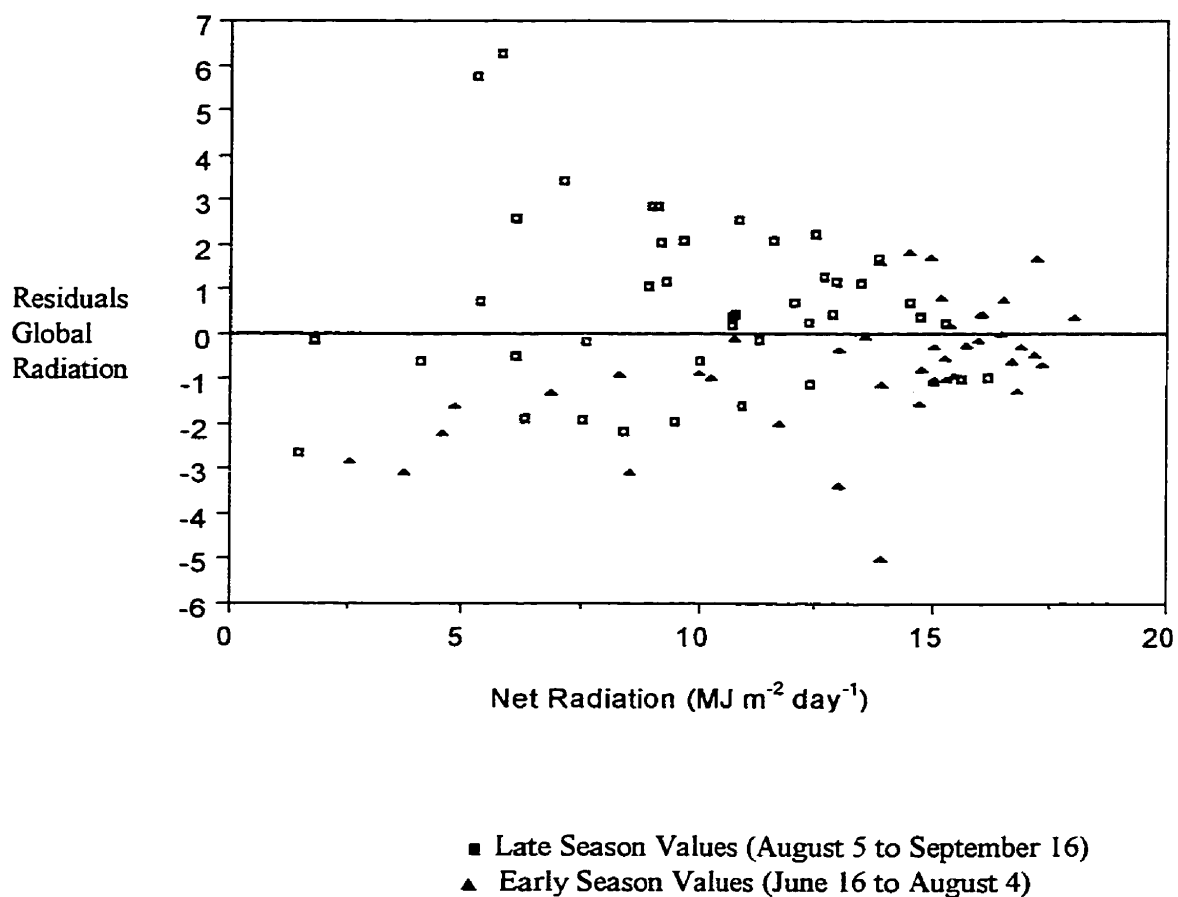


Figure 4.7 Global radiation model residuals with measured net radiation, Carberry, 1997

Results from the global radiation model are plotted in Figure 4.8 with measured global radiation for the period of June 24 to September 16, 1997. Although the model slightly overpredicts when actual daily solar radiation is low and slightly underestimates radiation when actual values are high (using the 1:1 line as reference), the differences are small.

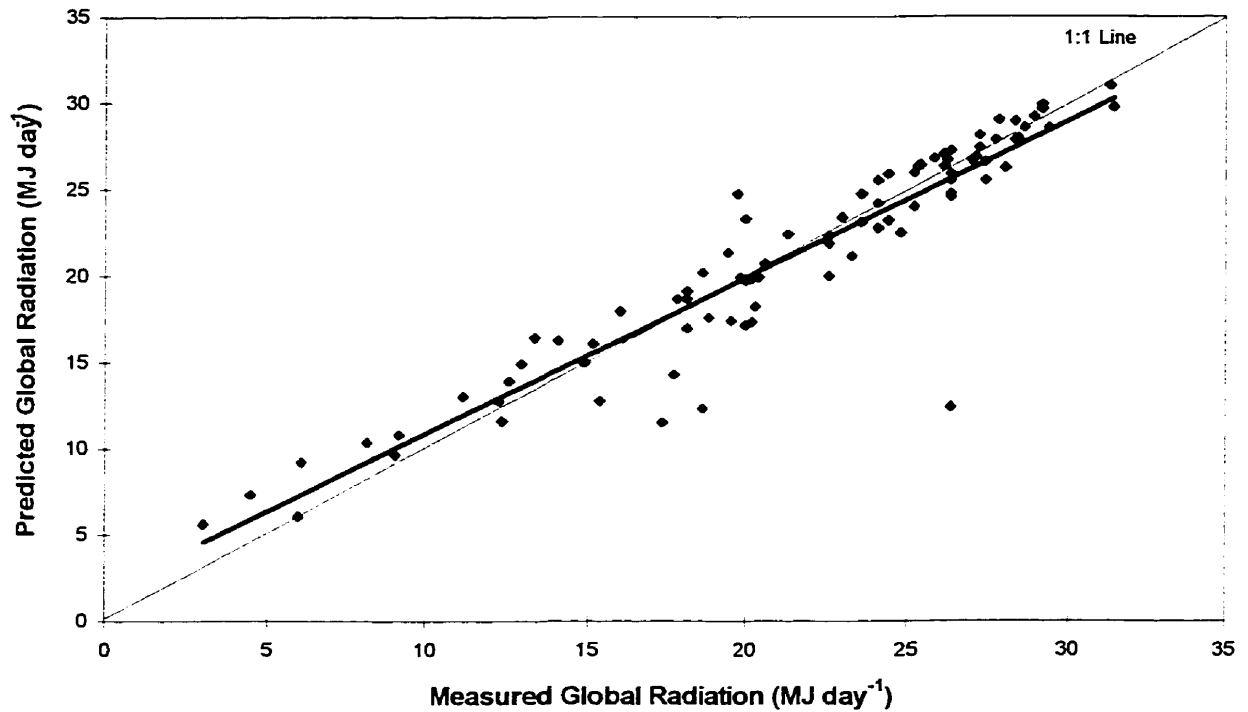


Figure 4.8 Modeled global radiation with measured global radiation, Carberry, 1997

Equation 4.10 was then used to estimate the missing global radiation data needed to run SIMPOTATO between May 20 and June 16, 1997 as well as for estimating global radiation which was not measured in 1996.

4.1.3 Crop Measurements

4.1.3.1 Growth Measurements

A number of measurement were taken to determine the growth of each treatment for each variety for each of the trial years. These measurements included emergence counts, percent crop cover (not in 1998), haulm and tuber biomass accumulation, leaf area, stem

length (1997 only) and root depth (not in 1998). After each variety had matured, they were harvested and total fresh yield was determined for each irrigation treatment.

Emergence counts were made daily from the time the first sprouts began to emerge till there was no appreciable increase in new sprouts. The measurement procedure involved recording the number of plants with a height of at least 1 cm above the soil surface. These counts were taken on the two 13 m centre rows of each moisture treatment for each variety. This procedure was repeated for each of the four experimental blocks and the data was averaged. Percent emergence is calculated by dividing the number of emerged plants by the total number of viable seed tubers per row. Emergence was defined as the time when 50 % of the viable seeds had emerged. Emergence data for Russet Burbank and Shepody for each of the trial years is presented in Table 4.7.

Table 4.7 Time to emergence for Russet Burbank and Shepody for 1996, 1997 and 1998

Year	Variety	Emergence Date	Days to Emergence
1996	Russet Burbank	June 6	24
	Shepody	June 12	30
1997	Russet Burbank	June 12	23
	Shepody	June 15	26
1998	Russet Burbank	June 13	23
	Shepody	June 17	27

Crop cover was also measured during the time when emergence counts were made until complete (100%) ground cover occurred. Crop cover was measured with the aid of a two meter long rod with markers which protruded out of the rod at 20 cm intervals. At each interval there were two markers spaced approximately 3 cm apart and oriented

perpendicular to the length of the rod. Measurements were taken by placing the rod above the plant canopy, perpendicular to the row direction, and visually recording the number of intervals which had green plant directly beneath each pair of vertical markers out of a maximum of 20. Measurements were taken approximately 1 m apart above the two centre harvest rows of each treatment (13 m). These measurement were replicated for all 64 of the 13 m long harvest rows. Percent crop cover was calculated by dividing the total number of green matter observations by the maximum possible (multiplied by 100) for each treatment. The measurement were taken once or twice weekly until crop coverage was complete. Crop cover data for 1996 and 1997 are presented in Table 4.8.

Table 4.8 Crop cover information for the 1996 and 1997 field trials at Carberry

Year	Variety	Date of Complete Cover	Days to Complete Cover
1996	Russet Burbank	July 16	64
	Shepody	July 20	68
1997	Russet Burbank	July 24	65
	Shepody	July 29	70

Starting two to three weeks after emergence, leaf area and haulm biomass measurements were made. This process was done weekly to determine changes in these parameters throughout the growing season. To determine leaf area index values during the 1996 and 1997 seasons, three undamaged representative plants were taken from each of the four moisture treatments from two of the four experimental blocks. Prior to the first irrigation in each treatment, the leaf area values obtained were averaged for the different samples to get a representative value. It was evident that the variability between replicates was too great in 1996 and 1997 to obtain reliable leaf area data and more replication was needed

for those trial years. As a result, additional plants were collected during the 1998 season to gain more representative data. Initially, six plants were collected from the sampling area for each variety in 1998. As available soil moisture decreased during the season, the designated irrigation treatments reached the point where they required their first irrigation. Since measuring leaf area is a very time consuming activity and given the amount of assistance available, it was necessary to decrease the amount of sampling as more irrigation treatments received their first irrigation. After all four irrigation treatments had received irrigation, five plants were collected from each treatment to determine leaf area. The total measured leaf area from the sample plants was divided by the ground area from which they were extracted to get values for leaf area index. For both varieties, the ground area for each plant was calculated as follows:

$$\text{sample ground area} = \text{intrarow spacing} \times \text{the row spacing} \quad (4.11)$$

The average row spacing was the same for the two varieties (95 cm), and the intrarow plant spacing for Russet Burbank was 31 cm and for Shepody was 38 cm. The plant densities then, for Russet Burbank is 2.76 plants per m² and Shepody 3.45 plants per m² in all trial years. All the measurements for each treatment were then averaged.

After leaf area measurements were taken the samples were then dried for biomass measurement. In 1997 and 1998 extra top biomass samples were also taken from each treatment to gain more representative values for both varieties. In 1998, 20 plants were taken for each variety to determine average biomass per plant. The number of samples decreased as irrigation was applied to each treatment. Six or seven plants were collected

from each treatment after treatments A, B and C had received irrigation. These measurements were averaged with the extra biomass samples taken from the leaf area samples.

Root depth observations were also made every week during the 1996 and 1997 seasons. These measurements began shortly after emergence and continued until the measurements remained unchanged from the preceding week's measurements. Each week, 16 sites were sampled on two of the four blocks. At each sample site, the potato plant and its tubers were removed from the row and a hole was then dug into the soil with a large auger. Soil was removed from the hole and inspected for root material. Root depth (cm) was then recorded as that depth where root matter stopped appearing in the soil removed from the auger hole. The measurements were then averaged between replicates. Root depth measurements allow for the calculation of the amount of water potentially extractable from the soil profile. As root depth gradually increases the amount of potentially extractable water within the soil also increases.

4.1.3.2 Phenologic Measurements

Phenologic observations were made for both varieties during their development in each trial year. Tuber initiation (beginning of stage 2 - exponential tuber growth) was determined from visual inspection of plant stolons for each variety. Initiation is considered to occur when the majority of the plants inspected had accumulations at the stolon tips. Tuber initiation data are presented in Table 4.9 for each cultivar.

Table 4.9 Tuber initiation date for variety and trial year

Year	Variety	Observed Tuber Initiation Date	Days to Tuber Initiation
1996	Russet Burbank	July 2	50
	Shepody	July 4	52
1997	Russet Burbank	July 3	44
	Shepody	July 7	48
1998	Russet Burbank	July 2	42
	Shepody	July 8	49

Following initiation, weekly tuber samples were taken for each treatment to determine tuber number and accumulated tuber dry matter per plant throughout the growing season. During 1996 and 1997, this procedure was performed twice (on two of the four blocks) for each treatment to gain a more representative sample. Three adjacent plants within a row were removed. The tops were used for biomass determinations and the hill was then carefully examined to collect all the tubers from the three plants. A total of seven plants were measured for each treatment and then averaged. The seventh plant was used for the additional detailed physiological measurements. In 1996 and 1997 these detailed measurement were done approximately every week on two representative plants for each moisture treatment. These additional measurements included stolon number, stolon length and tuber length in 1996 and included stem number and stem length in 1997.

The plant tops and fresh tubers collected were dried at 70°C until the weight remained constant. The replicates were averaged and the tuber dry matter values were graphed with sampling day. Tuber biomass accumulation is a sigmoidal function of time and tuber bulking occurs during the linear portion of this curve. The date when linear growth occurred was observed from the graph and was recorded as the date of tuber bulking.

Tuber bulking information is provided in Table 4.10 for each variety in 1997 and 1998.

Table 4.10 Date of tuber bulking and days to tuber bulking from planting for Russet Burbank and Shepody, 1997 and 1998

Year	Variety	Observed Tuber Bulking Date	Days to Tuber Bulking
1996	Russet Burbank	N/A	
	Shepody	N/A	
1997	Russet Burbank	July 25	66
	Shepody	Aug 3	75
1998	Russet Burbank	July 23	63
	Shepody	July 27	68

No tuber biomass data was collected during the 1996 trial year. The rapid tuber growth stage began earlier in 1998 than it did in 1997, particularly for Shepody.

4.1.3.3 Yield Data

In 1996 and 1997, there were dramatic effects of moisture regime on yields (Table 4.11, 4.12). Soils irrigated above 75% of water holding capacity had the highest yields, while the rainfed treatment had the lowest. Russet Burbank had higher yields than Shepody. More detailed information is provided to the reader in Appendix C on yield quality for the three trial years.

Table 4.11 Gross potato yields obtained in 1996.

Cultivar	Gross Potato Yields (T ha ⁻¹)				
	Treatment A	Treatment B	Treatment C	Treatment D	Mean
Russet Burbank	50.1 (447) ^z	44.5 (397)	43.4 (387)	41.1 (367)	44.7 (399)
Shepody	44.2 (394)	41.2 (368)	38.3 (342)	36.4 (325)	40.0 (357)
Mean	47.2 (421)	42.9 (383)	40.9 (365)	38.8 (346)	

^z Values in parentheses are in cwt ac⁻¹.

Table 4.12 Gross potato yields obtained in 1997.

Cultivar	Gross Potato Yields (T ha ⁻¹)				
	Treatment A	Treatment B	Treatment C	Treatment D	Mean
Russet Burbank	48.4 (432) ^z	45.5 (406)	44.4 (396)	34.4 (307)	43.2 (385)
Shepody	47.9 (427)	43.8 (391)	38.6 (344)	30.7 (274)	40.2 (359)
Mean	48.2 (430)	44.7 (399)	41.5 (370)	32.6 (291)	

^z Values in parentheses are in cwt ac⁻¹.

