

MODELLING THE SOIL WATER BALANCE OF POTATOES  
FOR IMPROVED IRRIGATION MANAGEMENT

by

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Submitted in partial fulfilment of the requirements for the degree

M.Sc. Soil Science

In the Faculty of Natural and Agricultural Sciences

University of Pretoria

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December 2006

*This document is dedicated to Jeanne, Faustin (Fofu), and Prince*

## **ACKNOWLEDGEMENT**

I would like to thank Dr J.M Steyn and Prof. J.G Annandale for their invaluable advices and guidance during the research programme. Your supervision throughout my time in the irrigation unit helped me gain so much knowledge from this research.

I would also like to thank the Department of Plant Production and Soil Science for providing laboratory facilities and the necessary field work equipments.

Special thanks go to the Government of Rwanda through the Institut des Sciences Agronomiques du Rwanda (ISAR) for funding without which this degree would not have been possible.

Finally, my deepest gratitude goes to my darling wife, Jeanne d'Arc N.safari for her love, encouragement and moral support as well as for virtually raising alone our lovely sons, Faustin Kagabo and Prince Kagabo, while I was away completely taken up by this study.

Kind regards,

KAGABO Desire MBARUSHIMANA

Pretoria

December 2006

## ABSTRACT

Soil Water Balance (SWB), is a generic and mechanistic crop growth model that has been successfully used to model the water balance of several crops. Its ability to combine crop water modelling and irrigation scheduling approaches allows it to be used as a research tool and an irrigation management tool. Since SWB is a tool that could be used as decision making tool for farmers, its accuracy in simulating crop growth, development and soil water balance should be high. To highlight the importance of improved irrigation management for potato crop by the means of a mechanistic soil water balance model and the importance of the photoperiod factor in potato modelling in sub-tropical region, two potato experiments were carried out in two contrasting seasons, namely, spring and autumn. Growth and development responses of potato under both well irrigated and water stressed conditions for spring and autumn plantings were examined.

This study successfully quantified the water use and potato growth responses to water stress. The water use efficiency varied with irrigation treatments and planting time, and autumn experiment had generally higher values than spring. Unstressed treatment gave the highest tuber yields irrespective of planting season and marketable tuber yield was higher in autumn than spring. Water stress imposed at tuber initiation until end of tuber bulking was revealed to be the most detrimental to biomass and tuber production. This suggests that water stress at tuber initiation and bulking stage should be avoided if high tuber yield is the target.

Growth analysis data were used to determine crop parameters for SWB calibration and validation. The model simulated reasonably well growth, development and soil water balance in both unstressed and stressed conditions. However, simulations results of total and harvestable dry matter towards the end of the exponential tuber bulking stage (50 - 65 DAP) were deteriorated. As a result, the model did not simulate accurately the final yield. This is an indication that the model fails to simulate the size of the canopy and its duration.

The time at which tuber initiation commences appeared not be affected by the planting seasons since variation of the duration between emergence and tuber initiation in different seasons was small. This small variation could be attributed to the fact that the potato growing season in South Africa (Pretoria) in spring 2004 and autumn 2005 experiences minimum and maximum temperatures which are acceptable for the growth of potato. In Pretoria, emergence and tuberisation take place under relatively cool temperatures late in September and also early in April when temperatures are relatively cool. Consequently, potato grown in this period may escape the early autumn and late spring high temperatures. However, autumn planting experiences an abrupt change of day lengths from long days to short days towards tuber initiation. This brusque change of day length may change the crop physiology and affect the subsequent normal course of plant growth. If the day length factor could be integrated into SWB, it appears that the model will better simulate potato growth and development. The poor simulation results of total dry matter and harvestable dry matter early in the growing season suggest that the model should be improved by allowing it to simulate the start of tuber initiation.

A linear function of average temperature between a base and an optimal temperature corrected with photoperiod factor was found to be the most appropriate method to estimate thermal time required for tuber initiation. This method suggests that the time of tuber initiation can be estimated from its thermal time within two days.

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## CHAPTER 1

### GENERAL INTRODUCTION

Potato (*Solanum tuberosum* L.) is the fourth most important food crop in the world (Manrique, 2000) and is grown in various climates through out the world (Haverkort, 1990). Contrary to the most developed countries where a gradual decline of potato production has been noticed, potato production growth rates have been increasing in developing countries (CIP, [www.cipotato.org](http://www.cipotato.org), 2002). This increase of potato production in developing countries is coupled with the increase of cultivated areas. However, where potato is grown intensively, for instance South Africa and Egypt, the increase of production is attributed to the expansion of irrigation, which facilitates high average yields (14-28 t/ha) (CIP, [www.cipotato.org](http://www.cipotato.org), 2002).

Potato is widely known to be very sensitive to soil water deficit. An extensive literature reviewed by Van Loon, (1981), and recent research by Jefferies and Mackerron, (1993); Gregory and Simmonds, (1992); Jefferies, (1995); Costa *et al.* (1997); Steyn (1997), Shock *et al.* (1998); Iqbal *et al.* (1999); Costa and Mackerron (2000); Fabeiro *et al.* (2001); Kashyap and Panda (2002), Hassan *et al.* (2002); Yuan *et al.* (2003) and Ierna and Mauromicale (in press) describe the effect of even a moderate water shortage on yield and quality of potato. Even in well-irrigated potato crops particularly on hot and sunny days, undergo temporary water stress (Jefferies, 1995). This shows that potato is very sensitive to water stress although it was suggested by Jefferies and Mackerron (1993) and Costa and Mackerron, (2000) that the severity of water stress effects depends on the time when the stress occurs, its duration and intensity. To optimise yields, Doorenbos and Kassam (1979) and Costa and Mackerron (2000), suggest that the total available soil water content should not be depleted by more than 30 to 50%, whereas Kashyap and Panda (2002) proposed a value of 45% for potato grown on sandy loam soil in a sub-humid sub-tropical region in order to attain maximum water use efficiency.

Crop water simulation models have been identified as appropriate tools to describe the soil water behaviour and the crop response under a given environment and irrigation management strategy (Teixeira, Fernando and Pereira, 1995). Such models can provide information on crop water use and soil water depletion for real time irrigation scheduling. Most crop water

simulation models are able to predict the effect of water constraints on the plant correctly since they take account of dynamic functions by using a mechanistic approach. An example is the Soil Water Balance (SWB) model (Annandale *et al.*, 1999).

SWB is a generic, mechanistic crop growth and irrigation-scheduling model, which estimates crop water use despite the complexities of this dynamic system. The model has been packaged in an extremely user-friendly format (Annandale *et al.*, 1999) in an attempt to make it usable for real-time irrigation scheduling. The ability of SWB to combine crop water modelling and irrigation scheduling approaches allows it to be used as a research tool and an irrigation management tool. Since SWB is a tool that could be used as decision-making tool for farmers, its accuracy in simulating potato crop growth, development and soil water balance should be high. However, as pointed out by Steyn (1997), SWB accuracy should not be expected to be as good as for more mechanistic and specific crop models. Generic models embody a general principle applied to all crops, whatever divergences in physiological and ecological principles between crop classes such as cereals and root crops (Gayler *et al.*, 2002). Being a generic crop model, SWB has the ability to recognize the general process common to all crops and the overall model structure is applied to all crop types. As suggested by Gayler *et al.* (2002) generic models may require modifications of a single process formulation where divergences in physiological and ecological principles between crop classes may occur.

SWB has been thoroughly calibrated for potatoes grown in both spring and autumn seasons in South Africa. However, this was a temporary alternative since one set of parameters for both spring and autumn plantings could not be obtained. Validation of the model for the spring season was done using available data from an autumn season, which led to inconsistent simulation results. These inconsistent results were attributed to the failure of the model to take into account the effects of photoperiod and high temperatures on development and assimilate distribution (Steyn, 1997). The inclusion of day length in the model as suggested by Steyn (1997) may improve the universal applicability of the model in different growing seasons (spring or autumn).

Factors like temperature, irradiance, soil water and photoperiod are regarded as important in affecting the growth and development of the potato crop (O'Brein, Allen and Firman, 1998). Except for photoperiod, these factors listed are all taken into account in the simulation

process by the SWB model. Crops like potato in many subtropical countries are grown in two seasons; a spring crop grown when days are initially short and temperatures relatively cool and autumn crop grown when days are initially long and temperatures high. These relatively long days and high temperatures during the initial stages of potato growth in autumn favour foliar growth, which delays the time of tuber initiation and tuber growth (Ewing and Struik, 1992, Kooman, 1995).

Initiation of tubers has been established to lead to a preferential partitioning of assimilates to the tubers (Ewing and Struik, 1992, Kooman, 1995) and is regarded as a key developmental stage in the crop's life, having profound implications for subsequent growth and development (O'Brien *et al.*, 1998). In temperate climate with photoperiods ranging from 12 to 17 hours with similar temperatures and daily amounts of incident radiation during initiation, O'Brien *et al.* (1998) found no differences in interval between the time of plant emergence and onset of tuber initiation in three cultivars, namely, Desiree, Maris Piper and Estima. However, in tropical environment these varieties were reported by Demagante and Van der Zaag (1988b) to be sensitive to photoperiod ranging from 12 to 16 hours. O'Brien *et al.* (1998) attributed the variation in effects of photoperiod in both temperate and tropical environments to the differences in temperature between the two sites, as the combination of high temperatures and long photoperiod have been shown to be particularly inhibitory to tuber formation. This indicates that photoperiod effects on potato growth in sub-tropical regions could significantly alter the duration of tuber initiation, while it could be quite stable in temperate regions.

From the above background the objectives of this study were:

- 1) to examine the relations between potato growth and water use for improved irrigation management by means of a mechanistic soil water balance model;
- 2) to calibrate and evaluate SWB for potato under both well irrigated and deficit irrigation conditions;
- 3) to investigate ways in which photoperiod might contribute to the improvement of SWB in simulating potato growth and development.

The present study is subdivided into seven chapters. The first chapter is a general introduction, highlighting the importance of improved irrigation management for potatoes by means of a mechanistic soil water balance model, and also emphasises the importance of the

photoperiod factor in potato modelling in sub-tropical regions where potatoes are grown in two contrasting seasons (spring and autumn). Chapter 2 reviews the effect of photoperiod on potato growth and development and investigates simulation models of potato, which take into account the effect of photoperiod on growth and development. Furthermore, the chapter briefly reviews the effect of irrigation water regimes on potato growth and development. In Chapter 3, the general methodology applied to the field experiment is presented. However, specific methodologies or approaches relevant to other chapters are presented within these chapters. Chapter 4 presents and discusses results of the effect of irrigation water regimes applied at different potato crop stages on growth, development, yield and water use. Simulation results of SWB subsequent to its calibration and evaluation are presented in Chapter 5. In Chapter 6, estimation of thermal time for tuber initiation using different methods is carried out. As crop development is mainly influenced by thermal time, these methods were used to investigate whether thermal time for tuber initiation in two contrasting seasons (spring and autumn) would improve by integrating photoperiod as an additional factor on growth and development of potato. Finally, the conclusions and recommendations of this study are compiled in Chapter 7.



## CHAPTER 2

### LITERATURE REVIEW

#### 2.1. Concept definitions

##### 2.1.1. Crop modelling

Sinclair and Seligman (1996) defined crop modelling as the dynamic simulation of crop growth by numerical integration of constituent processes with the aid of computers, whereas Monteith (1996) defined crop modelling as a quantitative scheme for predicting the growth, development and yield of a crop given a set of genetic coefficients and relevant environmental variables. Boote, Jones and Pickering (1996) provided potential uses and limitations of crop models. They pointed out that crop models provide structure to a research programme, and are particularly valuable for synthesizing research understanding. Several authors (Penning de Vries and Spitters, 1990; Boote *et al.*, 1996; Sinclair and Seligman, 1996; Graves, Hess and Matthews, 2002) have reviewed the benefits and different uses of crop models. Matthews (2002) pointed out that a major advantage of simulation approaches is their potential transferability, in that they should be able to be used in different circumstances without having to rewrite the model.

##### 2.1.2. Crop growth and development

Spitters (1990), Goudriaan and Van Laar (1994) and Campbell and Norman (1998) define **crop growth** as the increase of dry matter over time. Furthermore, Campbell and Norman (1998) define **crop development** as the orderly progress of an organism through defined stages from germination to death. Thornley and Johnson (1990) suggest that it is often useful to consider growth and development as processes that can occur independently, although this is only an approximation. In plants, developmental stages such as germination, emergence, leaf appearance, flowering and maturity can be distinguished. These processes of plant growth and development were studied at several levels of detail.

Goudriaan and Van Laar (1994) described two levels of plant growth, where the first is the physiological level in which the formation of new plant tissue is analysed in terms of effects

of plant hormones, biochemical pathways, and the way substances are transported from one organ to another.

The second level of study is at the agronomic level, where these physiological processes are ignored and yield formation is immediately related to management factors such as nutrition, irrigation, crop rotation and tillage.

### **2.1.3. Photoperiod**

Noggle and Fritz (1976) and Salisbury and Ross (1991) stated that plants which flower following exposure to short days, are termed short-day plants, while those that flower after exposure to long days are called long-day plants. They also identified another group of plants that appear to flower regardless of the length of the photoperiod. Such plants are termed day-neutral plants.

Two types of day lengths are distinguished, namely, absolute and quantitative, for both short and long day plants (Goudriaan and Van Laar, 1994). In the case of absolute day length sensitivity, a threshold value is required before development to flowering can proceed. For quantitative day length sensitivity (example potato crop), development to flowering stage takes longer only if day length is somewhat unfavourable. The most striking effect of day length or photoperiod is the shift from vegetative growth to reproductive growth (Noggle and Fritz, 1976). In potato, it is well known that tuber initiation is highly responsive to photoperiod (Ewing and Sandlan, 1995). Ewing and Sandlan (1995) assert that photoperiod has another effect besides controlling the time of tuber initiation. Exposure of plants to short photoperiods has the long-term effect of increasing the percentage of assimilate allocated to tubers at the expense of all other parts of the plants (Ewing and Sandlan, 1995).

## **2.2. Modelling approach**

When computers became easily available to help researchers deal with the complexity of quantitative crop growth description, the expertise of crop simulation modelling developed rapidly (Passioura, 1996). Spitters (1990) and Passioura (1996) revealed that two main types of crop growth models emerged early in the 1970's, namely:

- (1) Empirical models were, essentially practical and combined a few rules of thumb to predict the behaviour of crops, and
- (2) Mechanistic models, which were seemingly scientific in spirit and sought to represent the biological and physiological processes thought to occur in plants and their environments.

Spitters (1990) attempted to distinguish the two approaches. The empirical models describe the observed plants with some empirical function. This means that they describe the effects only at a level of observation. Monteith (1996) mentioned that empirical models consist of functions that are chosen, often arbitrarily, to fit measurement from field or laboratory. The mechanistic models, on the other hand, explain the observed growth rates from the underlying physiological processes and in relation to the environmental factors. These models describe the mechanism of crop growth in an explanatory way. Spitters, (1990) provided an example of governing equations for dry matter accumulation in plants used in empirical and mechanistic models.