Table 4.13 lists the gross yield data for 1998. Compared to 1996 and 1997 yield data, there are smaller differences between the wettest irrigation treatments and the non-irrigated treatments for both varieties. Treatment A yields are comparable to 1996 and 1997 values, however, rainfall was more abundant in 1998 which reduced moisture stress and increased the yield on the rainfed treatment.

Table 4.13 Gross potato yields obtained in 1998.

Cultivar	Gross Potato Yields (T ha ⁻¹)				
	Treatment A	Treatment B	Treatment C	Treatment D	Mean
Russet Burbank	47.6 (425) ^z	44.3 (395)	44.3 (395)	42.6 (380)	44.7 (399)
Shepody	49.2 (439)	44.4 (396)	42.9 (383)	42.4 (378)	44.7 (399)
Mean	48.4 (432)	44.3 (395)	43.6 (389)	42.5 (379)	

^z Values in parentheses are in cwt ac⁻¹.

Chapter 5 Results and Discussion

5.1 Plant Development

The simulated phenological development of the crop closely matched observed crop measurements. Table 5.1 demonstrates this comparison and shows that Russet Burbank was more accurately modeled than Shepody.

Table 5.1 Simulated and observed dates for emergence, tuber initiation and tuber bulking for variety and trial year

	1997				1998			
	Russet Burbank		Shepody		Russet Burbank		Shepody	
	Sim ^z	Obs ^y	Sim	Obs	Sim	Obs	Sim	Obs
Emergence	June 13	June 12	June 16	June 15	June 14	June 13	June 18	June 17
Tuber Initiation	July 6	July 3	July 8	July 7	July 6	July 2	July 6	July 8
Tuber Bulking	July 27	July 25	July 23	Aug 3	July 24	July 23	July 20	July 27

^z Simulated Dates

^y Observed Dates

Model prediction of emergence is good despite the consistent one day over-prediction for both varieties in both years. Tuber initiation was also well estimated and was within one to four days of observed dates. Tuber bulking estimates were not as accurate as emergence and tuber initiation. Simulated bulking was good for Russet Burbank, as model estimates were only two days late for 1997 and one day late for 1998. Results for Shepody, however, were poor, with underpredictions of tuber bulking date by 11 days in 1997 and 7 days in 1998. Further calibration of the model for the Shepody variety is required. This can be achieved by gathering experimental data on Shepody tuber induction response. At present, when the tuber induction variable reaches a value of 300, tuber bulking is assumed to occur. The accumulation of the tuber induction variable depends upon six induction factors used to adjust the individual cultivar induction

response (see section 3.4 and Appendix A for a description of the induction factors). Each of these six components of induction need to be modified to reflect the genetic characteristics of the Shepody cultivar.

5.2 Comparing Simulated to Observed Plant Growth and Yield for Russet Burbank

Growth analysis is the mathematical study of changes in structure and form of a plant during its development (Dawes *et al.*, 1983). Many of the growth and developmental parameters simulated by SIMPOTATO have been measured in the field in order to evaluate the accuracy of the model's predictions. Initial model estimates of growth and yield proved to be greatly underestimated for the Russet Burbank variety in all experimental years. These parameters include a model underestimation of tuber dry matter, overall top biomass (haulm) and maximum leaf area. Table 5.2 shows model simulation results with measured values for these growth parameters along with the standard deviation (SD) of the observed replicates for each of the trial years.

Table 5.2 Simulated and observed crop growth variables for Russet Burbank

Year	Irrig Treat	Tuber Fresh Yield (Tonnes/ha)			Tuber Dry Yield (kg/ha)			Haulm Dry Matter (kg/ha)		Leaf Area Index		
		Sim ^z	Obs ^y	SD Obs ^x	Sim	Obs	SD Obs	Sim	Max Obs ^w	Sim	Max Obs	SD Obs
1996	A	37.8	50.1	2.42	7562	11464	553.6	2307	-	3.4	3.2	-
	B	37.8	44.5	3.57	7558	10187	818.2	1887	-	3.2	5.1	-
	C	38.4	38.3	4.11	7681	9938	941.5	1357	-	2.9	2.8	-
	D	36.1	41.1	2.51	7219	9420	573.9	1242	-	2.6	3.8	-
1997	A	31.5	49.6	1.74	6304	11359	397.9	2233	4062	3.2	8.1	-
	B	28.3	44.5	6.02	5651	10187	1379.4	1105	-	2.6	6.6	-
	C	20.8	44.4	8.21	4163	10166	1556.2	778	2943	1.5	6	-
	D	11.9	34.4	2.90	2389	7800	975.6	773	2483	1.3	4.7	-
1998	A	34.3	49.2	2.56	6858	10441	124.9	2942	6309	4.2	5.7	2.0
	B	33.2	44.3	3.06	6635	9603	1290.2	1479	4893	3.9	5.6	1.1
	C	32.2	44.2	3.32	6443	9288	302.8	1302	5213	3	4.8	1.8
	D	30.9	42.6	4.35	6177	9067	815.2	1235	3990	2.7	5	0.8

^z Simulated, ^y Observed, ^x Standard deviation of the observed, ^w Maximum Observed

The maximum observed yield values are an average of eight 13 meter rows from the four blocks. The standard deviation provides a measure of the variability of the treatment replicates. The 1997 B and C Treatments have large variation among replicates, as indicated by a standard deviation (SD) of 8 Tonnes ha⁻¹. The 1997 A Treatment replicates are the most consistent with a SD of 1.74 Tonnes ha⁻¹. Model estimates were well below one SD of the observed fresh yield except for the 1996 C Treatment. To more clearly see these differences, model estimates from Table 5.2 are presented in Table 5.3 as a percent of the observed values.

Table 5.3 SIMPOTATO estimates as a percent of observed plant measurements for Russet Burbank

Year	Irrigation Treatment	Tuber Fresh Yield (%)	Tuber Dry Yield (%)	Haulm Dry Matter (%)	Leaf Area Index
1996	A	75.5	65.9	-	106.3
	B	84.9	74.2	-	62.7
	C	100.3	77.3	-	103.6
	D	87.8	76.6	-	68.4
1997	A	63.5	55.5	55.0	39.5
	B	63.6	55.5	-	39.4
	C	46.9	41.0	26.4	25.0
	D	34.6	30.6	31.1	27.7
1998	A	69.7	65.7	46.6	73.7
	B	74.9	69.1	30.2	69.6
	C	72.9	69.4	25.0	62.5
	D	72.5	68.1	31.0	54.0

Table 5.3 shows that the 1996 fresh tuber yield is moderately underpredicted by SIMPOTATO, while tuber dry yield was more greatly underestimated. The greatest error in the 1996 yield estimates were for the two wettest moisture treatments (A and B). Leaf area predictions for this same year were good for Treatments A and C, but poor for

Treatments B and D. Sampling error was likely the cause of this discrepancy. Model yield and leaf area estimates in 1997 were much lower than the observed values. For this year, model accuracy decreased with the drier irrigation treatments for all of the plant measurements presented. This may indicate an oversensitivity in the model to a drier soil moisture regime. The 1998 yield and leaf area predictions were closer to the observed values than the 1997 values but predictions were still too low. Model estimates for 1998 yield were consistent between irrigation treatments, but model error increased with the drier treatments for leaf area prediction. The low simulation values for Russet Burbank may indicate that a calibration of the model is necessary in order to account for the local conditions of the experimental plot and the regional climate.

Hodges (1997) notes that the Russet Burbank cultivar tends to have a higher percent dry matter than many other common varieties. Measurements taken at the field trials have shown that percent dry matter was consistently underpredicted by the model, and likely account for the poorer tuber dry yield estimates. Of the two varieties in the experiment, measurements revealed that Shepody had higher tuber dry matter contents than Russet Burbank for every moisture treatment in 1997 and 1998.

5.3 Comparing Simulated to Observed Plant Growth for Shepody

Cultivar coefficients for the Shepody variety were not available to run the model. Model simulations of the Shepody variety using the cultivar coefficients for Russet Burbank yielded unexpectedly good results for model runs on 1996 and 1998 data, and

underestimated yield and leaf area in 1997. Model predictions and observed values differed by as much as 7 T ha⁻¹ for the A irrigation treatment and as much as 6 T ha⁻¹ for the non-irrigated treatment for the 1998 trials. Using the Russet genetic coefficients to run the model for 1997 proved to be much less accurate. For this year the A treatment simulated tuber fresh yield was 18 T ha⁻¹ below observed values, and the D treatment was 21 T ha⁻¹ below observed values. Model estimates for Shepody using the Russet Burbank genetic coefficients are provided in Appendix D.

5.3.1 Calibration of the Shepody Cultivar to SIMPOTATO

Since many crop growth measurements were taken during the 1997 and 1998 growing seasons, a calibration of the Shepody cultivar to SIMPOTATO was performed. The genetic coefficients file in SIMPOTATO uses maximum potential leaf expansion and tuber growth rates determined for a particular cultivar from experimental data under ideal growing conditions. For this calibration then, the leaf area and tuber growth measurements for the 1997 and 1998 Shepody A irrigation treatments were used as they most closely approximate ideal growth conditions. This procedure assumes that there are no limitations on the growth of the Shepody A treatment, and maximum growth rates were achieved. This assumption is reasonable given that moisture stress during plant growth was minimal or non-existent for this treatment and soil fertility was maintained above standards.

The growth rates were calculated for the Shepody A Treatments using the method presented by Manrique *et al.* (1990), and were averaged for the 1997 and 1998 years. These coefficients are provided below (section 5.5). A crude test of these cultivar coefficients was performed by using them to run SIMPOTATO for all three experimental years. Simulated results from the model runs are provided with observed values along with the standard deviation of the observed replicates (Table 5.4).

Table 5.4 Simulated and observed crop growth variables for Shepody

Year	Irrig Treat	Tuber Fresh Yield (Tonnes/ha)			Tuber Dry Yield (kg/ha)			Haulm Dry Matter (kg/ha)		Leaf Area Index		
		Sim ^z	Obs ^y	SD Obs ^x	Sim	Obs	SD Obs	Sim	Max Obs ^w	Sim	Max Obs	SD Obs
1996	A	68.1	44.2	1.55	13614	9230	355.8	4365	-	4.8	6.5	-
	B	67.3	41.2	1.14	13457	8415	262.0	3533	-	4.2	6.0	-
	C	61.5	38.3	2.26	12302	8185	517.5	2694	-	3.5	3.6	-
	D	63.9	36.4	2.54	12776	7967	581.0	1576	-	2.8	4.6	-
1997	A	47.4	47.9	5.39	9488	10010	1026.5	4068	5486	4.8	8.8	-
	B	47.5	43.9	2.43	10861	12275	531.9	1353	3322	3.8	7.9	-
	C	40.4	38.6	6.62	8078	8265	1821.7	1213	3082	3.4	8.1	-
	D	44.2	30.8	7.04	8838	6736	1738.1	1167	3359	3.5	4.6	-
1998	A	61.4	47.6	4.65	12275	10819	1054.7	5682	4515	6.0	7.5	3.4
	B	62.3	44.4	0.45	12451	10440	550.1	3454	4564	5.5	6.8	1.2
	C	57.7	42.9	2.79	11548	9766	1207.4	2376	4303	4.6	5.7	1.7
	D	58.6	42.2	2.55	11715	9801	698.2	1927	3701	4.4	6.6	2.9

^z Simulated, ^y Observed, ^x Standard deviation of the observed, ^w Maximum Observed

The 1997 and 1998 model predictions, using the Shepody coefficients, should approximate the measured tuber and leaf expansion data for those years, as it was the A Treatment observations that were used to calculate the coefficients. Irregularities between model estimates and observed values indicate either an oversensitivity of the model to other environmental conditions, unrealistic simulated photosynthetic processes or unrealistic biomass partitioning for this cultivar. Comparisons between model estimates

and observed plant measurements in Table 5.4 are provided in Table 5.5 as a percent of observed values.

Table 5.5 SIMPOTATO estimates as a percent of observed plant measurements for Shepody

Year	Irrigation Treatment	Tuber Fresh Yield (%)	Tuber Dry Yield (%)	Haulm Dry Matter (%)	Leaf Area Index
1996	A	154.1	147.5	-	73.9
	B	163.4	159.9	-	70.0
	C	160.6	150.3	-	97.2
	D	175.6	160.4	-	60.9
1997	A	99.0	94.8	74.2	54.6
	B	108.2	88.5	-	48.1
	C	104.7	97.7	39.4	42.0
	D	143.5	131.2	34.7	76.1
1998	A	129.0	113.5	125.9	80.0
	B	140.3	119.3	75.7	80.9
	C	134.5	118.3	55.2	80.7
	D	138.9	119.5	52.1	66.7

Table 5.5 reveals that the yield estimates for 1997 were very good, but leaf area and top biomass predictions are quite poor. Simulated yield for 1996 and 1998 was grossly overestimated for each of the irrigation treatments, while top biomass was markedly overestimated for the A Treatment in 1998 and greatly underestimated for every other treatment/year. Leaf area index was underestimated for every treatment/year, but somewhat less so for 1998 where treatments A, B and C were within 20% of observed values.

Since leaf expansion is the product of the maximum leaf expansion coefficient and daily thermal time, the poor 1997 simulated leaf area results might indicate an inadequate model growth response to daily thermal time. Leaf area estimates for 1998 were closer to the

observed values than the 1997 estimates; however, thermal conditions during 1998 were only slightly more favorable for leaf expansion (Figure 5.1), and can not explain the very poor leaf area index estimates for 1997.

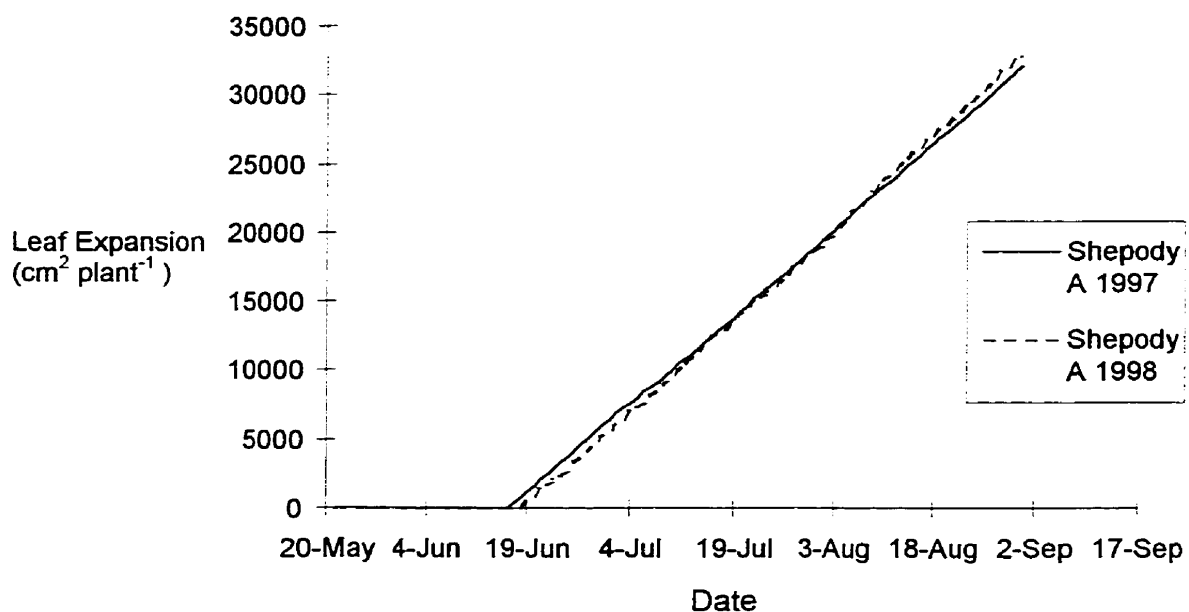


Figure 5.1 Thermal potential for leaf expansion, Carberry, 1997 and 1998

An independent test of the Shepody coefficients is shown by the 1996 model results provided in Tables 5.4 and 5.5. Yield estimates for each of the 1996 treatments were much greater than the observed data. Leaf area predictions were still low for 1996, but comparable to the 1998 results. Model results for 1996 indicate that the tuber growth rates used from the 1997 and 1998 Carberry data allow the model to greatly overestimate tuber yield. Although the tuber growth rate used in this analysis is calculated from real growth measurements, the model may be allocating photosynthate to the tubers too early in the season at the expense of leaf growth. Further model calibration for dry matter partitioning between tops and tubers would likely improve model estimates.