Empirical model (polynomial):

$$W_t = a_0 + a_1 t + a_2 t^2 + \dots + a_n t^n \quad (2.1)$$

Where  $W_t$  is the biomass at time  $t$ , and  $a_0 \dots a_n$  are regression coefficients. These functions are purely empirical and the regression coefficients do not have a biological meaning.

Mechanistic function:

$$W_t = W_m (1 \pm b * \exp(-k * t))^{-\frac{1}{v}} \quad (2.2)$$

$W_t$  is the biomass at time  $t$ , and  $W_m$ ,  $b$ ,  $k$  and  $v$  are regression coefficients, to which some biological interpretation can be given. The plus sign applies when  $v > 0$ , the minus sign when  $-1 \leq v < 0$ , while the function is not defined for  $v < -1$  or for  $v = 0$ . In the case of  $v = 1$ , the logistic function is obtained. Actually, models are required that explain the major processes occurring in the system, and this is met by eco-physiological models (Spitters, 1990). Regression or empirical models may provide a first method of analysis by summarising the data with a small number of parameters (Spitters, 1990). Compared to empirical or regression models, simple mechanistic models as defined by Spitters (1990) have the

advantage of greater flexibility and allowing for some insight into the mechanisms underlying the variation in yield.

### **2.3. Crop growth pattern**

Within the life cycle of seasonal crops, as defined by Goudriaan and Van Laar (1994), three growth phases are distinguished, namely, an exponential phase, linear phase and senescence phase. These phases have served as the basis for simple crop growth model development. The first growth phase is considered as exponential when most of the space around the plants has not yet been occupied. Each new leaf that is formed, contributes to more radiation being intercepted, so that growth increases even more. There is no mutual shading yet and the contribution of a new leaf is identical to that of the older ones. The second phase is linear, occurs when leaves start to overshadow each other. The linear phase is assumed to occur above a Leaf Area Index (LAI) of  $3 \text{ m}^2 \text{ m}^{-2}$ . After LAI has attained a value of 3, new formed leaves hardly contribute to any increase in radiation interception. The final growth phase is senescence, which starts when radiation interception decreases, and LAI has decreased to below  $3 \text{ m}^2 \text{ m}^{-2}$ .

### **2.4. Climate and potato production**

Potato is the fourth most important food crop in the world (Manrique, 2000) and is grown in various climates throughout the world (Haverkort, 1990). The crop has attained great importance in tropical and sub tropical climates since the late 1960s (Zaag and Horton, 1983). However, the potential production and the ratio between actual and potential production are lower in tropical and sub tropical climates (Kooman *et al.*, 1996). One of the causes of lower yields is the shorter growth cycle due to unfavourable weather conditions in these climates (Kooman *et al.*, 1996).

Based on the results of Kooman *et al.* (1996), potential and actual tuber dry matter production of potato is mainly determined by the length of the growth period. High average temperatures during the growing season, and short day lengths at emergence, shorten the duration of potato growth. Tropical climates prone to high average temperatures and short day lengths usually produce lower potato yields, as highlighted by Kooman *et al.* (1996). The highest tuber yield is obtained in areas with temperate climates (Kooman *et al.*, 1996) where commercial potato

varieties were subjected to repeated breeding selection in order to adapt tuberisation to longer summer days. Haverkort and Harris (1987) attribute the cause of poor adaptation of potato to tropical climates, to unfavourable allocation of assimilates within the plant. In tropical highlands, where potato is also grown, cool temperature and short day conditions induce tuber initiation extremely early when shoot growth is still too small to support good tuber yields (Haverkort and Harris, 1987). After tuber initiation, most assimilates are partitioned to the tubers, resulting in a small canopy that cannot sustain high tuber yields.

Van Dam *et al.* (1996) found that low mean temperatures (15 – 19°C) under short photoperiods (<12 hours) are most suitable for early tuber growth. A slight increase in temperatures reduces dry matter partitioning rates, whereas a further increase also has a large negative impact on the onset of growth and absolute growth rates. Under optimal growth conditions, Kooman *et al.* (1996) found that temperature and photoperiod exert the greatest influence on the duration of the growth cycle, and thus on final yields, through their effect on the period between emergence and tuber initiation.

Kooman *et al.* (1996) conducted trials in different climates in order to determine the effect of climate on different potato genotypes. The results from these trials showed that the periods between emergence and tuber initiation, and between tuber initiation and the end of leaf growth, in most of the cultivars tested, were affected by temperature and photoperiod, but not by radiation. The only potato growth phase insensitive to photoperiod was found to be the maturity phase.

## **2.5. Potato growth and development as influenced by photoperiod**

### **2.5.1. Biomass accumulation and partitioning during vegetative and tuber growth stages**

Tuber initiation elicits several fundamental changes in the growth of the potato plant, especially biomass partitioning to competing organs or sinks (Ritchie *et al.*, 1995). According to these authors partitioning during tuber bulking is a dynamic process, potentially influenced by many factors, such as low temperature, short photoperiod, and soil water or nitrogen (N) availability. Ewing and Sandlan (1995) showed that these factors influence the onset of tuber initiation and therefore, influence both initiation and partitioning of biomass after initiation. Variations in any of these factors can lead to substantial changes in the percentage of total

plant biomass allocated to tubers (Ewing and Sandlan, 1995). The fraction of total assimilate that is partitioned to tubers tends to decrease as photoperiod is long, temperature is raised, irradiance is decreased, nitrogen fertilisation is increased, physiological age of the mother tuber is reduced, or later maturing genotypes are selected (Ewing and Sandlan, 1995).

### **2.5.2. Tuber initiation**

The effects of temperature and photoperiod are crucial to the onset of early tuber growth and subsequent dry matter partitioning (Van Dam *et al.*, 1996). Kooman and Haverkort (1995) show that tuber initiation and partitioning of dry matter to the tubers are affected by photoperiod and temperature in a cultivar dependent way. This means that maximum tuber production requires an optimal temperature-photoperiod combination. In studies where potatoes were grown under changing day lengths, Kooman *et al.* (1996) reported that short days hastened tuber initiation and longer days postponed it. Van Dam *et al.* (1996), in their experiment on the effect of temperature and photoperiod on early growth and final number of tubers in potato, found that the longer photoperiod delayed onset of tuber bulking and growth. However, absolute tuber growth rate was not affected by photoperiod.

### **2.5.3. Canopy development**

Kooman *et al.* (1996) and Van Delden (2001) found that when management practices (water and nutrients) do not limit crop growth and if growth is not reduced by pests and diseases or by competition with weeds, the leaf area expansion of a canopy mainly depends on temperature, photoperiod, leaf assimilate availability and genotype. However, in potato, Firman *et al.* (1991) reported that individual leaf expansion rates, as well as the appearance rate of new leaves, depend largely on thermal time. Kooman *et al.* (1996) conducted experiments in different climatic conditions in order to analyse the variation in tuber dry matter production among sites and cultivars. They found that early tuber initiation results in less foliage biomass production. In climates with short days, the duration of the period between full emergence and tuber initiation was reduced. As a result, the plant canopy did not attain maximum capacity, since most assimilates were partitioned to the reproductive organs (tubers). Tuber formation is thus induced extremely early when shoot growth is still too small to support good tuber yields. In climates with long days, tuber initiation was delayed and leaf growth was prolonged as a result.

#### **2.5.4. Dry matter production**

As mentioned in section 2.3, growth and development of plants is divided into three phases, namely: the exponential, linear and senescence phases. In potato, during the time of exponential increase of dry matter, the rate of net assimilation increases rapidly to a level of 7-8 g dry matter per m<sup>2</sup> leaf area per day (Kolbe and Stephan-Beckmann, 1997). The rate of net assimilation, as explained by Kolbe and Stephan-Beckmann (1997), strongly depends on cultivar, photoperiod and other environmental conditions. Normally, dry matter concentration of very young leaves is relatively high at the early stage of plant growth, where after it declines to an intermediate level (about 10% dry matter content) which remains relatively constant (Kolbe and Stephan-Beckmann, 1997). These authors also explained that during leaf senescence the dry matter concentration increases markedly.