5.4 Simulated Soil Moisture

SIMPOTATO calculates soil moisture status on a daily basis. When simulated transpiration exceeds simulated total root water uptake (section 3.5.3), the water stress variables are used to reduce simulated photosynthesis (SWDF1) and cell growth (SWDF2). Model estimates of available soil moisture in the profile for each of the trial years have been compared to measured available soil moisture in the profile for Treatments A and D for each variety in 1998 (Figures 5.2 and 5.3) and 1997 (Figures 5.4 and 5.5).

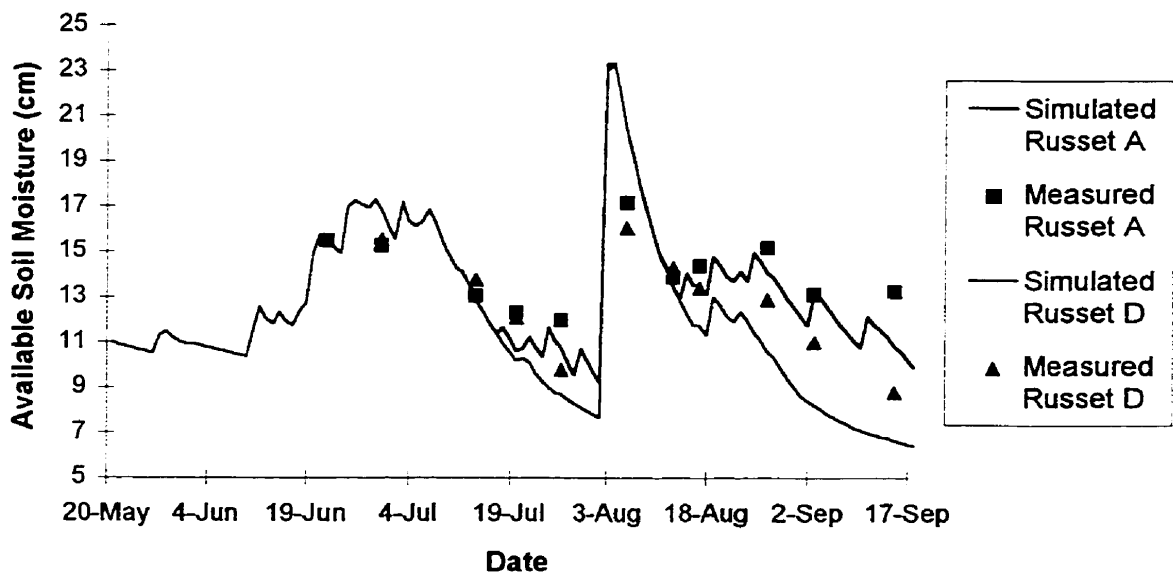


Figure 5.2 Simulated and observed available soil moisture with date for Russet Burbank A and D treatments, Carberry, 1998 (Mean standard deviation for A Treatment = 0.49 cm, D Treatment = 0.35 cm)

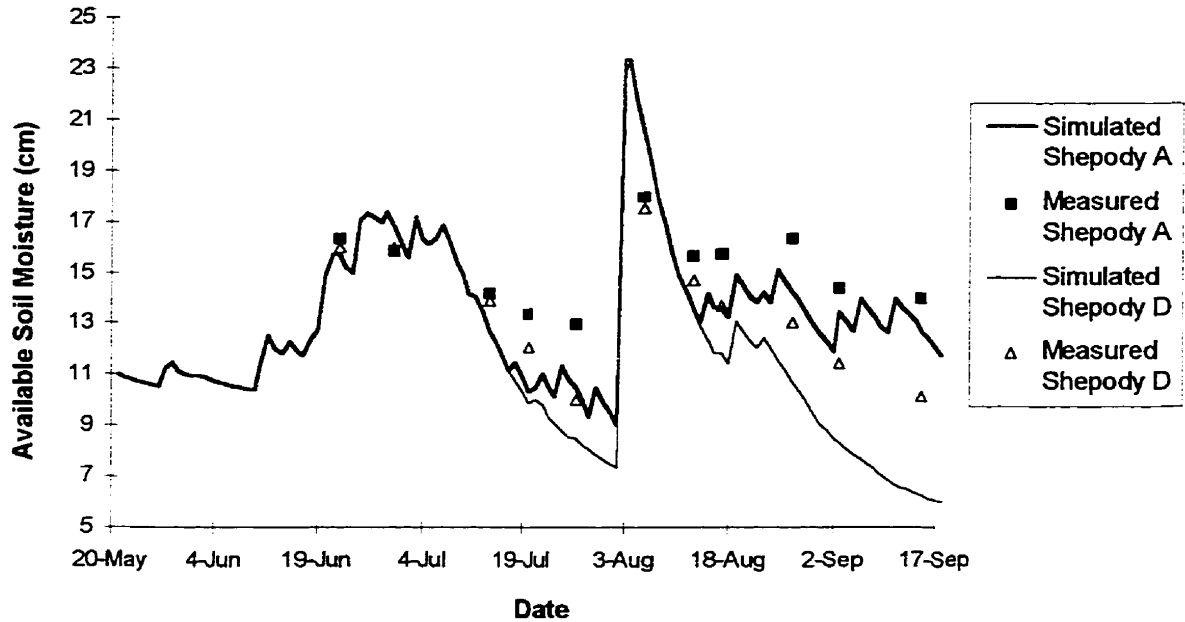


Figure 5.3 Simulated and observed available soil moisture with date for Shepody A and D treatments , Carberry, 1998 (Mean standard deviation for A Treatment = 0.30 cm, D Treatment = 0.33 cm)

The 1998 figures both reveal that SIMPOTATO underestimated available soil moisture late in the season and when soil moisture was low. The drier D Treatments for both varieties were underestimated more than the A Treatments.

Modeled soil moisture in 1997 was greatly underestimated, often by 3 to 6 cm (Figures 5.4 and 5.5). Simulated soil moisture for this year was closer to observed values when available soil moisture was low; that is, D Treatments were more accurately simulated than A Treatments when available soil moisture is low (late season). This comparison contrasts that of observed and simulated available soil moisture for 1998, where the model performed more poorly at lower soil moisture contents.

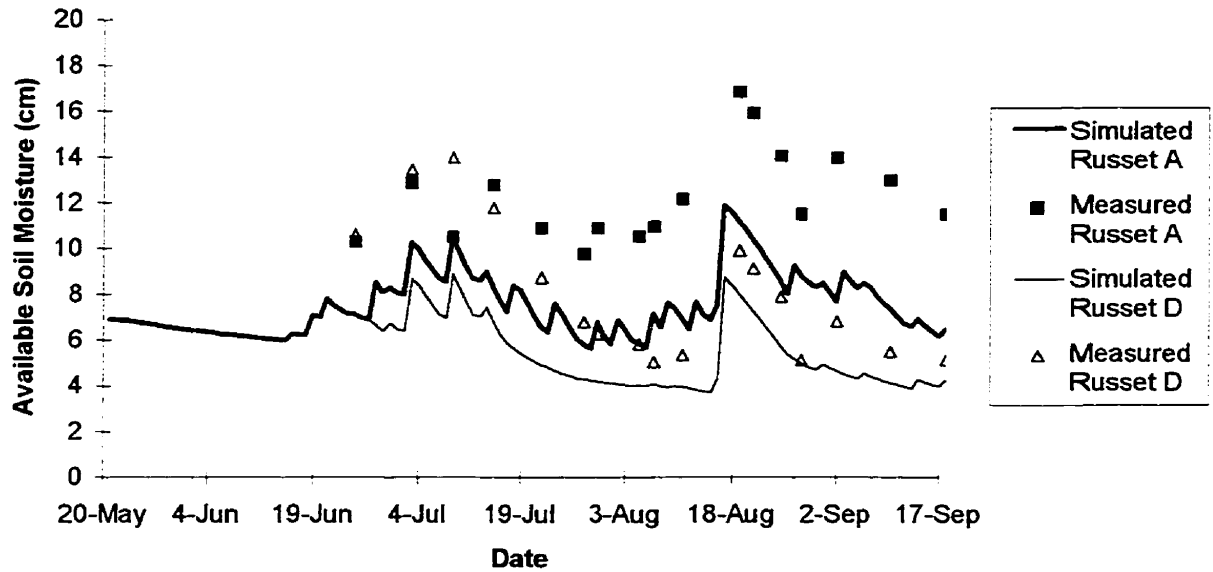


Figure 5.4 Simulated and observed available soil moisture with date for Russet Burbank A and D treatments, Carberry, 1997 (Mean standard deviation for A Treatment = 0.57 cm, D Treatment = 1.06 cm)

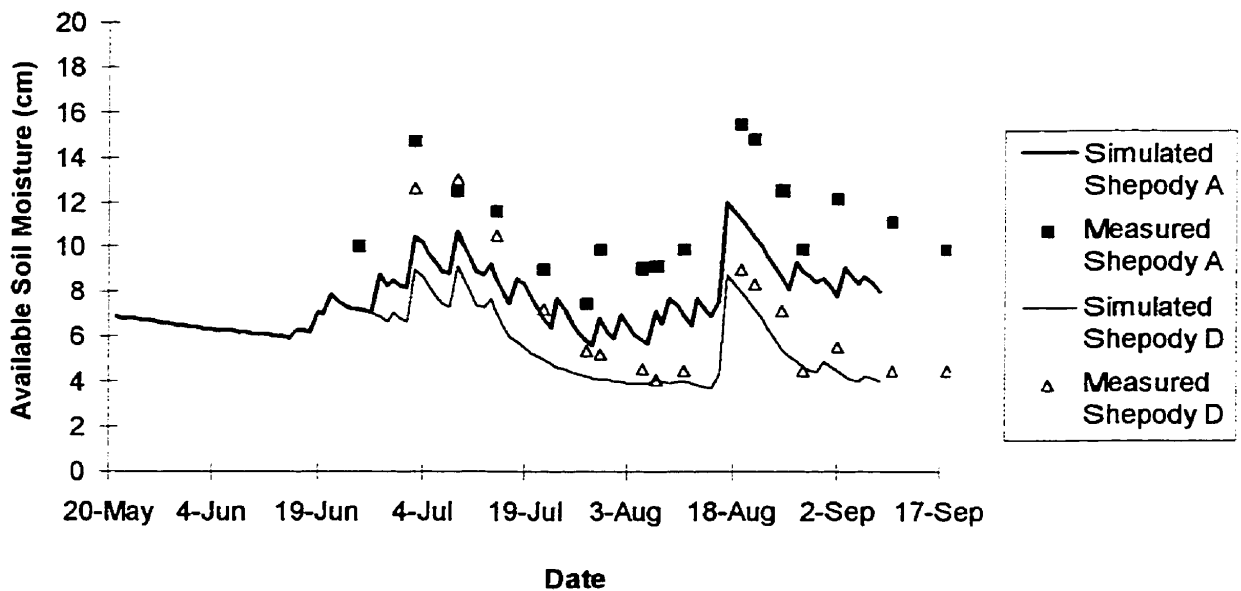


Figure 5.5 Simulated and observed available soil moisture with date for Shepody A and D treatments, Carberry, 1997 (Mean standard deviation for A Treatment = 0.69 cm, D Treatment = 0.74 cm)

The results for the other Russet Burbank and Shepody irrigation treatments (B and C) are not presented here because they show differences similar to those illustrated in Figures 5.2, 5.3, 5.4 and 5.5 for their respective trial years.

Since no deep soil drainage was simulated during 1997, the poorly estimated seasonal moisture contents can not be attributed to inaccurately modeled unsaturated hydraulic flow. The difference between the simulated and observed available soil moisture status can be explained in part by inaccurate estimates of rooting depth for Russet Burbank.

Figure 5.6 illustrates this observation.

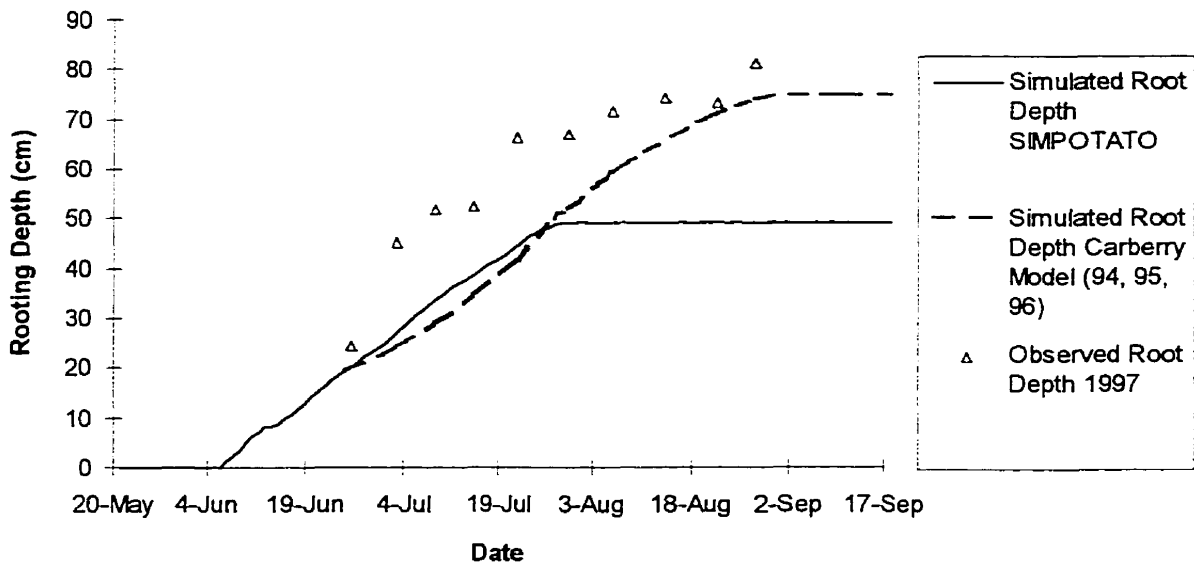


Figure 5.6 Simulated and observed rooting depth with date for Russet Burbank irrigation treatment A, Carberry, 1997

In Figure 5.6, SIMPOTATO stops extension root growth late in July at 47 cm. Observed root depth for 1997 exceeded simulated maximum depth by 30 cm. The 1994, 1995 and 1996 Carberry root depth model was modified from Raddatz *et al.* (1996) and Shaykewich *et al.* (1998) and corresponds reasonably to the observed 1997 root depth. Both the observed root depths for 1997 and the modified Carberry model indicate that SIMPOTATO's simulated maximum root depth is too shallow. SIMPOTATO estimates new daily root depth (RTDEP) as a function of DTT and the minimum of the soil water deficit factor for photosynthesis and transpiration (SWDF1) or the soil water deficit factor

for the deepest layer in which roots are growing (SWDF). Model runs for other irrigation treatments in both 1997 and 1998 show a simulated maximum root depth comparable to that shown in Figure 5.6.

The maximum daily root extension rate simulated by SIMPOTATO has been 1.3 cm for Russet Burbank. The root depth model developed from the Carberry experiments during 1994, 1995 and 1996, has a maximum daily root depth increase of 1.5 cm for Russet Burbank. A root depth model developed at Carberry for Shepody, over the same years, has a daily maximum of 1.6 cm. Daily root growth was reasonably simulated by SIMPOTATO, however, maximum root extension was simulated too shallow. As a result available soil moisture was underestimated in the model. This means that root growth routines need to be modified so that available soil moisture and plant moisture stress can be more accurately simulated.

5.4.1 Evaluating Simulated Potential Evapotranspiration

In order to successfully simulate growth and yield of a crop a model must accurately account for the relationship between plant water use and atmospheric demand.

SIMPOTATO's estimates of potential evapotranspiration (PET) were evaluated by comparing estimates of PET with other models. A three variable model using solar radiation at the top of the atmosphere, daily maximum temperature and daily temperature range and a six variable model which used these first three variables as well as a measure of daily wind, global radiation and vapor pressure deficit (Baier and Robertson, 1965; Baier, 1971) are used in this comparison. In addition, a crop-soil-atmospheric water use

model developed by Raddatz (1993) and Raddatz *et al.* (1996) is also used. In Table 5.6, accumulated PET estimates were summed for three field measured periods for each of these models: 1) planting to 100% ground cover, 2) 100% ground cover to harvest and 3) planting to harvest. Rainfall and Treatment A irrigation plus precipitation are also presented in Table 5.6. Realistic values of PET should approximate the sum of precipitation and irrigation for this treatment during the period of complete ground cover (initial soil moisture content is not incorporated). At 100% ground cover, it is assumed that atmospheric evaporative demand is wholly met by crop transpiration.

Table 5.6 Assessing evaporative models

Category	Trial Year		
	1996	1997	1998
Rainfall (mm)	247	203	380
Treatment A Water Use (rainfall + irrigation)	343	400	452
Potential Evapotranspiration (mm)			
Planting to 100% Ground Cover			
SIMPOTATO	193	293	297
Baier and Robertson (3 Variable Model)	287	280	276
Baier and Robertson (6 Variable Model)	215	305	238
Planting to Harvest			
SIMPOTATO	434	542	520
Baier and Robertson (3 Variable Model)	537	534	514
Baier and Robertson (6 Variable Model)	440	561	448
100% Ground Cover to Harvest			
SIMPOTATO	241	204	223
Baier and Robertson (3 Variable Model)	252	206	238
Baier and Robertson (6 Variable Model)	226	211	211
Raddatz (Crop water demand) ^z	247	217	264

^z More precisely this is a water demand model incorporating the degree of ground cover (maximum 98%).

Because complete ground cover does not occur until mid season, estimates of PET for the entire growing period should exceed the water demand by the crop. Table 5.6 shows that estimates of potential evapotranspiration by all models were indeed greater than both precipitation and Treatment A water use. This indicates that PET estimates by SIMPOTATO and the other models were within a reasonable range for all three simulation years. Differences between the models were small for the period from 100% ground cover to harvest. The three models used for the period prior to complete ground cover show larger differences in predicted PET. The 1997 estimates for this period were consistent between models, the 1998 values show the complex Baier and Robertson six variable model to be more than 40 mm below the three variable and SIMPOTATO model estimates.

Early growing season estimates of PET for 1996 were less consistent between the models, and show the SIMPOTATO and six variable model estimates to be much lower than the three variable. These accumulations were noticeably lower than 1997 and 1998 estimates for the same period. The reason for these low 1996 predictions may be attributed to an underestimation of daily global radiation values from the global radiation/net radiation model (section 4.1.2) used to estimate missing 1996 radiation data. Global radiation was used by both the six variable and SIMPOTATO models to estimate PET, but not by the three variable model. A plot of daily PET estimates for each model in 1996 show the three variable model to have consistently larger daily estimates. Similar plots for 1997 and 1998 do not show this daily consistency, and suggests that the 1996 early season global radiation estimates used by SIMPOTATO and the six variable model are too low.

As noted in section 4.1.2, early season predictions by the global radiation/net radiation model were underestimated until net radiation exceeded $14 \text{ MJ m}^{-2} \text{ day}^{-1}$. The lower values may have caused SIMPOTATO to underestimate soil evaporation early in the growing season and therefore caused an overestimate of soil moisture content during early crop growth. However, in general, PET was reasonably estimated by the SIMPOTATO

5.5 Plant Growth Rates

Maximum potential daily growth rate coefficients are estimated for common cultivars from experimental data in which no forms of plant stress occur. These optimum conditions for plant growth would allow for the maximum growth potential of the plant to be reached. The amount of daily growth as a fraction of the total growth, under optimum conditions, is determined. Leaf growth rates are calculated between the period of tuber initiation to tuber bulking. Using this period of growth, accounts for changes in leaf extension as it is affected by tuber growth throughout the life of the plant. Maximum daily leaf growth occurs during the vegetative stage (prior to tuber initiation), and decreases at an increasing rate during Stage 2 (early tuber growth). During stage 3 of plant development (bulking), photosynthate is partitioned to the tuber at a constant rate, where all available carbohydrate supports tuber growth. Tuber growth measurements for stages 2 and 3 of plant growth are used to calculate tuber growth rates under optimum conditions.

Leaf expansion rate, tuber growth rate, plant growth rate and tuber partitioning coefficients were calculated from the 1997 and 1998 Carberry plant measurements using the methods presented by Manrique *et al.* (1990). Growth rates were calculated for the

most frequently irrigated treatment (Treatment A) in the field experiments for both Russet Burbank and Shepody cultivars (Appendix E). Because very little or no moisture stress was allowed during the growth of the A treatment, it was assumed that the calculated growth rates should be comparable to the maximum potential growth rates used by SIMPOTATO for the Russet Burbank cultivar. Since cultivar coefficients were not available for the Shepody variety, comparisons of growth rate calculations for the Shepody A Treatments were not possible. The calculated growth rates for Russet Burbank were compared to the maximum growth rates used in SIMPOTATO (Table 5.7).

Table 5.7 Growth rates and partitioning coefficients calculated for Russet Burbank A and Shepody A irrigation treatments for the 1997 and 1998 experiment years

Source	LGR ^z (cm ² plant ⁻¹ day ⁻¹)		TGR ^y (g plant ⁻¹ day ⁻¹)		CGR ^x (g plant ⁻¹ day ⁻¹)		PC ^w	
	Russet	Shepody	Russet	Shepody	Russet	Shepody	Russet	Shepody
Carberry 1997	483	480	8.66	7.19	9.75	7.56	0.567	0.703
Carberry 1998	467	600	5.95	6.57	8.36	7.00	0.415	0.945
SIMPOTATO	400		5.00					*

^z Leaf growth rate

^y Tuber growth rate

^x Crop growth rate

^w Partitioning coefficient

* This factor in SIMPOTATO varies linearly with the variable for tuber induction and is 0 prior to tuber initiation and increases to a value of 1 at the beginning of tuber bulking.

The observed leaf growth rates (LGR) for the Russet A treatment was 483 cm² plant⁻¹ day⁻¹ in 1997 and 467 cm² plant⁻¹ day⁻¹ in 1998. Both of these growth rates were greater than the maximum LGR of 400 cm² plant⁻¹ day⁻¹ used by SIMPOTATO. The tuber growth rate (TGR) for Russet A was 8.66 g plant⁻¹ day⁻¹ in 1997 and was 5.95 g plant⁻¹ day⁻¹ in 1998. Both the 1997 and 1998 observed TGR values were greater than the

maximum TGR used by SIMPOTATO which was $5 \text{ g plant}^{-1} \text{ day}^{-1}$. This data indicates that the coefficients used to estimate the maximum potential daily leaf expansion and daily tuber growth are unrealistic when used to simulate plant growth and yield within the Carberry climate for the years tested..

The difference between the calculated LGR values and the coefficient used in SIMPOTATO does not account for the large difference between observed and simulated leaf area index. The observed LGR of $483 \text{ cm}^2 \text{ plant}^{-1} \text{ day}^{-1}$ for Russet Burbank in 1997 means that there would be $83 \text{ cm}^2 \text{ plant}^{-1} \text{ day}^{-1}$ more leaf expansion than the coefficient used in the model. As a result, at the end of the 40 day period the simulated LAI would only be 0.92 lower than the observed value. The actual difference between observed and simulated LAI at the end of tuber bulking is 5.0 for the Russet Burbank 1997 A Treatment. Clearly there are other variables influencing expansion growth that are not accurately simulated by SIMPOTATO.

Low model leaf area estimates may have been influenced by an oversensitivity within the model to simulated moisture stress. An analysis into the cause of this problem was made by comparing estimated and observed leaf area expansion data. The daily potential maximum leaf expansion variable (PLAG) is a product of the theoretical daily maximum growth coefficient for the cultivar and a factor calculated by the model that expresses the amount of useful heat available for daily leaf expansion (optimum 22°C). Figure 5.7

reveals that measured leaf area values for Russet Burbank A were more comparable to modeled maximum potential leaf expansion than modeled leaf area.

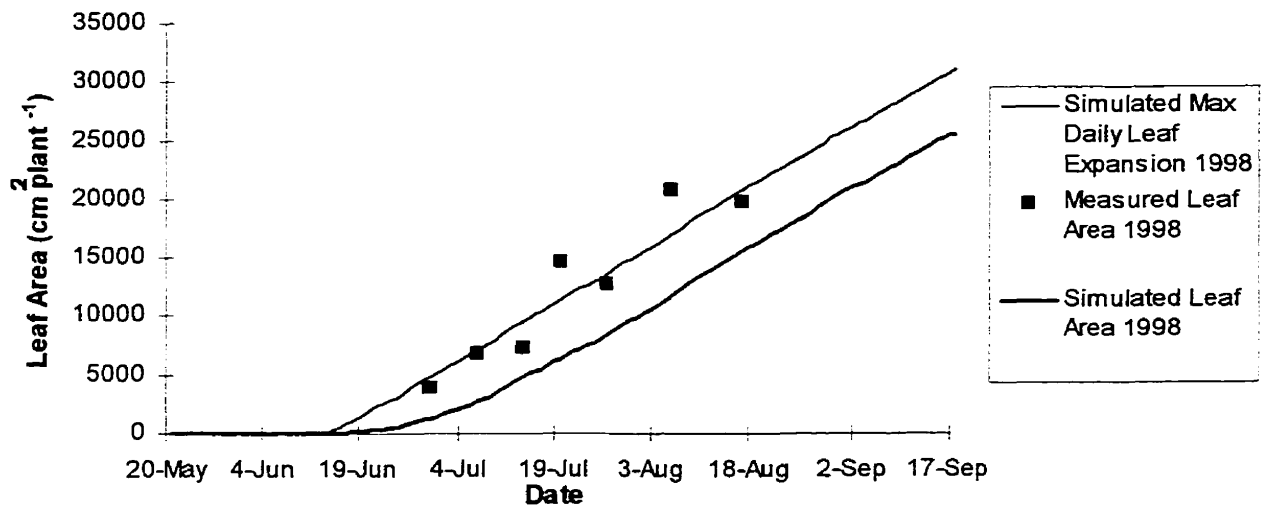


Figure 5.7 Simulated and observed daily leaf expansion for Russet Burbank treatment A, Carberry, 1998

In this Figure we can see that measured leaf area was much greater than simulated leaf area for the Russet Burbank A treatment in 1998. Plant stress was not a significant factor for this treatment in 1998. It is evident from Figure 5.7 that not only was simulated leaf area accumulating too slowly during the linear portion of leaf expansion, but that early leaf expansion was also too slow when compared to observed values. Since the observed leaf area was as large, or larger, than the maximum leaf expansion rate used in SIMPOTATO a larger rate is needed for Russet Burbank. The inaccurate simulation of leaf area may then be attributed to a combination of factors which lead to an underestimated genetic performance of the Russet Burbank cultivar: 1) low maximum potential leaf expansion rate, 2) slow early exponential leaf expansion and 3) an inaccurate specific leaf weight coefficient (g of dry weight cm⁻² of leaf area) for this variety.

As with leaf area expansion, tuber growth rates were underestimated for Russet Burbank. This consistent underestimation suggests that the factors for maximum potential daily dry matter accumulation and daily leaf expansion used in the model were not realistic values for the environment where the field trials took place. An error such as this has a great affect on simulated plant growth and yield. Having a lower possible leaf area would result in less intercepted global radiation. Since daily photosynthesis is a function of intercepted daily global radiation, in SIMPOTATO, low simulated leaf areas suggest that daily photosynthesis was underestimated by the model and that daily simulated carbohydrate production was negatively affected.

5.6 Sensitivity Analysis

An examination of the sensitivity of a model should distinguish between two types of errors. First, the sensitivity of the output from the model to changes in functions within the model. These errors may originate from a mistaken understanding of the processes or from differences in genetic performance between cultivars. The genetic coefficients used in the model are all multipliers used to match the response of a given cultivar to its environment. Any changes in these values has direct consequences on simulated plant growth and yield. Second, errors associated with the sensitivity of the system described by the model to changes in the starting conditions or inputs variables (MacKerron and Waister, 1985).

A sensitivity analysis was performed to quantify the impact of selected genetic and plant parameters on SIMPOTATO's output. The analysis was done for the wettest and driest

irrigation treatments for the Russet Burbank cultivar for each trial year. Input base values were assigned to each input parameter. The input base values chosen were those used to run the model initially, and are the Russet Burbank genetic coefficients supplied with SIMPOTATO. For the plant parameters, the observed emergence for each trial year was used as the input base value, as was the actual plant population (plants m⁻²) for Russet Burbank. The input base and upper and lower modified values are provided in Table 5.8.

Table 5.8 Input base values used for the sensitivity analysis

Parameter	Input base	Lower Modified Base	Upper Modified Base
Genetic			
G2 Leaf Expansion (cm ² plant ⁻¹ day ⁻¹)	400	300	500
G3 Tuber Growth (g plant ⁻¹ day ⁻¹)	5	4	6
G4 Specific Leaf Weight (g cm ⁻²)	0.005	0.004	0.006
Daily Temperature Range Factor	1.0	0.8	1.2
Photoperiod Factor	1.6	1.2	2.0
Plant			
Plant Population Density (Plants m ⁻²)	2.76	1.38	4.14
Emergence Date	163	156	170

The model was then run and output base values were determined. The output base values consisted of tuber initiation date (TubIni), tuber bulking date (TubBulk), total fresh yield (FreshYld), total dry yield (DryYld), maximum leaf area index (MaxLAI) and top dry matter (Haulm). Two variations were then imposed on the input base parameters. For the genetic parameters, base value + 20% and base value - 20% were used. These values were chosen because genetic parameters are calculated from experimental data and a larger modification was thought to be too drastic. The date of emergence was fixed for each trial year with a variation of 7 days, and plant population density was varied by a value of 1 from the actual density of the trials. The model was run separately for each

modified input parameter to obtain its output values. Variations in the output values were quantified on a percentage basis using the maximum absolute difference between the output base values and the modified base values following the method used by Mahdian and Gallichand (1997):

Table 5.9 Sensitivity of SIMPOTATO to genetic and plant parameters

Parameter	Maximum Deviation (% of base)						
	TubIni	TubBulk	FreshYld	DryYld	MaxLAI	Haulm	Row Average
Genetic							
G2 Leaf Expansion	1.7	1.8	6.1	6.1	18.1	21.7	9.3
G3 Tuber Growth	0.0	0.1	19.1	19.0	3.8	3.6	7.6
G4 Specific Leaf Weight	0.5	0.1	1.8	1.7	2.4	21.4	4.7
Daily Temperature Range	1.0	1.0	3.5	3.4	5.3	4.7	3.1
Photoperiod	0.0	0.6	1.6	1.6	2.8	3.3	1.7
Plant							
Plant Population Density	3.6	2.4	51.5	51.6	42.9	48.2	33.4
Emergence Date	5.9	2.4	9.2	9.2	13.6	12.6	8.8
Column Average	1.8	1.2	13.3	13.2	12.7	16.5	

Maximum deviation values, presented in Table 5.9, show that date of tuber initiation is more sensitive to the two plant parameters and is little affected by the genetic parameters tested here. Although date of tuber bulking appears to be slightly more influenced by the plant parameters than the genetic parameters tested, absolute values show little difference between base and modified output. An emergence date of seven days earlier had little affect on tuber initiation and bulking. A later emergence date of seven days delayed tuber initiation in 1997 A and D treatments by 15 and 14 days respectively, and only delayed 1998 results by 9 days. Data was not complete to run the test for 1996.