##### **2.5.4.1. Stem dry mass**

Kolbe and Stephan-Beckmann (1997) found that the accumulation of stem dry matter, including remobilisation during senescence, is parallel to the time course for total leaf biomass. In total, the leaf dry matter is 25% higher than that of the stems. The results from the experiment of Wheeler and Tibbitts (1997), determining the influence of changes in photoperiod and carbon dioxide on the growth of potato, showed that stem dry matter per plant responded to photoperiod treatments. Higher stem biomass was produced by the plants that were grown in short photoperiod conditions and later changed to long photoperiod than plants that were grown first in conditions of long photoperiod and changed into short photoperiod towards the end of the growing period.

##### **2.5.4.2. Tuber dry mass**

Wheeler and Tibbitts (1997) conducted a controlled environment study in which potato plants were moved between long and short day rooms at different stages of development. Results from this study showed a greater tuber dry matter yield from plants that received short days followed by long days. From these results, they suggested that potato grown in the field should do well if planted early in the season when day lengths are still short. Van Dam *et al.* (1996) tested two cultivars (Spunta and Desiree) in different photoperiod conditions and found that the two cultivars showed the same qualitative reaction to photoperiod. They both

responded to extension of the photoperiod by shifting partitioning of assimilates towards the shoot

## 2.6. Comparison of potato growth models simulating the effects of photoperiod

Kooman and Haverkort (1995) developed a model called LINTUL-POTATO (Light INTerception and UtiLisation) which simulates potential dry matter production in different environments through the relative effect of temperature on rates of emergence, light use efficiency, tuber initiation and tuber growth. Moreover, the effect of photoperiod on development rate until tuber initiation is represented and potential tuber dry matter production is calculated under some regimes of temperature and photoperiod. In LINTUL-POTATO, total crop dry matter production is determined by the length of the growth cycle that is divided into four phases, each starting and ending with a characteristic stage of development.

Phase 0 starts at planting and ends at emergence. Phase 1, when only foliar growth takes place, is from emergence to tuber initiation. Phase 2 is from tuber initiation until the end of leaf growth (when 90% of assimilates produced daily are partitioned to the tubers). Phase 3, is from the end of leaf growth until the end of crop growth. This model explains the effects of temperature and photoperiod on final tuber dry matter production through the quantification and integration of temperature and photoperiod effects on the major growth and development processes described in the phases 0 - 3 (Kooman and Haverkort, 1995).

Out of these four growth cycles, the effect of photoperiod on crop growth and development is only simulated for phase 2 (tuber initiation until the end of the leaf growth). The equation describing tuber initiation in the model is presented below:

$$R_{ti} = ST_T * T_{Tub} - ST_p * P + ST_c \quad t > t_{cm} \quad (2.3)$$

where,

$R_{ti}$  is the development rate until tuber initiation,  $ST_T$  is a temperature ( $^{\circ}C$ ) parameter in calculating the initiation of tuber growth,  $T_{Tub}$  is the effective air temperature for tuber growth,  $ST_p$  is the photoperiod (hour) parameter, estimating the start of tuber growth,  $ST_c$  is a



constant for calculating the start of tuber growth,  $t$  is time in days,  $t_{cm}$  is day of emergence (d) and  $P$  is photoperiod (hour).

Ritchie *et al.* (1995) developed a model called SUBSTOR (Simulate Underground Bulking Storage Organs), where the timing of tuber initiation is a function of cultivar response to both temperature and photoperiod. They established that cultivars differ in the threshold photoperiod above which tuber initiation is inhibited. This idea was incorporated in SUBSTOR, where a relative day length factor for tuber initiation (RDLFTI) was developed and is described in equation 2.4:

$$RDLFTI = \begin{cases} 1 & ; \text{PHPER} \leq 12 \\ (1 - P2) + P2/144 (24 - \text{PHPER})^2 & ; \text{PHPER} > 12 \end{cases} \quad (2.4)$$

Where:

PHPER = photoperiod (h)

If the function RDLFTI returns a negative value (i.e., for long PHPER), RDLFTI is set to zero. For photoperiods greater than 12 h, different cultivars are not equally sensitive to increasing PHPER, with early cultivars being less sensitive than late cultivars (Ritchie *et al.*, 1995). In equation 2.4,  $P2$  is a dimensionless parameter, which is an input genetic coefficient for cultivar sensitivity to photoperiod. RDLFTI is used to calculate tuber induction index (TII) each day after emergence as a function of the relative temperature.

These two models developed by Ritchie *et al.* (1995) and Kooman and Haverkort (1995) only simulate the effect of photoperiod on the onset of tuber initiation. Kooman and Haverkort (1995) reported that photoperiod does not influence the sprout growth rate (Phase 0 which starts at planting and ends at emergence). Therefore, the simulation effect of photoperiod was not done for this phase. For phase 3 (end of leaf growth until the end of crop growth) the effect of photoperiod was minor and Kooman and Haverkort (1995) explained that the difference in the final canopy size at various locations was due to a shift in tuber initiation rather than to the influence of photoperiod. Gayler *et al.* (2002) reported that there is no effect of photoperiod on flowering date in potato. However, date of tuber initiation is affected by photoperiodism. Gayler *et al.* (2002) used the Soil Plant Atmosphere System Simulation (SPASS) model to simulate potato growth. An additional tuberisation rate,  $R_{tub}$ , was introduced in the model to estimate when assimilate transfer to the tubers begins. Contrary to

the two models previously discussed, in SPASS parameterization of the module simulating phenological development is based on time of flowering, an event that can easily be observed in practice for most crop species, including most potato varieties.

Developmental rates during the three developmental phases are calculated as follows:

$$R_{\text{dev}} = \begin{cases} \frac{f_T}{\text{PDD}_1}; & \text{Development rate for germination to emergence} \\ \frac{f_T}{\text{PDD}_2}; & \text{Development rate for emergence to flowering} \\ \frac{f_T}{\text{PDD}_3}; & \text{Development rate for flowering to maturity} \end{cases} \quad (2.5)$$

Where  $f_T$  represents the temperature response of the development rate ( $f_T$  equals 1 at  $T_{\text{opt}}$  and is zero beyond the interval  $[T_{\text{min}}, T_{\text{max}}]$ .  $\text{PDD}_1$  is the minimum number of physiological development days from germination to emergence and can be estimated by multiplying the maximal growth rate of the sprout,  $\text{Spr}_{\text{ext, max}}$  [ $\text{cm day}^{-1}$ ], and the planting depth of the seed potato  $d_{\text{seed}}$  [cm]:

$$\text{PDD}_1 = d_{\text{seed}} \text{Spr}_{\text{ext, max}} \quad (2.6)$$

$\text{PDD}_2$  and  $\text{PDD}_3$  are the minimal numbers of physiological development days from emergence to flowering, and to maturity, respectively. Emergence occurs if  $\sum R_{\text{dev}} = 1$ , flowering starts if  $\sum R_{\text{dev}} = 2$ , and maturity is reached if  $\sum R_{\text{dev}} = 3$ .  $\text{Spr}_{\text{ext, max}}$ ,  $\text{PDD}_2$  and  $\text{PDD}_3$  are species-specific parameters.