In terms of yield, the model was most sensitive to plant population density, daily maximum tuber growth rate and emergence date. Maximum absolute deviation for fresh yield

ranged between treatments years from 14.0 and 20.8 T ha⁻¹ for plant population, 17.8 and 20.1 T ha⁻¹ for tuber growth rate and 1.3 and 4.5 T ha⁻¹ for emergence date. Tuber dry yield was not any more sensitive than fresh yield for the parameters tested. Modeled leaf area as a percentage of output base values was most sensitive to plant population density, maximum daily leaf expansion rate and emergence date. The maximum absolute leaf area index differences for the trial years range between 0.5 and 2.0 for plant population, 0.4 and 1.0 for leaf expansion rate, and 0.1 and 0.7 for emergence date. Modeled above ground dry matter, as with leaf area, was particularly sensitive to plant population density (497 to 1494 kg ha⁻¹), leaf growth rate (249 to 696 kg ha⁻¹) and emergence (53 to 460 kg ha⁻¹). In addition, haulm was also very sensitive to the specific leaf weight coefficient (261 to 582 kg ha⁻¹).

Treatment D from 1997 was excluded from the sensitivity analysis above. This treatment responded very differently within the sensitivity analysis than other treatment years.

Simulated plant growth essentially stopped for this rainfed treatment due to a model overestimation of moisture stress. Model output thus was inconsistent with the other treatment years. In general, the output variables were sensitive to the two plant parameters and to the leaf expansion, tuber growth and specific leaf weight coefficients.

5.7 Suggested Modifications to SIMPOTATO

5.7.1 Calibrating Russet Burbank

By calculating daily tuber growth rates from field data for the Russet Burbank A treatment (as was done with Shepody) for both experimental years, and assuming non-limiting

conditions for this treatment, a new theoretical maximum daily growth rate can be tested.

Table 5.10 lists the simulated yield results (New Simulation) for the 1997 and 1998 treatment/years using the treatment A growth rates, the observed yield, the simulated yield using SIMPOTATO's default growth rates (Old Simulation) and the standard deviation of the observed replicates.

Table 5.10 Observed yield and simulated yield using larger daily tuber growth rates for Russet Burbank , 1997 and 1998

		FRESH TUBER YIELD (TONNES HA ⁻¹)			
		Russet Burbank			
Year	Treatment	New Simulation	Observed	Old Simulation	SD Observed ^z
1997	A	46.3	49.6	31.5	1.74
	B	38.6	44.5	28.3	6.02
	C	25.5	44.4	20.8	8.21
	D	14.5	34.4	11.9	2.90
1998	A	50.8	49.2	34.3	2.56
	B	45.8	44.3	33.2	3.06
	C	42.6	44.2	32.2	3.32
	D	39.8	42.6	30.9	4.35

^z Standard deviation of observed

The New Simulation is not a true independent test of the model, however, the results for the other 1998 treatments (B, C and D) show good potential for using a higher tuber growth coefficient in Manitoba. For 1997, the New Simulation yield predictions are better than the original estimates, and are likely influenced by moisture stress resulting from an inaccurate estimate of available soil moisture for that year. Using a larger coefficient for a theoretical maximum daily leaf expansion in the model also improves modeled yield and leaf area estimates for 1997 Russet Treatments, but inaccurate modeling of soil moisture was still a limiting factor.

Chapter 6 Summary and Conclusions

The SIMPOTATO crop growth and development model (Hodges, 1997; Hodges *et al.*, 1992) was tested under Manitoba environmental conditions on irrigated and dryland sites near Carberry, Manitoba. At this location, both Russet Burbank and Shepody varieties were grown. SIMPOTATO is a weather driven model, and requires daily rainfall, global radiation, and maximum and minimum air temperature. Soil physical properties such as field capacity and permanent wilting point were measured and used as input parameters for the model. The field data required to run the simulation model was collected, and model estimates of crop growth, development and yield were compared to field data collected during the growing seasons of 1996, 1997 and 1998. Simulated phenologic development and soil moisture were also compared to observed data for those same years.

6.1 Plant Development

The simulated phenological development of the crop closely matched observed measurements. Simulated emergence was accurate for both cultivars in 1997 and 1998. Date of tuber initiation was also well estimated and was within one to four days of observed dates. Date of bulking was closely predicted for Russet Burbank, but was too early for Shepody. More experimental data is needed to quantify the genetic response of Shepody for the six components of the tuber induction variable in order to more accurately simulate bulking.

6.2 Plant Growth and Yield

6.2.1 Summary of Simulated Growth and Yield for Russet Burbank

The initial simulated tuber growth and leaf area were lower than the observed values for every trial year for the Russet Burbank cultivar. Tuber fresh yield, tuber dry yield, maximum top biomass and maximum leaf area were also underestimated by the model.

Simulated yield for 1996 was very similar for all four moisture treatments, and does not reflect the range of observed treatment yields. The least accurate yield estimates for 1996 are the two wettest moisture treatments (A and B). This indicates that moisture stress was not a great factor in the model estimates for 1996, but that the simulated growth potential for well irrigated treatments was not attained by SIMPOTATO. Leaf area predictions for this same year are good for Treatments A and C, but were underestimated for Treatments B and D.

For 1997, model predictions were far below observed values and model accuracy decreased with the drier irrigation treatments for all of the plant measurements presented. This suggests again that not only was growth under non-limiting conditions (Treatment A) not properly simulated, but that the model was too sensitive to a drier seasonal soil moisture regime (Treatment D) which resulted from below average precipitation at the experimental site during 1997.

Yield and leaf area simulations for 1998 were closer to the observed values than they were in 1997, but predictions were still too low. Model accuracy for 1998 yield was consistent between irrigation treatments, but accuracy decreased with the drier treatments for estimates of leaf area index. The range of observed yields between the wettest and driest irrigation treatments was lower than that measured for 1996 and 1997. This may be due to the fact that precipitation in 1998 was abundant, and as a result the soil moisture content was high in every treatment during the period of tuber growth.

The results for the three trial years suggest that the theoretical maximum daily tuber growth and leaf expansion rates used in SIMPOTATO for Russet Burbank may not reflect the real potential of this crop in the climate and soil conditions at Carberry, Manitoba during 1996, 1997 and 1998. Seasonal soil moisture was underpredicted for 1997 and 1998, but estimates were less accurate for 1997. Simulated water stress was overestimated by the model which restricted all aspects of simulated plant growth for that year. The low simulated growth and yield for Russet Burbank indicate that a calibration of the model was necessary in order to account for the local conditions of the experimental plot and the regional climate of the area.

6.2.1.1 Suggested Modifications for Russet Burbank

In order to approximate the observed yield of the field experiments at Carberry, existing maximum tuber growth rates provided with SIMPOTATO were found to be too limiting and new tuber growth rates were calculated. Field data for the Russet Burbank A

treatment for 1997 and 1998 were used for this procedure, and values were averaged for the two years. Assuming non-limiting conditions for this treatment, a new theoretical maximum daily growth rate was calculated. SIMPOTATO was then run for all of the moisture treatments using these new growth rates. The results for treatments B, C and D for 1998 show very good potential for using a higher maximum potential tuber growth coefficient in Manitoba. For 1997, the New Simulation yield estimates were much better than the original estimates, but were still lower than the observed yield. Similar to the yield results using the old growth rates, model yield estimates using the new growth rates were less accurate with the drier irrigation treatments for 1997. Apart from the new tuber growth rates, it was found that model yield and leaf area predictions were improved by using only a larger maximum daily leaf expansion coefficient (also calculated from 1997 and 1998 Treatment A field data). However, the result was not as effective as that provided by the new tuber growth rate coefficient.

6.2.2 Summary of Simulated Growth and Yield for Shepody

Cultivar coefficients for the Shepody variety were not available to run the model. Model simulations of Shepody using the cultivar coefficients for Russet Burbank produced unexpectedly good yield results for model runs on 1996 and 1998 data, but underestimated yield for 1997. Field testing of Shepody, then, was an exercise in calibrating this variety to the model for this climate and not an exercise in validating it. To run the model for Shepody, maximum potential growth rates were calculated for daily leaf

expansion and plant and tuber growth following the method used by Manrique *et al.* (1990).

The genetic coefficient file in SIMPOTATO contains the maximum potential leaf expansion and tuber growth rates determined for a particular cultivar from experimental data under ideal growing conditions. For this calibration then, the leaf area and tuber biomass measurements for the 1997 and 1998 Shepody A irrigation treatments were used as they most closely approximate ideal growth conditions.

Model estimates for Shepody were low for leaf area and above ground biomass. Leaf area index was underestimated for every irrigation treatment for all three trial years, with the greatest underestimation being the 1997 simulation. Model yield results for Shepody were good for the 1997 A, B and C Treatments and poor for Treatment D. The model was not as sensitive to the differences in the amount of water applied on the 1997 treatments, as indicated by the greater differences between the observed yields of the Shepody irrigation treatments for that trial year. To a lesser degree, observed yield data for 1996 and 1998 also reveal a low sensitivity of the model to the irrigation differences between treatments.

Shepody yields were greatly overestimated for every 1998 irrigation treatment. Model overestimation for the 1998 A Treatment was surprising because the growth rates used to run the model were in part calculated from this treatment. Model yield for the 1996 simulation, like the 1998 simulation, were greatly overestimated. Measured tuber growth for 1996 was independent of the 1997 and 1998 data used to calculate the maximum

growth rates for Shepody. Since the model growth rates used for this cultivar were measured, they would be lower than the maximum potential rates required by SIMPOTATO if any limiting moisture, fertility or disease conditions existed during growth of this treatment.

Given that plant top biomass and leaf expansion were consistently underestimated, it seems reasonable that seasonal accumulation of the tuber induction variable needs to be modified for Shepody. In SIMPOTATO, this variable determines when tuber initiation and bulking begin, and partitioning of photosynthate to tubers increases linearly with this induction variable. Observed data shows that simulated tuber bulking began too early for Shepody. A more realistically slower accumulation of tuber induction for Shepody would allow a greater accumulation of top biomass, while at the same time reducing the total accumulation of tuber biomass. This would bring model estimates more in line with observed data.

Although model results for Shepody are certainly not perfect using these new Shepody coefficients, they show potential, and indicate that further model calibration reflecting the genetic characteristics of this variety on tuber induction and dry matter partitioning would improve model estimates.

6.3 Soil Moisture

SIMPOTATO slightly underestimated available soil moisture late in the 1998 season when soil moisture was low. This error was larger in the drier moisture treatments, however, in general available soil moisture was reasonably estimated for this year. Simulated available soil moisture for 1997 was closer to observed values when soil moisture was low. This comparison contrasts that of the observed and simulated available soil moisture for 1998, where the model performed more poorly at lower soil moisture contents. Daily root growth has been found to be reasonably simulated, but maximum root extension was too shallow and as a result available soil moisture was underpredicted in the model. This means that root growth routines need to be modified so that available soil moisture and plant moisture stress can be more accurately simulated.

6.4 Crop-Soil Water Balance

Model estimates of potential evapotranspiration are indeed greater than both precipitation and Treatment A water use (precipitation plus irrigation), and indicates that PET estimates by SIMPOTATO and the Baier and Robertson and Raddatz models used in the analysis are within a reasonable range for all three simulation years. Differences between the PET models tested are small for the period from 100% ground cover to harvest. The three PET models used for the period prior to complete ground cover show larger differences of predicted PET. The 1997 estimates for this period are consistent between models, 1998 values show the complex Baier and Robertson six variable model to be more than 40 mm below the three variable and SIMPOTATO model estimates. The results for 1996 reveal

low estimates for both the SIMPOTATO and six variable model relative to the three variable model for 1996 and other 1997 and 1998 estimates. Both SIMPOTATO and the six variable model were run using estimated global radiation data which was likely too low for that year, particularly early in the growing season. The affect of using low global radiation values to run the model for 1996 should not have restricted simulated photosynthesis, since most of this occurs after complete ground cover.

6.5 Model Sensitivity

A sensitivity analysis was performed to quantify the impact of selected genetic and plant parameters on SIMPOTATO's output. The analysis was done for the wettest and driest irrigation treatments for the Russet Burbank cultivar, for each trial year.

Tuber initiation was sensitive to the two plant parameters but was not significantly affected by the genetic parameters used in the analysis. Although tuber bulking was influenced more by the plant parameters than the genetic parameters tested, absolute values show little difference between base and modified output. An earlier emergence date of seven days had little affect on tuber initiation and bulking in all the trial years. A later emergence date of seven days delayed tuber initiation in 1997 A and D treatments by 15 and 14 days respectively, and delayed 1998 initiation by 9 days. Data was not available to run the test for 1996. Modeled yield was shown to be most sensitive to plant population density, emergence date and daily maximum tuber growth rate.

6.6 Conclusion

Inaccuracies between model estimates of SIMPOTATO and observed values for important crop growth measurements have shown that the default model tuber and leaf expansion growth rate coefficients for Russet Burbank are unrealistic for the trial years, 1996, 1997 and 1998 at Carberry. Results for Shepody suggest that in order to reasonably simulate growth and development, the genetic response of this variety has to be further calibrated for these same cultivar coefficients. Simulated tuber induction and carbohydrate partitioning to plant components are cultivar specific responses, and this study has shown that these modeled processes need to be improved for both potato varieties before SIMPOTATO can be used successfully in Manitoba.

Additional field testing of the simulation model would provide more information about its performance, and would allow the model to be better calibrated to Manitoba's climate.

The large amount of variability between treatments replicates in the Carberry experiments, particularly for leaf area sampling, reveals that more replicates would have been desirable in order to more accurately evaluate model simulations.

Further testing of the model should include an expansion of the sensitivity analysis conducted in this study to include an analysis on each climate variable and soil input parameter. This process involves the modification of weather and soil input values in order to see how the model responds in terms of physiological development, organ growth and yield. Such a procedure would quantify the importance of these model inputs.

Modeled processes can be corrected if shown to be oversensitive. After a successful calibration of the model, the potential exists to use weather and soil information for various agricultural areas of the province in order to estimate yield risk assessments for those areas.

Development of the SIMPOTATO model is more recent relative to the CERES-Wheat and Maize simulation models from which many model routines are based. As a result, the authors of the model have not been able to perform the research needed to provide quantitative descriptions of many growth processes. Calibration of the model's parameters have been mainly conducted at Prosser, Washington, and they have not been tested under a wide range of environmental conditions. As more spatially and temporally independent data is collected on the growth and development of the potato, SIMPOTATO can be evaluated more rigorously.

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Appendix A

SIMPOTATO Genetics Input File (Tom Hodges, 1997, Input Files for SIMPOTATO v1.60, for Windows95).

G2 = Maximum potential leaf area expansion ($\text{cm}^2 \text{ plant}^{-1} \text{ day}^{-1}$)

G3 = Maximum potential tuber growth (g of dry weight $\text{plant}^{-1} \text{ day}^{-1}$)

G4 = Specific leaf weight (g dry weight cm^{-2} of leaf)

G1 = Determinancy. Indeterminant cultivars more strongly continue leaf growth after tuber initiation and respond more strongly with new vegetative growth and branching to high levels of nitrogen availability (0.0 - 1.0)

A1 to A10

Calculate the effects of temperature, plant leaf area, light, daylength and nitrogen on tuber initiation. The various effects are multiplied together to get a single measure of daily progress toward tuber initiation so values of 1 have no effect on tuber initiation, values less than 1 slow or reverse progress and values greater than 1 hasten progress toward tuber initiation.

A1, A2 Daily mean temperature effect on tuber initiation.

Maximum effect of A1 at 15 C and zero effect (no progress) at 5 and 25 C. Set values so that $A1 - 1.0 = A2 * 10$

A3 Plant leaf area effect.

Larger values of A3 slow tuber initiation. Effect ranges from 1 (no effect) at zero leaf area to 20 at full cover with $A3 = 2.0$

A4 Light intensity (daily solar radiation daylength^{-1}) effect.

Ranges From 1 (no effect) at zero light to 1.3 for a clear day at the summer solstice (June 22).

A5, A6 Daily temperature range effect.

Ranges from 1 (no effect) when maximum = minimum daily temperature to A6 when the range is 25 C. Set so that $A6 = A5 + 1$.