Calculation of tuberisation rate begins, if emergence is reached:

$$R_{\text{tub}} = \frac{f_T f_p}{\text{PDD}_{\text{tub}}} \quad (2.7)$$

where,

$$f_p = \begin{cases} 1 & ; \text{if } h_{\text{php}} \leq 12\text{h} \\ 1 - \exp\left(\frac{-4(h_{\text{max}} - h_{\text{php}})}{(h_{\text{max}} - 12)}\right) & \end{cases} \quad (2.8)$$

where:

$f_p$  is photoperiod response function,  $h_{\text{php}}$  is photoperiod in hours and  $h_{\text{max}}$  is maximal photoperiod at which no tuberisation occurs. The numbers of physiological developmental

days needed for tuberisation ( $PDD_{\text{tub}}$ ) are estimated from  $PDD_2$  and a variety-dependent parameter  $f_{\text{tub}}$ :  $PDD_{\text{tub}} = f_{\text{tub}} PDD_2$ .

Tubers begin to grow, if

$$\sum R_{\text{tub}} \geq 1 \quad (2.9)$$

These three models discussed, integrate the effects of photoperiod and temperature on growth and development rate of the potato crop in their simulation models. Temperature and photoperiod are linked in their effects on crop development and growth. According to Kooman and Rabbinge (1996), growth and development are mutually dependent and are difficult to analyse separately in experiments.

## 2.7. Effect of water stress on growth and yield of potato

Potatoes compared to other crops, are shallow rooted and more sensitive to soil water stress than many other deep-rooted crops, for instance cereals (Van Loon, 1981). The sensitivity of potatoes to water stress has been highlighted by several authors such as Steyn (1997); Shock *et al.* (1998); Iqbal *et al.* (1999); Fabeiro *et al.* (2001); Kashyap and Panda (2002) and Yuan *et al.* (2003). Jefferies (1995) and Epstein and Grant (1973) point out that potatoes show signs of water stress when the soil water potential drops below -25 kPa. This is an indication of how sensitive the potato plant is to water stress, which implies that planned deficit irrigation should be followed with extensive caution. Iqbal *et al.* (1999) studied the yield response of potato to planned water stress. Seven irrigation treatments were used comprising water stress and non-stress periods imposed at four growth stages. The results showed that the irrigation imposed at the ripening stage caused the least reduction in yield and tuber formation. The water stress imposed during early development caused the greatest yield reduction, followed by tuber formation stage. Similar results were obtained by Yuan *et al.* (2003). Kashyap and Panda (2002) reported higher yield from a crop that received high irrigation frequency (maximum 10% of allowable soil water depletion) than low frequency irrigation (maximum 75% of allowable soil water depletion). Shock *et al.* (1992) reported that potato can respond to water stress with yield reduction and loss of tuber grade.

## 2.8. Conclusions

The literature relating to the modelling of potato crop growth and development shows that most research has the same opinion that models should integrate the effects of photoperiod. Photoperiod plays a major role in the partitioning of assimilates and evidently, it affects tuber initiation as well as tuber growth (Kooman and Haverkort, 1995; Wheeler and Tibbitts, 1997).

Throughout this review, it has been shown that the effect of photoperiod is closely associated with temperature. Temperature and day length influence production indirectly through their effect on development. The literature substantiates that short day lengths hasten tuber initiation, whereas long days postpone it. This in turn, determines final dry matter production by the potato plant. This considerable role of photoperiod sensitivity for potato development highlights the need for models to incorporate this feature. In this literature review, it has been shown that understanding potato crop growth and development has reached the stage that the potential yield of a crop, i.e. limited by temperature, solar radiation and day length alone, can be estimated with reasonable confidence. However, there is much uncertainty about the partitioning of dry matter to different organs. This is seen as a challenge to many modellers. Different approaches in attempting to model the distribution of assimilates in the potato crop show that there is a divergence of opinion among modellers. Regarding the response of potato to water use, it has been observed from the literature that potato is very sensitive to water stress. In semi arid zones, some authors advise farmers against using deficit irrigation because of the small financial benefits would not offset the high risks of reduced yields.

## CHAPTER 3

### MATERIALS AND METHODS

#### 3.1. Experimental site

The trials were conducted in two successive years on a sandy loam soil (28% clay, 10% silt and 62% sand, classified by FAO-UNESCO 1974 as a Ferralsol) at Hatfield experimental station, University of Pretoria, South Africa. This area is located at an elevation of 1350 m above sea level, latitude of 25° 45' S and longitude of 28° 16' E. For each year, two experiments were carried out, both inside a rain shelter and in an open field. The first experiment started in September 2004 and the second was carried out from February 2005. The seasons were chosen to represent a variation of day length conditions in which potatoes are likely to be grown in South Africa. Early in September day lengths are short (12.5 hours), but increase with time until they reach their maximum value towards the end of the growing season in December (14.5 hours at 106 days after planting). In February, day lengths are long (13.8 hours) but decrease with time and reach their lowest value towards the end of the growing season in May (11.6 hours).

#### 3.2. Experimental design

The field trials were laid out in a randomised block design (RBD) with four different irrigation regimes (treatments), to establish the effect of water supply on crop growth, development and water usage. Water stressed treatments were based on three developmental stages namely, vegetative, tuber initiation and tuber bulking. Each treatment was replicated four times and the local high yielding potato cultivar BP1 was used. The treatments are referred to as NNN, SNN, NSN and NNS. The treatment NNN stands for a non-stressed treatment and this implies that plants were irrigated throughout the growing period. SNN is the treatment that was water stressed during the vegetative growth stage. NSN stands for the treatment that was water stressed from tuber initiation to end of tuber bulking. NNS stands for the treatment that is water stressed from end of tuber bulking to maturity. Irrigations were carried out using a drip irrigation system to ensure good emergence and establishment of the crop and all plots were initially irrigated uniformly using sprinklers. This implies that treatments started after 50% of potato plants had emerged. However, due to a delay in

equipment supply (drippers), water stress treatments started one week later in spring 2004. Standard crop management practices recommended locally for potato was followed to ensure optimal growing conditions.

### **3.3. Data collection**

In order to parameterize the Soil Water Balance (SWB) model and test its suitability to simulate potato development and growth, data related to weather variables, soil water content and crop growth were collected.

#### **3.3.1. Weather data**

Weather data was recorded by an automatic weather station located 300 m from the experimental site. Daily values of solar radiation, maximum and minimum relative humidity, maximum and minimum temperature, wind speed and rainfall were collected for the duration of the experiment.

#### **3.3.2. Soil water content**

To assess the change in soil water content in the root zone, a neutron probe (Campbell Pacific Nuclear Inc, USA, model 503 DR CPN Hydroprobe) was used, after it was calibrated for the experimental site. The calibration used volumetric water content measured for 0.2 m soil layers down to 1.2 m and count ratio of the neutron probe. Irrigation was carried out according to water use of the crop, calculated from neutron probe measurements. Two readings per week were taken from the middle of each plot, for 0.2 m soil layers down to 1.2 m depth. Total crop evapotranspiration (ET) was calculated by the soil water balance method as follows:

$$ET = (P + I) \pm \Delta S - Dr - R \quad (3.1)$$

Where,

ET is crop water use in mm, P is precipitation in mm, I is irrigation in mm, Dr is drainage in mm and is assumed to be negligible, R is runoff in mm and is assumed to be negligible, and  $\Delta S$  is change in soil water storage in mm.

### 3.3.3. Growth analysis

Growth analysis was carried out on a fortnightly basis by harvesting plant material from 1 m<sup>2</sup> in the fourth replication of each treatment. Due to insufficient plots, samples were taken only in one replicate. Within each plot, plants were harvested and divided into leaves, stems and tubers. The fresh and dry mass of each organ were determined. Dry matter of plant organs was determined by drying samples in an oven at 65°C for four days. Leaf area was measured with an LI 3100 belt-driven leaf area meter (LiCor, Lincoln, Nebraska, USA). Fractional interception of Photosynthetically Active Radiation (PAR) was measured with a Sunfleck Ceptometer (Decagon Devices, Pullman, Washington, USA). At harvest, a representative tuber sample was taken from each of the remaining three replicates for tuber quality assessment. At the same time, tubers were graded into different sizes and weighed (Theron, 2003). Tubers weighing less than 50 g were considered unmarketable. The tuber quality parameters evaluated relates to tuber specific gravity and chip colour. Specific gravity was determined by weighing a 2 kg sample (100 g – 120 g) tubers in air and under water.