A7, A8 Photoperiod (civil twilight or dusk to dawn) effect.

Ranges from 1 (no effect) for 18 hour days to A8 for 12 hour days. Potato is a short day plant (actually responds to long nights) so it develops faster in short days than long days (all else being equal). Set so that $A8 = A7 + 1$.

A9, A10 Plant nitrogen effect

Ranges from a maximum effect of A10 with low plant N content to a minimum of A9 with high plant N content. High levels of plant N tend to slow progress towards tuber initiation (more so in indeterminate cultivars like Russet Burbank).

Table A.1 Example of genetic coefficients file for SIMPOTATO

001 'MAJESTIC	' 300.0	3.0	.005	1.0	1.7	.07	1.9	1.9	1.0	2.0	0.0	1.0	0.8	1.2
002 'SEBAGO	' 300.0	3.4	.005	1.0	1.7	.07	2.9	2.9	0.5	1.5	0.0	1.0	0.8	1.2
003 'R-BURBANK	' 400.0	5.0	.005	0.0	1.7	.07	1.9	1.9	1.0	2.0	0.2	1.2	0.8	1.2
013 'Highlite	' 300.0	5.0	.006	1.0	2.0	.10	2.2	2.2	1.5	2.5	0.5	1.5	0.8	1.2
98 'RUSSET SANGRE'	450.0	6.5	.005	0.0	1.5	.05	2.5	1.9	0.7	1.7	0.0	1.0	0.6	1.0
99 'RUSSET NUGGET'	500.0	7.5	.005	0.0	1.2	.02	3.5	1.9	0.5	1.5	0.0	1.0	0.6	1.0

Appendix B

Plot Maps of the 1996 and 1998 Field Experiments, Carberry, Manitoba.

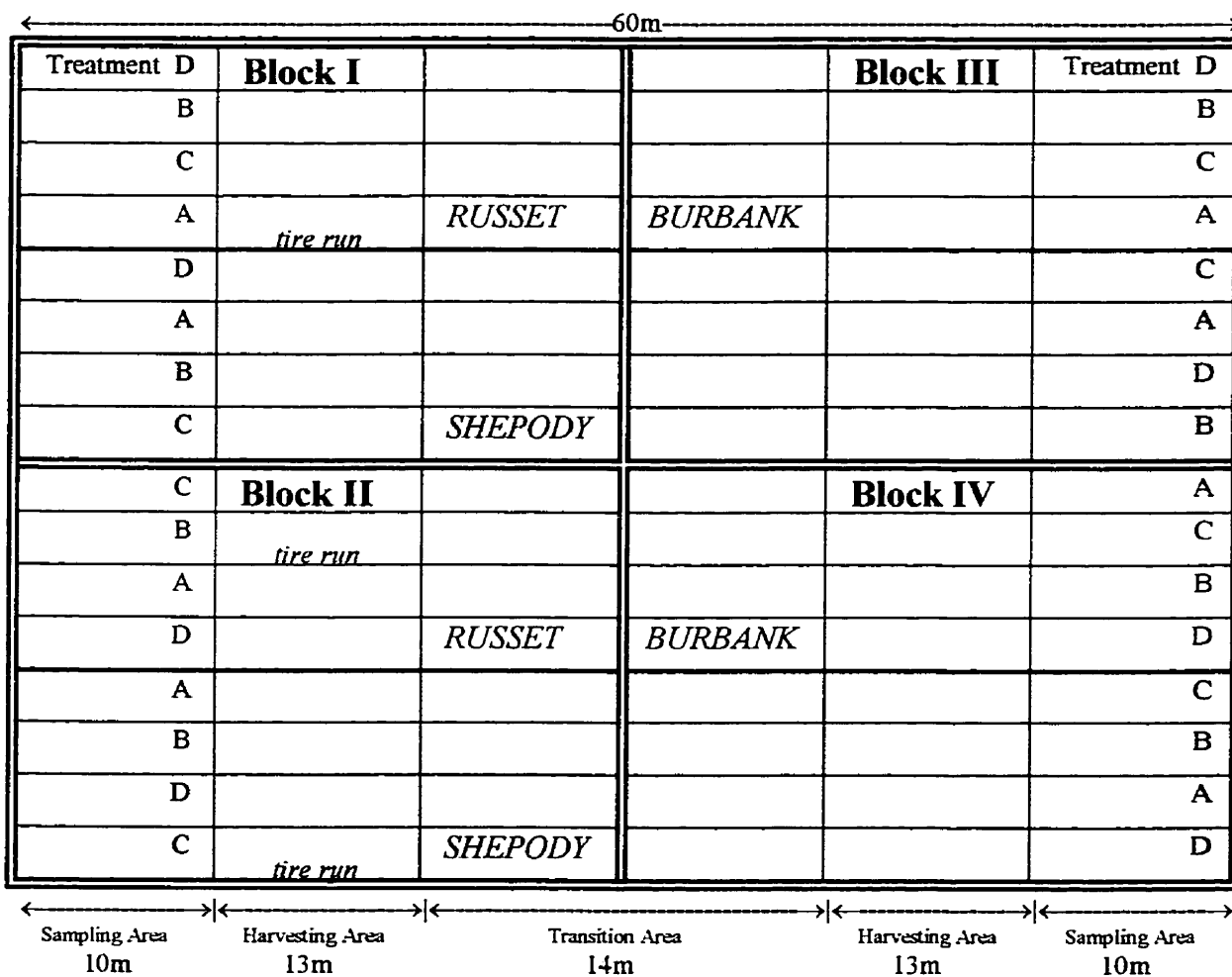


Figure B.1 MCDC potato trials, Carberry, 1996

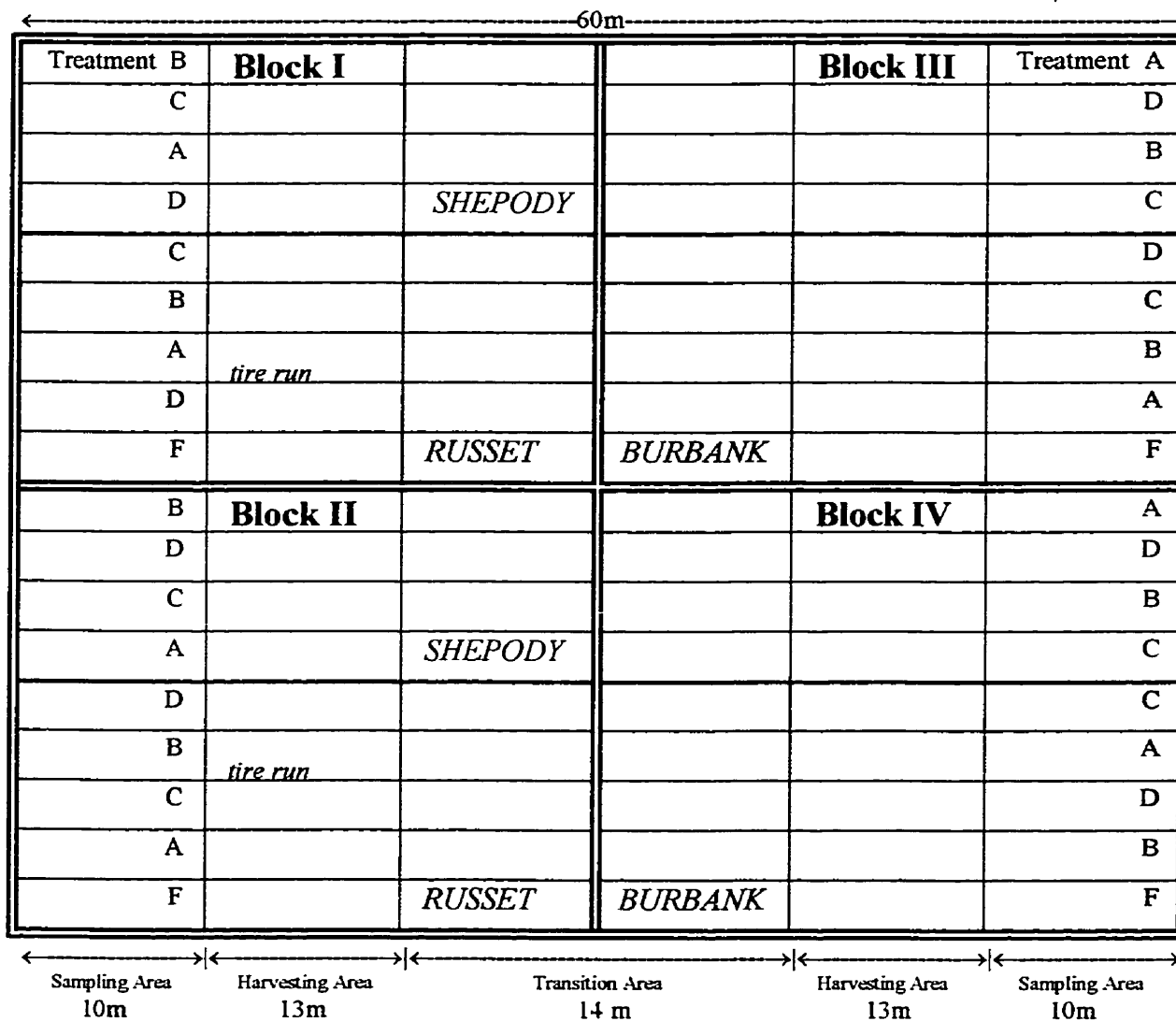


Figure B.2 MCDC potato trials, Carberry, 1998

The 1998 trial included an additional irrigation treatment (F) for the Russet Burbank cultivar. Management of Treatment F followed that of Treatment A until the crop was nearly mature. Additional irrigation was then applied to Treatment F at this stage for a separate experiment which assessed tuber quality as it is influenced by high late season soil moisture contents.

Appendix C

Yield and Quality of Tubers Harvested at the 1996, 1997 and 1998 Field Trials

Table C.1 Yield and quality of tubers harvested in 1996

Variety	Irrigation Treatment	Rainfall (mm)	Irrigation (mm)	Tuber Yield, T ha ⁻¹			
				Total	Small (< 2" diam.)	Marketable (> 2" diam.)	Bonus (> 10 oz)
Russet	A	267	76	49.1 (438)	4.9 (44)	44.1 (394)	15.6 (139)
	B	267	57	43.4 (387)	4.2 (38)	39.2 (349)	12.0 (107)
	C	267	19	42.6 (380)	5.5 (49)	37.1 (331)	11.0 (98)
	D	267	0	40.3 (360)	5.3 (47)	35.1 (313)	9.8 (87)
Shepody	A	267	76	44.2 (394)	1.7 (15)	42.4 (378)	25.4 (226)
	B	267	57	41.4 (370)	1.4 (12)	40.1 (358)	24.6 (219)
	C	267	19	37.7 (337)	1.5 (14)	36.2 (323)	16.0 (143)
	D	267	0	35.4 (316)	1.7 (15)	33.8 (301)	14.4 (128)

Values in parentheses are in cwt ac⁻¹.
1996 P-day accumulation = 897

Table C.2 Yield and quality of tubers harvested in 1997

Variety	Irrigation Treatment	Rainfall (mm)	Irrigation (mm)	Tuber Yield, T ha ⁻¹			
				Total	Small (< 2" diam.)	Marketable (> 2" diam.)	Bonus (> 10 oz)
Russet	A	203	196	49.7 (443)	4.2 (37)	41.9 (374)	12.3 (110)
	B	203	139	45.5 (406)	5.4 (48)	37.9 (338)	9.4 (84)
	C	203	82	44.4 (396)	4.7 (42)	38.0 (339)	9.0 (80)
	D	203	0	34.4 (307)	5.0 (45)	27.4 (244)	4.9 (44)
Shepody	A	203	196	47.9 (427)	2.6 (23)	43.3 (386)	27.5 (245)
	B	203	120	43.9 (392)	2.6 (23)	38.7 (345)	21.2 (189)
	C	203	57	38.6 (345)	2.7 (24)	33.5 (299)	20.3 (181)
	D	203	0	30.7 (274)	2.7 (24)	25.9 (231)	8.2 (73)

Values in parentheses are in cwt ac⁻¹.
1997 P-day accumulation = 857

Table C.3 Yield and quality of tubers harvested in 1998

Variety	Irrigation Treatment	Rainfall (mm)	Irrigation (mm)	Tuber Yield, T ha ⁻¹			
				Total	Small (< 2" diam.)	Marketable (> 2" diam.)	Bonus (> 10 oz)
Russet	A	359	130	49.2 (439)	11.1 (99)	36.1 (322)	15.2 (135)
	B	359	46	44.3 (396)	11.1 (99)	32.1 (286)	9.1 (81)
	C	359	19	44.3 (395)	8.1 (72)	34.7 (310)	14.3 (127)
	D	359	0	42.6 (380)	12.8 (114)	29.2 (260)	8.5 (76)
	F	359	168	50.5 (451)	11.2 (100)	37.0 (330)	10.7 (96)
	Shepody	A	359	149	47.6 (425)	4.5 (40)	42.0 (375)
B		359	65	44.4 (396)	3.9 (34)	39.7 (355)	16.9 (151)
C		359	19	42.9 (383)	5.1 (46)	36.8 (328)	13.3 (119)
D		359	0	42.4 (379)	4.2 (37)	37.0 (330)	15.5 (138)

Values in parentheses are in cwt ac⁻¹.

1998 P-day accumulation = 887

Table C.4 Total and marketable yields of the wettest irrigation treatments (A)

Year	Pdays	Precipitation + Irrigation (mm)	Tuber Yield (T ha ⁻¹)					
			Total		Marketable (> 2" diam.)		Bonus (> 10 oz)	
			Russet	Shepody	Russet	Shepody	Russet	Shepody
1996	897	343	49.1 (438)	44.2 (394)	44.2 (394)	42.4 (378)	15.6 (139)	25.3 (226)
1997	857	399	48.4 (432)	47.9 (427)	41.9 (374)	43.3 (386)	12.3 (110)	24.8 (221)
1998	887	452	49.2 (439)	47.6 (425)	37.0 (330)	42.3 (377)	15.1 (135)	20.5 (183)

Values in parentheses are in cwt ac⁻¹.

Bolded value is calculated on effective precipitation (above field capacity and lost to drainage)

Appendix D

Table D.1 Model yield, biomass and leaf area index model estimates for Shepody using Russet Burbank genetic coefficients

Year	Irrig Treat	Tuber Fresh Yield (Tonnes/ha)			Tuber Dry Yield (kg/ha)			Haulm Dry Matter (kg/ha)		LAI		
		Sim ^z	Obs ^y	SD Obs ^x	Sim	Obs	SD Obs	Sim	Max Obs ^w	Sim	Max Obs	SD Obs
1996	A	46.4	44.2	1.55	-	9230	355.8	-	-	4.7	6.5	-
	B	46.4	41.2	1.14	-	8415	262.0	-	-	4.4	6.0	-
	C	45.3	38.3	2.26	-	8185	517.5	-	-	3.8	3.6	-
	D	43.4	36.4	2.54	-	7967	581.0	-	-	3.4	4.6	-
1997	A	30.3	47.9	5.39	-	10010	1026.5	-	5486	-	8.8	-
	B	27.8	43.9	2.43	-	12275	531.9	-	3322	-	7.9	-
	C	18.1	38.6	6.62	-	8265	1821.7	-	3082	-	8.1	-
	D	10.1	30.8	7.04	-	6736	1738.1	-	3359	1.3	4.6	-
1998	A	40.5	47.6	4.65	-	10819	1054.7	-	4515	-	7.5	3.4
	B	40.3	44.4	0.45	-	10440	550.1	-	4564	-	6.8	1.2
	C	38.4	42.9	2.79	-	9766	1207.4	-	4303	-	5.7	1.7
	D	36.9	42.2	2.55	-	9801	698.2	-	3701	-	6.6	2.9

^z Simulated, ^y Observed, ^x Standard deviation of the observed, ^w Maximum Observed

Appendix E

Calculating Genetic Coefficients for both Russet Burbank and Shepody Cultivars from 1997 and 1998 Crop Growth Data, Carberry, MCDC

E1 G2 Leaf Growth Rate

The G2 variable is a genetic input setting the maximum potential leaf growth rate for a cultivar under optimum conditions. To estimate G2 for a cultivar, leaf growth rate (LGR) is computed as follows:

$$\text{LGR} = (\text{PLA}_{ii} - \text{PLA}_i) / (t_{ii} - t_i) \quad (\text{E1.1})$$

where PLA_i and PLA_{ii} are plant leaf areas at the beginning and end of time interval t_i (tuber initiation) and t_{ii} (20 and 40 days after t_i). Under optimum conditions LGR will be equal to G2.