## CHAPTER 4

### RESPONSE OF POTATO GROWTH, DEVELOPMENT AND YIELD TO IRRIGATION WATER REGIMES

#### 4.1. Introduction

The potato crop is very sensitive to soil water stress as reviewed by Van Loon (1981) and recently reported by Steyn (1997); Shock *et al.* (1998); Iqbal *et al.* (1999); Fabeiro *et al.* (2001); Kashyap and Panda (2002) and Yuan *et al.* (2003). Iqbal *et al.* (1999) report that the most sensitive period of growth to water stress is early development as compared to tuber bulking. Yuan *et al.* (2003) conducted a study to determine the effect of different irrigation regimes on the growth and yield of drip-irrigated potato. The result of this study showed that the highest yield was obtained in the treatment that was irrigated most although tuber quality decreased with the amount of water applied. This means that irrigation increased tuber quantity, but decreased tuber quality. Kashyap and Panda (2002), also conducted a field experiment on potatoes. Four treatments were applied based on the maximum allowable depletion of available soil water. The results show that the highest yield was obtained from the treatment that received a high frequency irrigation, rather than lower frequency irrigation. Shoch *et al.* (2002) reported that potato can respond to water stress with yield reductions and loss of tuber grade. This study suggested that deficit irrigation of potato in the semi arid environment of eastern Oregon, would not be a viable management option because the small financial benefit would not offset the high risks of reduced yields from the reduced water application.

Most of the above studies report results of potato growth and development in regions where it is grown once a year, mostly during summer. In subtropical regions where potatoes can be grown in two contrasting seasons, namely, autumn and spring, little is known about water use efficiency in both seasons. Furthermore, if crop modelling and irrigation scheduling approaches are to be used for irrigation management, an understanding of crop growth and development behaviour in sub-tropical regions is needed.



## 4.1. Materials and methods

Materials and methods of this chapter are fully presented in Chapter Three.

## 4.2. Results and discussion

### 4.2.1. Effect of irrigation regimes on above-ground biomass

Irrigation treatments were based on water stress imposed in the vegetative stage (SNN), tuber initiation stage (NSN) and maturity stage (NNS). The fourth treatment was a well watered control (NNN). The trend in above ground biomass (excluding roots and tubers) change of treatments NNN and NNS was found to be almost similar. This trend was comparable for both spring and autumn experiments (Figure 4.1a and 4.1b). The treatment that was stressed at an early stage (SNN) initially had lowest mass, but for spring planting seemed to recover and attained a maximum of 5586 kg ha<sup>-1</sup>. However, in the autumn planting there was no apparent recovery and the above-ground biomass attained a maximum value of only 2785 kg ha<sup>-1</sup>. Van Loon (1981), in his review on the effect of water stress on potato growth, development, and yield, pointed out that water stress which occurs before tuber-bulking, followed by a resumption of irrigation may favour the occurrence of secondary growth. As suggested by Van Loon (1981), top growth could be stimulated vigorously if plants are re-watered after a period of drought and high temperatures. Consequently, leaf duration is prolonged for such a crop, compared to one without secondary growth (Van Loon, 1981). Although in the spring planting SNN attained a high above-ground biomass, it did not attain a high tuber yield (Table 4.2). Therefore, its low yield proves that the high above-ground biomass in SNN was due to secondary growth. The reduction in above-ground biomass from NSN was severe due to the effect of water stress. In this treatment, water stress was maintained for 21 days starting from tuber initiation. Plants did not recover after the irrigation was resumed (Figures 4.1a and 4.1b) because of wilting. Van Loon (1981) pointed out that in field conditions the rate of recovery of photosynthesis depends upon the duration of the period of wilting. Yaun *et al.* (2003) found a low value of the above-ground biomass in treatments that were the most water stressed. Kashyap and Panda (2003) conducted a trial where treatments were based on maximum allowable depletion (MAD) of plant available water (PAW) and noticed a reduction in above-ground biomass in the treatment which was the most stressed (75% of MAD).

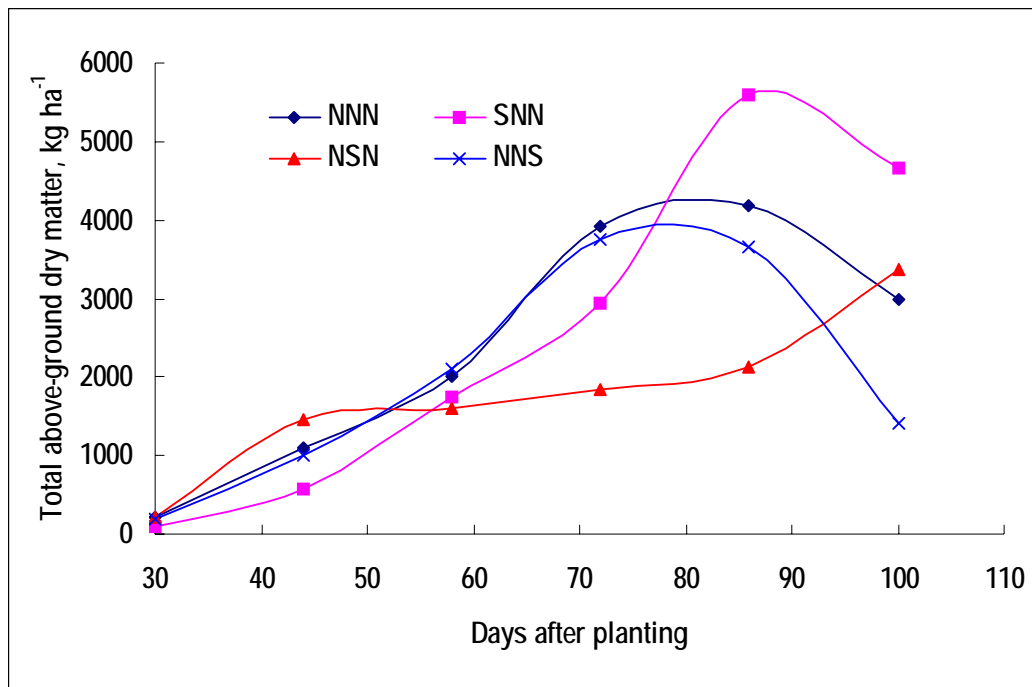


Figure 4.1a: Measured total above-ground dry matter under different irrigation regimes during Spring 2004

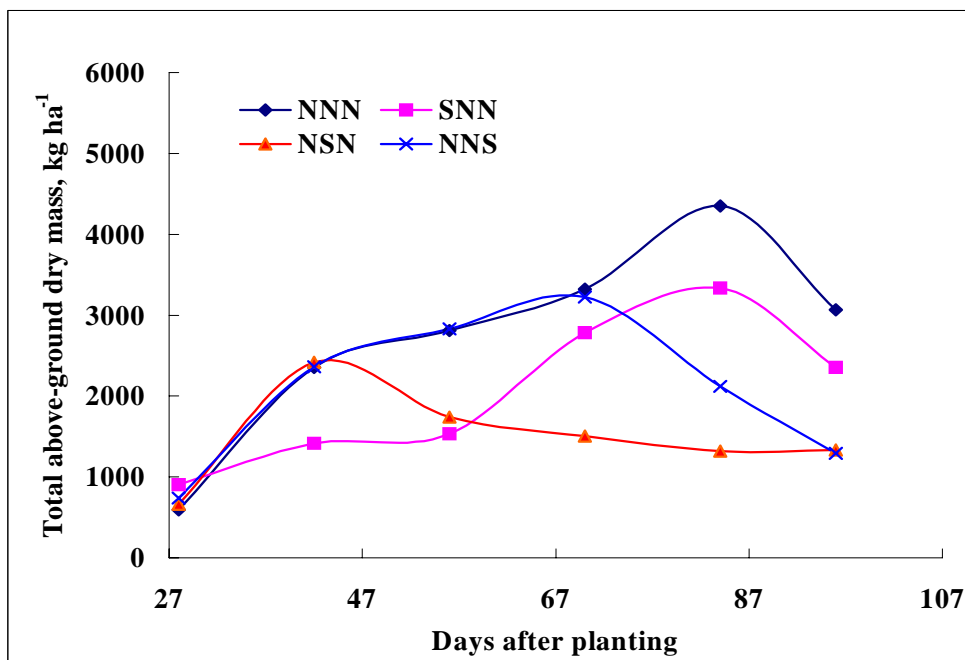


Figure 4.1b: Measured total above-ground dry matter at different regimes of irrigation during Autumn 2005

In potato experiment, conducted in a Mediterranean environment by Ierna and Mauromicale (2006) even a moderate water deficit resulted in a low above-ground biomass for the treatment that received the lowest total amount of water.

#### 4.2.2. Effect of irrigation regimes on leaf area index

Figures 4.2a and 4.2b present the changes in leaf area index (LAI) throughout the season for the treatments. Water stress imposed at any stage reduced leaf area expansion and leaf area duration. The highest LAI observed in spring 2004 was 3.8 for NNS and 3.6 for NNN. In autumn 2005, maximum LAI was relatively higher for both NNN and NNS treatments, with values of 5.5 and 5 respectively. During spring 2004, a strong wind between 56 and 72 DAP resulted in damage to plant canopies especially in NNN and NNS. This negatively affected further measurement of LAI due to an increasing amount of yellow leaves as a result of shading. LAI measurement considers only green leaves.

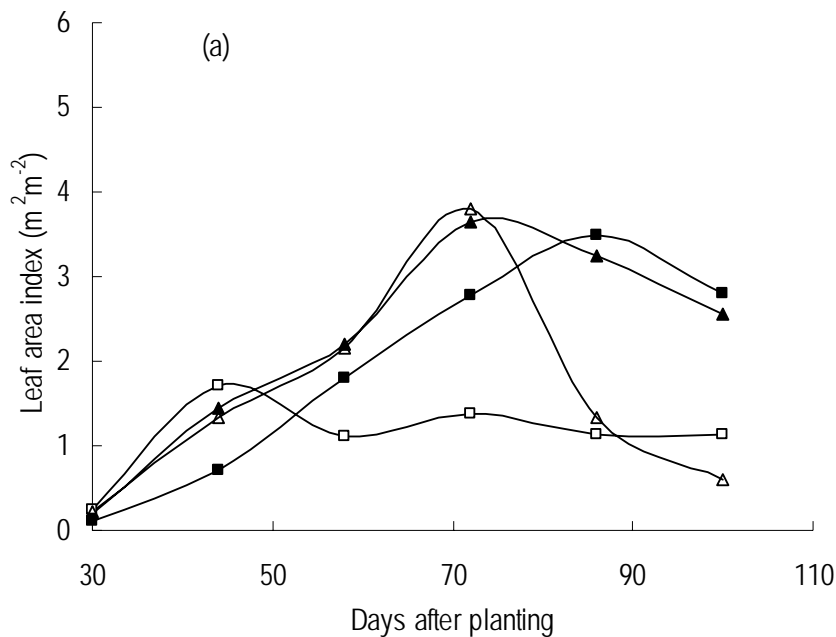


Figure 4.2a: The Seasonal pattern of leaf area index (LAI) during spring 2004 for potatoes exposed to different irrigations

In the autumn planting, canopy growth was most restricted in SNN and NSN, with maximum LAI of 2.9 and 3.8 respectively. In contrast, maximum LAI attained in SNN during spring

2004 was 3.5 (Figure 4.2a) a value close to that of the unstressed treatment (NNN). Soil water deficits for the autumn planting are presented in Figure 4.3 to illustrate the severity of water stress imposed during the vegetative, tuber initiation and maturity stages. In SNN, irrigation was resumed when the soil water deficit reached a value of 57 mm (Figure 4.3), which represents a depletion of about 84% of the plant available soil water (PAW). Similarly, in NSN, irrigation was resumed when the soil water deficit reached 51 mm, which represents a depletion of about 75% of the plant available soil water (PAW).

Mackerron and Jefferies (1986) and Epstein and Grant (1973) suggested that potato plants become stressed when the soil water potential is less than -25 kPa. Their experiments used a compost medium and silt loam soil, which suggests that some caution is necessary in applying these results to other soils. In an experiment carried on compost -25 kPa equates to a volumetric water content of about 33% and represents a depletion of about 82% of available soil water (Gregory and Simmonds, 1992).

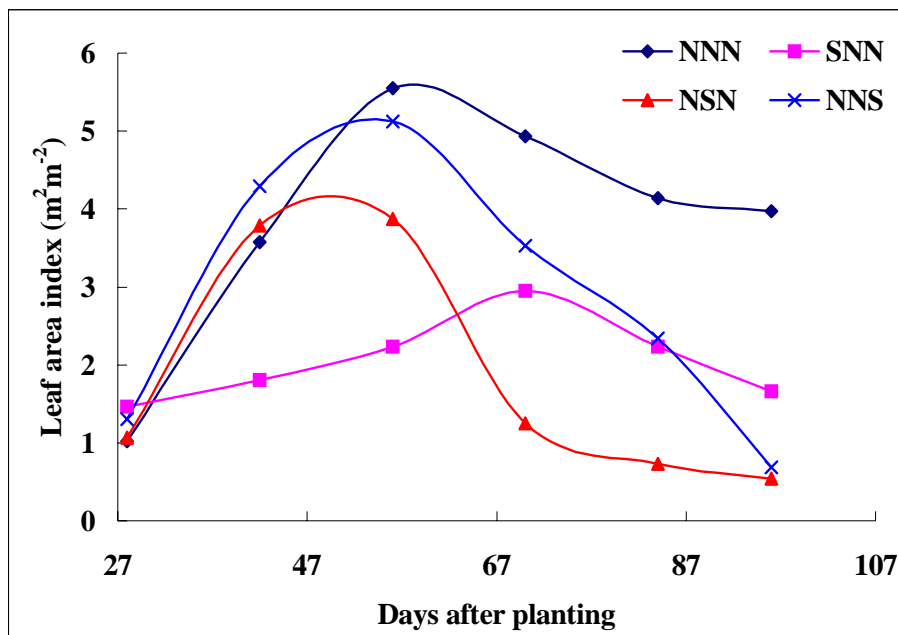


Figure 4.2b: Seasonal pattern of leaf area index (LAI) during Autumn 2005

Jefferies (1995) found that leaf area expansion was closely related to soil water deficit and that it declined rapidly when the soil water deficit was greater than 16 mm. Minimum growth occurred when the soil water deficit was 77 mm. Similarly, in this study the rate of leaf area was related to the soil water deficit in SNN and NSN. In SNN, soil water deficit attained a

value of 57 mm before irrigation was resumed (Figure 4.3) and NSN a value of 51 mm. In NSN, leaf area expansion declined very quickly and reached an irreversible point to such an extent that the resumption of irrigation did not help the plant to recover from water stress (Figure 4.2b). Shimshi and Susnoschi (1985) found that varieties that could keep their foliage longest under water stress conditions yielded lowest and concluded that persistence of foliage under water stress is not an indication of the yield potential. As mentioned earlier on in section 4.2.1, SNN attained the lowest yield despite its well-developed canopy (Figure 4.2a).