Calculations of LGR from 1997 Carberry data. Average data from all treatments were used up to the date of the first irrigation to get more representative samples. Moisture treatment A was used afterwards for the calculations, because this treatment was the closest to optimal conditions.

E1.1 Calculations for Russet 1997

Tuber initiation occurred on July 2, 1997.

PLA (plant leaf area) on July 3 (day 184) = 0.291 m² / plant

PLA (plant leaf area) on July 22 (day 203) = 0.915 m² / plant

PLA (plant leaf area) on Aug 14 (day 226) = 2.325 m² / plant

then,

$$\begin{aligned} \text{LGR day 184 to 203} &= (0.92 - 0.29) / (203 - 184) = 331.6 \text{ cm}^2 \text{ plant}^{-1} \text{ day}^{-1} \\ &0.092 \text{ m}^2 \text{ plant}^{-1} \text{ day}^{-1} \\ \text{LGR day 203 to 226} &= (2.32 - 0.92) / (226 - 203) = 608.7 \text{ cm}^2 \text{ plant}^{-1} \text{ day}^{-1} \\ &0.168 \text{ m}^2 \text{ plant}^{-1} \text{ day}^{-1} \\ \text{LGR day 184 to 226} &= (2.32 - 0.29) / (226 - 184) = 483.3 \text{ cm}^2 \text{ plant}^{-1} \text{ day}^{-1} \\ &0.133 \text{ m}^2 \text{ plant}^{-1} \text{ day}^{-1} \end{aligned}$$

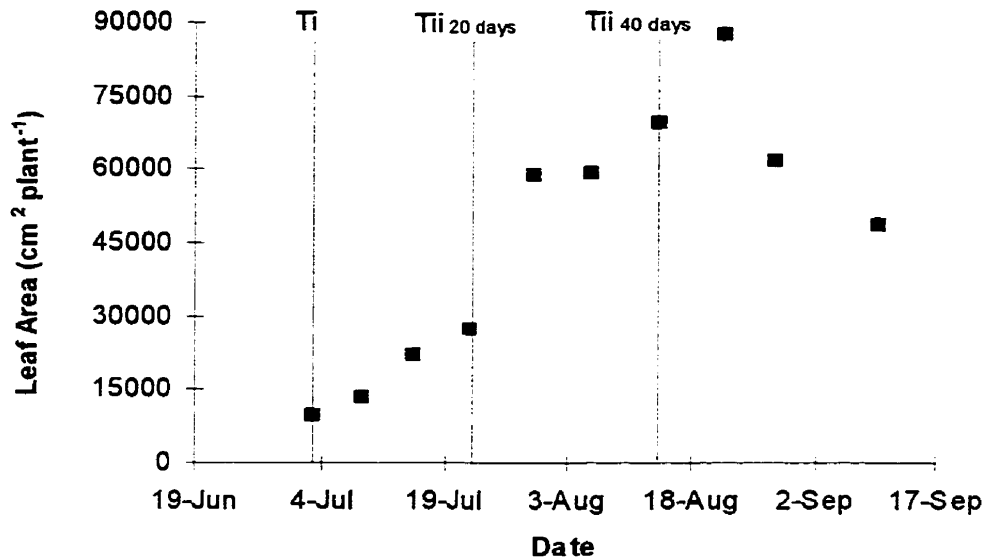


Figure E1 Average leaf area per plant with sampling date, Russet A Treatment 1997

E1.2 Calculations for Russet 1998

Tuber initiation occurred on July 2, 1998.

PLA (plant leaf area) on July 7 (day 188) = 0.677 m² / plant

PLA (plant leaf area) on July 27 (day 208) = 1.277 m² / plant

PLA (plant leaf area) on Aug 6 (day 218) = 2.078 m² / plant

then,

$$\begin{aligned} \text{LGR day 188 to 208} &= (1.277 - 0.677) / (208 - 188) = 299.99 \text{ cm}^2 \text{ plant}^{-1} \text{ day}^{-1} \\ &0.083 \text{ m}^2 \text{ plant}^{-1} \text{ day}^{-1} \\ \text{LGR day 208 to 218} &= (2.078 - 1.277) / (218 - 208) = 801.08 \text{ cm}^2 \text{ plant}^{-1} \text{ day}^{-1} \\ &0.221 \text{ m}^2 \text{ plant}^{-1} \text{ day}^{-1} \end{aligned}$$

$$\text{LGR day 188 to 218} = \frac{(2.078 - 0.677) / (218 - 188)}{0.129} = \frac{467.02 \text{ cm}^2 \text{ plant}^{-1} \text{ day}^{-1}}{0.129 \text{ m}^2 \text{ plant}^{-1} \text{ day}^{-1}}$$

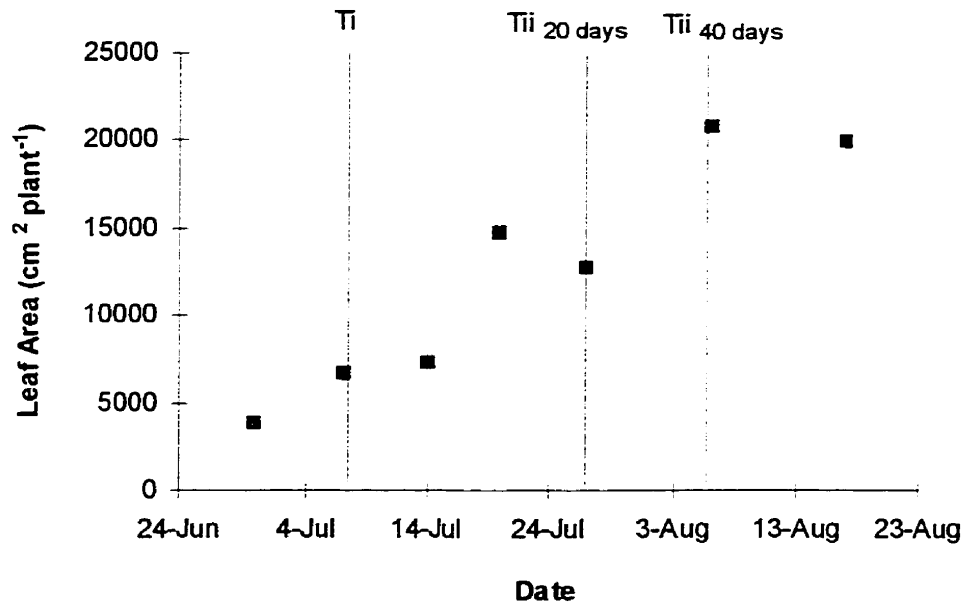


Figure E2 Average leaf area per plant with sampling date, Russet A Treatment 1998

E1.3 Calculations for Shepody 1997

Tuber initiation occurred on July 7, 1997.

PLA (plant leaf area) on July 9 (day 190) = 0.439 m² / plant

PLA (plant leaf area) on July 30 (day 211) = 1.466 m² / plant

PLA (plant leaf area) on Aug 22 (day 234) = 2.546 m² / plant

then,

$$\text{LGR day 190 to 211} = \frac{(1.47 - 0.44) / (211 - 190)}{0.169} = \frac{490.5 \text{ cm}^2 \text{ plant}^{-1} \text{ day}^{-1}}{0.169 \text{ m}^2 \text{ plant}^{-1} \text{ day}^{-1}}$$

$$\text{LGR day 211 to 234} = \frac{(2.55 - 1.47) / (234 - 211)}{0.162} = \frac{469.6 \text{ cm}^2 \text{ plant}^{-1} \text{ day}^{-1}}{0.162 \text{ m}^2 \text{ plant}^{-1} \text{ day}^{-1}}$$

$$\text{LGR day 190 to 234} = \frac{(2.55 - 0.44) / (234 - 190)}{0.165} = \frac{479.6 \text{ cm}^2 \text{ plant}^{-1} \text{ day}^{-1}}{0.165 \text{ m}^2 \text{ plant}^{-1} \text{ day}^{-1}}$$

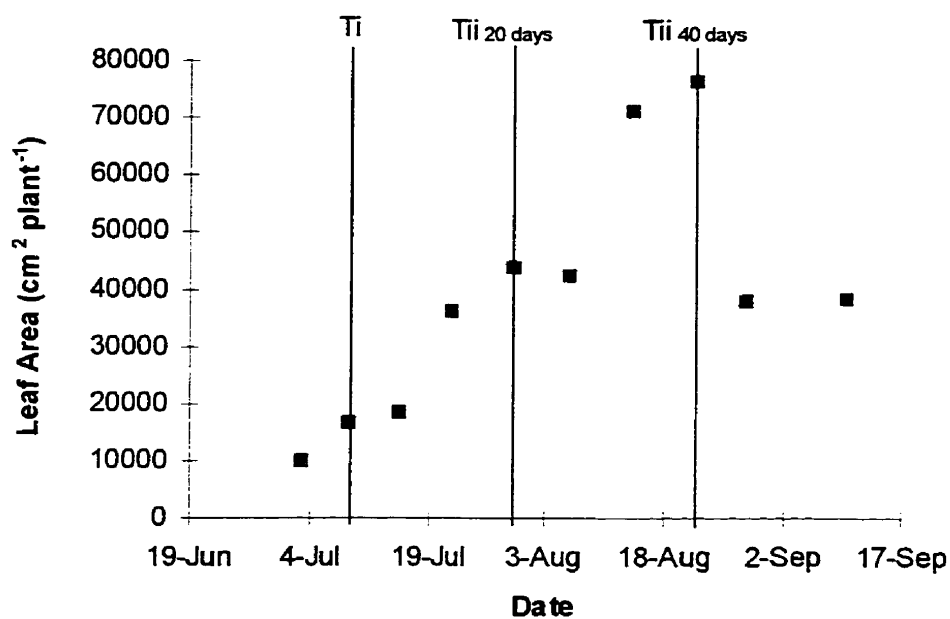


Figure E3 Average leaf area per plant with sampling date, Shepody A Treatment 1997

E1.4 Calculations for Shepody 1998

Tuber initiation occurred on July 8, 1998.

PLA (plant leaf area) on July 7 (day 188)= 0.079 m² / plant

PLA (plant leaf area) on July 27 (day 208)= 1.575 m² / plant

PLA (plant leaf area) on Aug 17 (day 229)= 2.100 m² / plant

then,

$$\begin{aligned} \text{LGR day 188 to 208} &= (1.575 - 0.079) / (208 - 188) = 748.33 \text{ cm}^2 \text{ plant}^{-1} \text{ day}^{-1} \\ &\quad 0.258 \text{ m}^2 \text{ plant}^{-1} \text{ day}^{-1} \\ \text{LGR day 208 to 229} &= (2.54 - 1.575) / (229 - 208) = 249.93 \text{ cm}^2 \text{ plant}^{-1} \text{ day}^{-1} \\ &\quad 0.086 \text{ m}^2 \text{ plant}^{-1} \text{ day}^{-1} \\ \text{LGR day 188 to 229} &= (2.54 - 0.079) / (229 - 188) = 493.05 \text{ cm}^2 \text{ plant}^{-1} \text{ day}^{-1} \\ &\quad 0.170 \text{ m}^2 \text{ plant}^{-1} \text{ day}^{-1} \end{aligned}$$

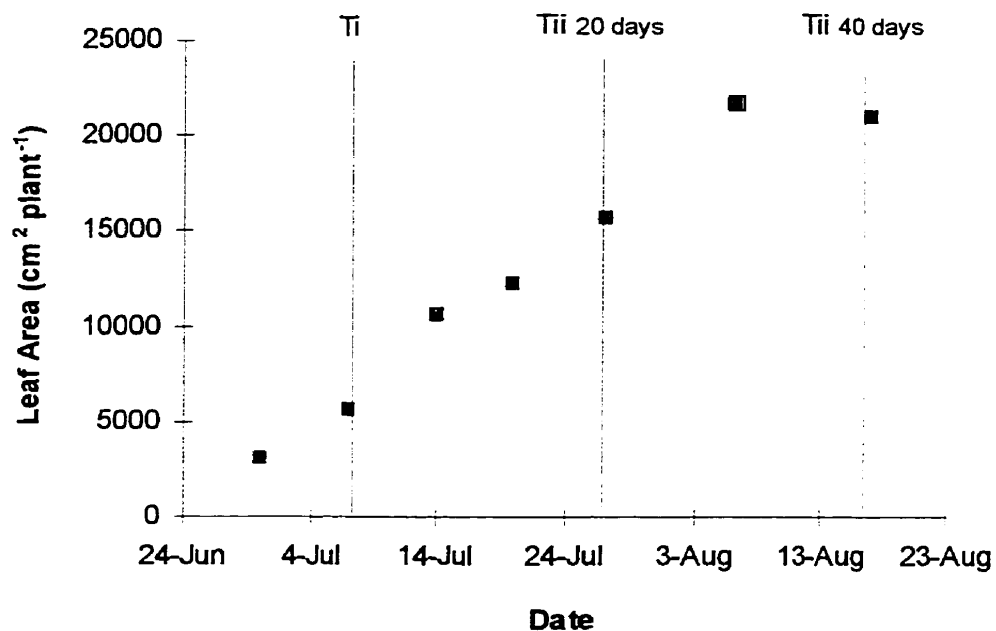


Figure E4 Average leaf area per plant with sampling date, Shepody A Treatment 1998

E2 Tuber Growth Rate

To estimate G3 for a cultivar, tuber growth rate (TGR) is computed as follows:

$$\text{TGR} = (M_{ii} - M_i) / (t_{ii} - t_i) \quad (\text{E1.2})$$

For a healthy potato canopy during the period of rapid tuber growth, growing at or near to maximum rate and not subject to any stresses. M_i and M_{ii} are tuber dry weights at the beginning and end of the time interval between t_i and t_{ii} . Under optimum conditions for growth will be equal to G3. Moisture treatment A was used for the calculations, because this treatment was the closest to optimal conditions.

E2.1 Calculations for Russet 1997

$$M \text{ (tuber dry weight) on July 29 (day 210)} = 65.53 \text{ g plant}^{-1}$$

$$M \text{ (tuber dry weight) on Sept 5 (day 248)} = 504.27 \text{ g plant}^{-1}$$

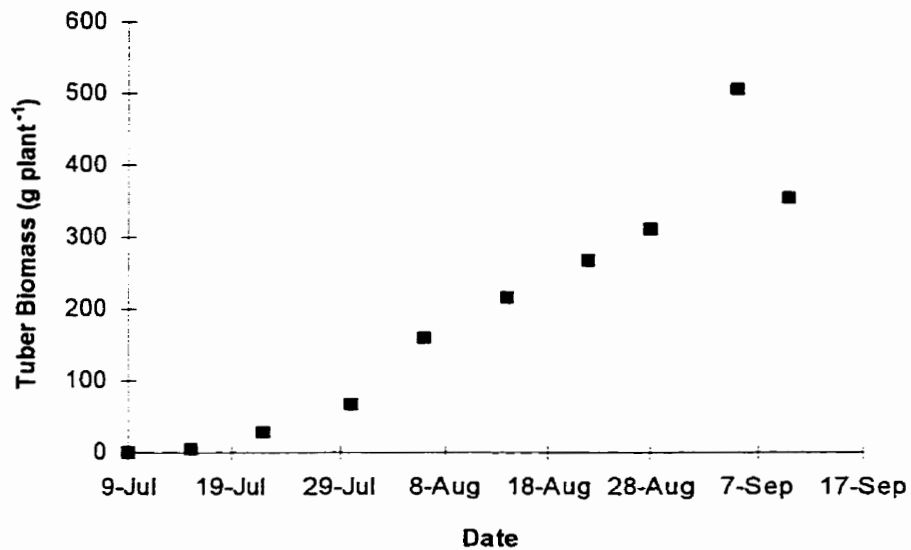


Figure E5 Tuber biomass with sampling date, Russet Burbank A, 1997

Russet tuber biomass sample for Sept. 5 with respect to the rest of the data (Figure E6) seems to be too high a value and likely would not provide accurate tuber growth rate estimates if used for Mii. Figure E6 below displays the linear growth portion of the Russet Burbank tuber growth data (rapid tuber growth). A linear trend line was fitted to this data. The slope of the linear equation was used as the tuber growth rate.

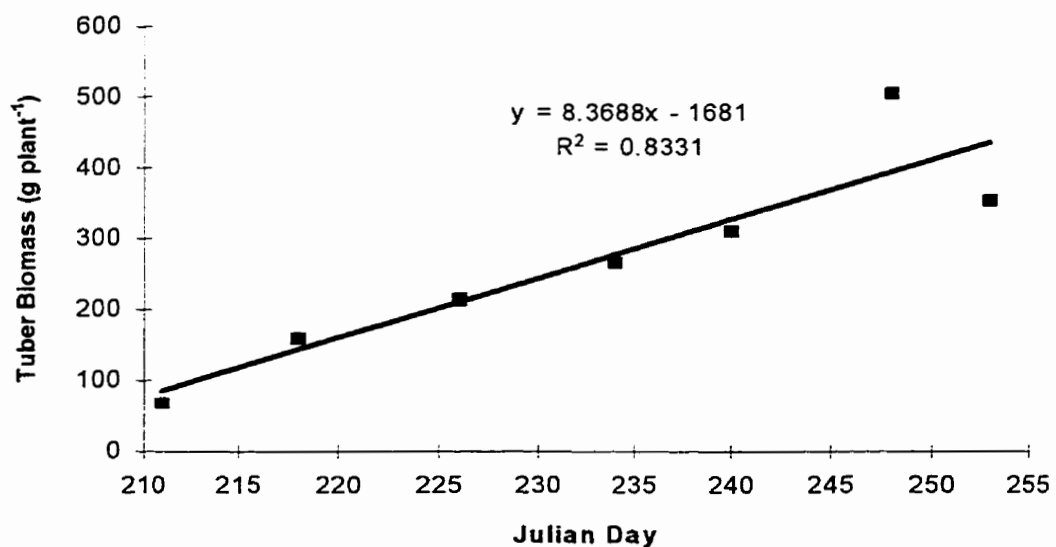


Figure E6 Tuber growth rate with Julian day for Russet Burbank A, 1997

Revised Russet Burbank tuber growth rates are calculated as follows:

$$\text{TGR day 210 to 248} = \frac{(394.5 - 65.53) / (248 - 210)}{23.893} = \frac{8.4 \text{ g plant}^{-1} \text{ day}^{-1}}{23.893 \text{ g m}^{-2} \text{ day}^{-1}}$$

E2.2 Calculations for Russet 1998

$$M \text{ (tuber dry weight) on July 20 (day 201)} = 34.19 \text{ g plant}^{-1}$$

$$M \text{ (tuber dry weight) on Aug 17 (day 229)} = 200.70 \text{ g plant}^{-1}$$

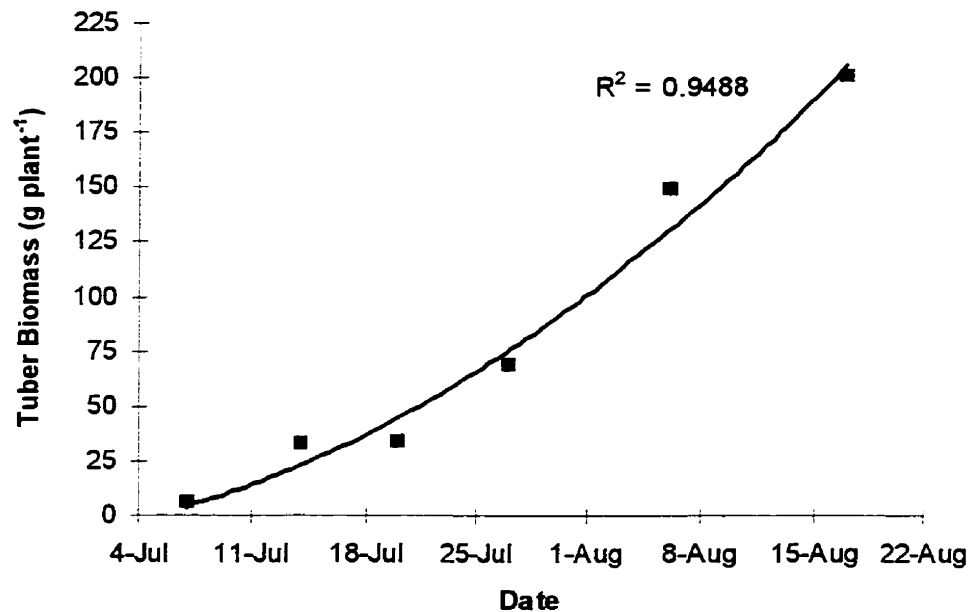


Figure E7 Tuber biomass per plant with sampling date, Russet A, 1998

then,

$$\text{TGR day 201 to 229} = \frac{(200.7 - 34.19) / (229 - 201)}{16.41} = \frac{5.947 \text{ g plant}^{-1} \text{ day}^{-1}}{16.41 \text{ g m}^{-2} \text{ day}^{-1}}$$

E2.3 Calculations for Shepody 1997

$$M \text{ (tuber dry weight) on Aug 6 (day 218)} = 87.29 \text{ g plant}^{-1}$$

$$M \text{ (tuber dry weight) on Sept 5 (day 248)} = 303.07 \text{ g plant}^{-1}$$

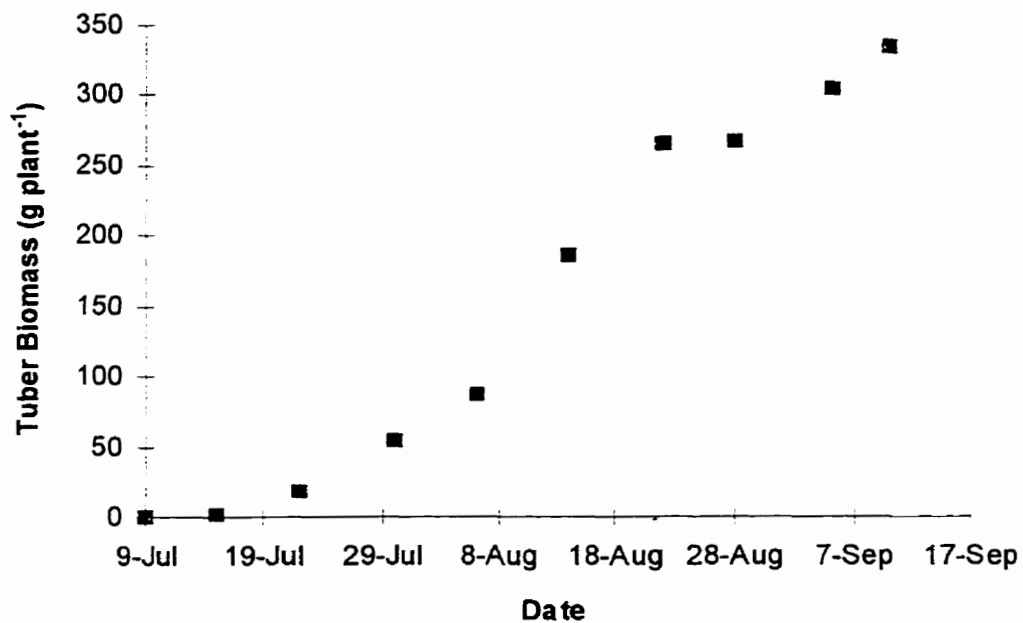


Figure E8 Tuber biomass per plant with sampling date, Shepody A, 1997

Shepody tuber growth rates are calculated as follows:

$$\text{TGR day 218 to 248} = \frac{(303.07 - 87.29) / (248 - 218)}{24.815} = 7.19 \text{ g plant}^{-1} \text{ day}^{-1} \\ 24.815 \text{ g m}^{-2} \text{ day}^{-1}$$

E2.4 Calculations for Shepody 1998

$$M \text{ (tuber dry weight) on July 20 (day 201)} = 33.15 \text{ g plant}^{-1}$$

$$M \text{ (tuber dry weight) on Aug. 17 (day 229)} = 217.14 \text{ g plant}^{-1}$$

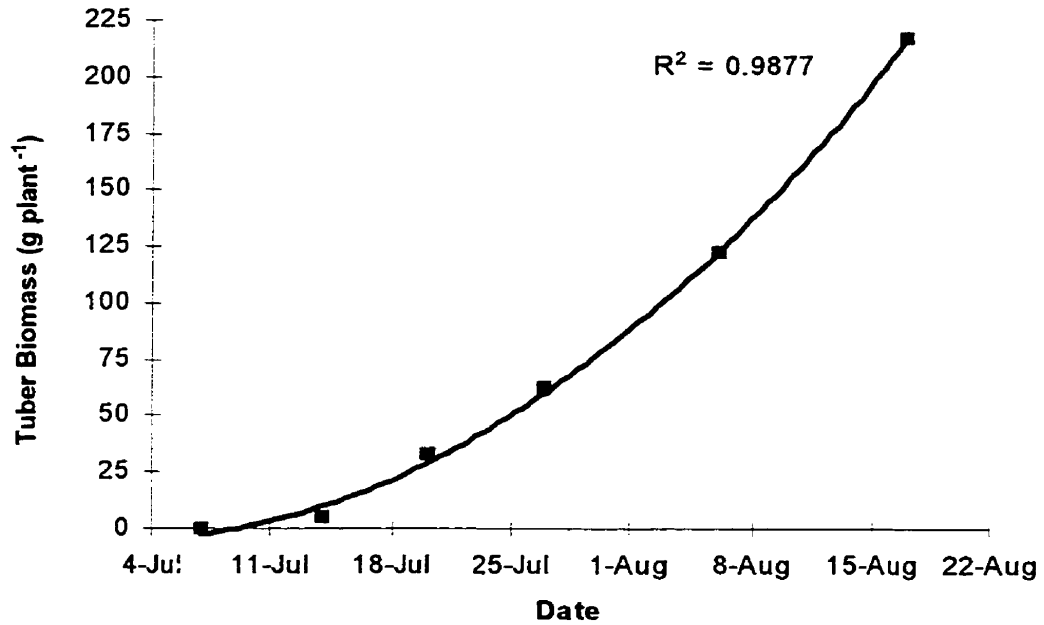


Figure E9 Tuber biomass per plant with sampling date, Shepody A, 1998

Shepody tuber growth rates are calculated as follows:

$$\text{TGR day 201 to 229} = \frac{(217.14 - 33.15) / (229 - 201)}{22.671 \text{ g m}^{-2} \text{ day}^{-1}} = 6.57 \text{ g plant}^{-1} \text{ day}^{-1}$$

E3 Partitioning Coefficient

The Partitioning Coefficient (G4) is a factor used to calculate the efficiency of allocating dry matter in tubers. PC is computed in the following way:

$$\text{PC} = \text{TGR} / \text{CGR}$$

where TGR is the tuber growth rate and CGR is crop growth rate. CGR is calculated according to the following equation:

$$\text{CGR} = (C_{ii} - C_i) / t_{ii} - t_i$$

where C_{ii} and C_i are total dry weights at times t_{ii} and t_i respectively. G4 should be calculated during some part of the period of rapid tuber growth, i.e., from 20 to 40

days after tuber initiation for plants growing under optimum conditions. Calculations of CGR from 1997 Carberry data. Average data from all treatment were used up to the first irrigation to get more representative samples. Moisture treatment A was used afterwards for the calculations, because this treatment was the closest to optimal conditions.

E3.1 Calculations for Russet Burbank 1997

Tuber initiation occurred on July 2, 1997.

C_i (Total plant biomass) on July 3 (day 184) = 26.67 g plant⁻¹
(sum of top and stolon biomass - no root or tuber biomass for this week)

C_{ii} (Total plant biomass) on Aug 28 (day 240) = 572.88 g plant⁻¹
(sum of top, stolon, tuber and partial root biomass)

CGR day 184 to 240 = $(573 - 27) / (240 - 184) = 9.75 \text{ g plant}^{-1} \text{ day}^{-1}$
 $26.91 \text{ g m}^{-2} \text{ day}^{-1}$

TGR day 184 to 240 = $309.93 / (240 - 184) = 5.535 \text{ g plant}^{-1} \text{ day}^{-1}$
 $15.275 \text{ g m}^{-2} \text{ day}^{-1}$

then,

PC day 184 to 240 = $\text{TGR} / \text{CGR} = 5.53 / 9.75 = 0.567$

E3.2 Calculations for Russet Burbank 1998

Tuber initiation occurred on July 2, 1997

C_i (Total plant biomass) on July 7 (day 188) = 72.00 g plant⁻¹
(average green biomass - no root or tuber biomass this week)

C_{ii} (Total plant biomass) on Aug 17 (day 229) = 414.87 g plant⁻¹
(sum of top and tuber biomass - root mass not considered)

CGR day 188 to 229 = $(414.87 - 72) / (229 - 188) = 8.363 \text{ g plant}^{-1} \text{ day}^{-1}$
 $23.08 \text{ g m}^{-2} \text{ day}^{-1}$

TGR day 188 to 229 = $200.7 - 6.3 / (229 - 188) = 3.471 \text{ g plant}^{-1} \text{ day}^{-1}$
 $9.581 \text{ g m}^{-2} \text{ day}^{-1}$

then,

PC day 188 to 229 = $\text{TGR} / \text{CGR} = 5.53 / 9.75 = 0.415$

E3.3 Calculations for Shepody 1997

Tuber initiation occurred on July 7, 1997.

Ci (Total plant biomass) on July 9 (day 190) = 48.37 g plant⁻¹
(sum of top and stolon biomass - no root or tuber biomass this week)

Cii (Total plant biomass) on Aug 28 (day 240) = 426.39 g plant⁻¹
(sum of top, stolon, tuber and partial root biomass)

$$\text{CGR day 190 to 240} = \frac{(426 - 48) / (240 - 190)}{26.08 \text{ g m}^{-2} \text{ day}^{-1}} = 7.56 \text{ g plant}^{-1} \text{ day}^{-1}$$

$$\text{TGR day 190 to 240} = \frac{(266.16 - 0.35) / 240 - 190}{18.341 \text{ g m}^{-2} \text{ day}^{-1}} = 5.3162 \text{ g plant}^{-1} \text{ day}^{-1}$$

then,

$$\text{PC day 190 to 240} = \text{TGR} / \text{CGR} = 5.316 / 7.56 = 0.703$$

E3.4 Calculations for Shepody 1998

Tuber initiation occurred on July 8, 1997.

Ci (Total plant biomass) on July 7 (day 188) = 56.14 g plant⁻¹
(average green biomass - no root or tuber biomass this week)

Cii (Total plant biomass) on Aug 17 (day 229) = 343.14 g plant⁻¹
(sum of top and tuber biomass - root mass not considered).

$$\text{CGR day 188 to 229} = \frac{(343.14 - 56.14) / (229 - 188)}{24.15 \text{ g m}^{-2} \text{ day}^{-1}} = 7.00 \text{ g plant}^{-1} \text{ day}^{-1}$$

$$\text{TGR day 188 to 229} = \frac{(217.1 - 0) / 229 - 188}{22.81 \text{ g m}^{-2} \text{ day}^{-1}} = 6.61 \text{ g plant}^{-1} \text{ day}^{-1}$$

then,

$$\text{PC day 188 to 229} = \text{TGR} / \text{CGR} = 6.61 / 7.00 = 0.945$$