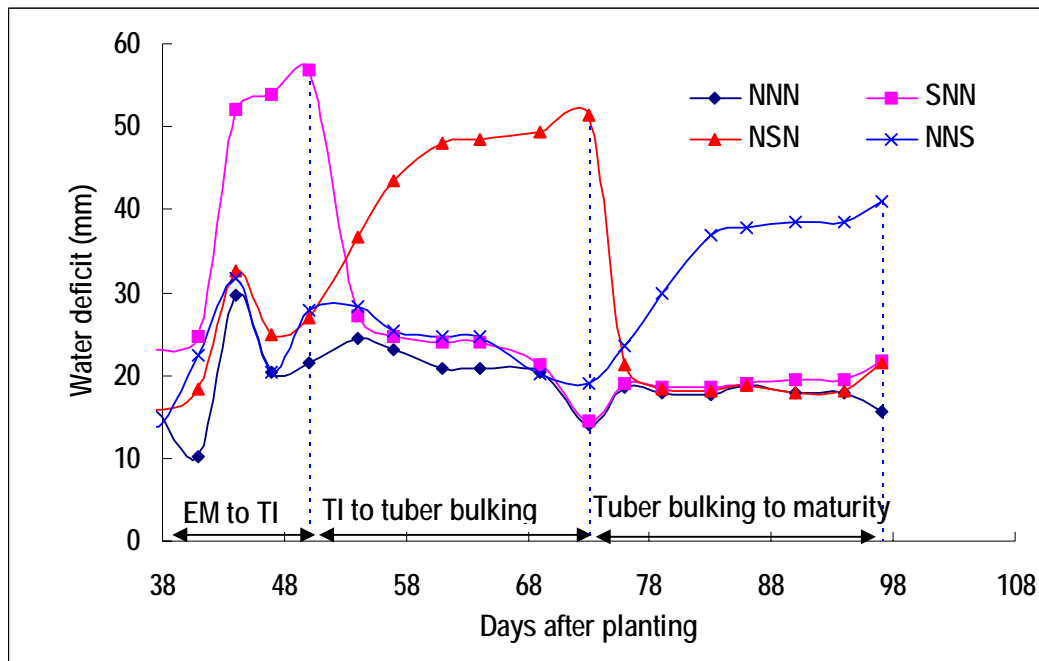


Figure 4.3: Cumulative soil water deficit at different stages during Autumn 2005. EM stands for emergence and TI stands for tuber initiation

Jordan (1983) has suggested that there is confusion regarding the role of water deficit in accelerating plant senescence. He argues that there is little evidence that supports a direct role of water deficit in senescence if the water deficit is not extreme. This appears to be realistic when one considers basic differences in plant response to water deficit before and after athesis. Jordan (1983) compared two treatments, dry and wet, in a sorghum experiment. He found that the fractional LAI lost to senescence was approximately the same for both treatments until 62 DAP, even though water availability greatly reduced LAI in the dry treatment. Jordan (1983) noticed that when irrigation of the wet treatment was stopped 55 DAP soil water was rapidly depleted as a result of the high LAI. This rapid fall in available

soil water caused greater LAI loss in the previously irrigated plot so that by 86 DAP the green LAIs of both treatments were converging. These results suggest that the leaf area duration of individual leaves is not seriously altered by water deficits that develop gradually, but rapid development of water deficits may accelerate senescence of lower leaves (Jordan, 1983). Similar results were obtained in the present study experiment when NSN was stressed 52 DAP and maintained for 18 days. As a result, LAI declined and attained a lower value than SNN although SNN was also stressed for 18 days. This suggests that water deficit imposed at tuber initiation appears to cause a more dramatic response in terms of senescence in both spring and autumn seasons although LAI expansion was most hindered in the autumn season. Iqbal *et al.* (1999) report that the most sensitive period of potato growth to water stressed, hence the most responsive to irrigation, is early development, compared to tuber formation and flowering. Jefferies and Mackerron (1993) found that yield in the water stress treatment was correlated with that in the irrigated treatment although the rate of canopy expansion and the maximum LAI was reduced in the water stress treatment. The results of the present study show that water stress is the most detrimental at the tuber initiation stage (Figure 4.2a and 4.2b). Water stress imposed at tuber initiation may limit nutrient uptake and photosynthate production to satisfy the presence of a strong reproductive sink that requires more photosynthate and nitrogen (Jordan, 1983). Furthermore, this study revealed that LAI expansion in autumn is the most sensitive to water stress compared to the spring season. In autumn, plant growth and development coincide with high temperatures as well as high evaporative demand, which, in addition to water stress, are probably responsible for the lower expansion of LAI.

In all treatments, maximum LAI in spring was attained at 72 days after planting, whereas in autumn it was attained at 56 days after planting (Figures 4.2a and 4.2b). Tuber initiation that was hastened by the change from long day-high temperature conditions to short day-low temperature conditions may have been the cause of the short time to reach the maximum LAI in autumn. The initiation of tubers corresponds to a time when most assimilates shift from leaves and stems to reproductive parts (tubers). This is regarded as the cause of foliage growth rate reduction and root growth cessation (Ewing, 1992).

### 4.3.3. Effect of irrigation regimes on leaf area duration

Water use efficiency in potato production requires a better understanding of the effects of water stress on processes determining yield. It has been established that the size and duration of leaf area were found to be a major determinant of yield under water limiting conditions (Demagante *et al.* 1996). Leaf area duration (LAD) indicates the length of time foliage remains photosynthetically active on plants and reflects the extent or seasonal integral of light interception and has been shown to correlate highly with yield (Gardner, Pearce and Mitchell, 1985 and Annandale, Hammes and Nel. 1984).

LAD was determined using the equation developed by Gardner *et al.* (1985):

$$LAD = \sum_n [(LAI_{n-1} + LAI_n)/2][t_n - t_{n-1}] \quad (4.1)$$

Where  $LAI_n$  is the LAI on the sampling date ( $t_n$ ) and  $t_n$  is the day of the year that sampling took place.

The LAD results are presented in Table 4.1 and show that LAD was higher in unstressed treatments in both spring and autumn experiments, although it was much greater in autumn 2005. In spring, NSN took less time to senescence than in autumn (Table 4.3). With regard to SNN, LAD was reduced in both years, especially in spring. Compared to their respective controls, the reductions in LAD for stress treatments were 36, 82, and 36  $m^2 m^{-2} d$  for SNN, NSN and NNS, in spring (Table 4.3). Thus, LAD reductions were greater in spring than in autumn, and were most affected by stress in tuber initiation stage in both plantings.

Surprisingly, LAD was lower in all treatments in spring than in autumn. One would expect an inverse reaction for NNN, even though the spring planting coincides with high atmospheric demand that prevails in summer. However, the growing period would be much longer if water is not a limiting factor, which in effect was the case for the unstressed treatment. The low maximum leaf area attained in all treatments in summer affected the LAD as this is calculated by integrating the LAI over the growing period (Eq. 4.1).

In the attempt to establish the correlation between LAD and tuber dry matter yield, a linear relationship was found in all treatments and in both years (Figure 4.4 and Table 4.1). For both

years, the coefficients of determination between LAD and tuber dry matter were high (Table 4.1). This indicates that irrigation treatment effects on leaf duration influenced final tuber yield of potato. Boyd, Gordon and Martin (2002) found similar results under different management practices where LAD explained 74 to 79% of the difference in total tuber yield. Wolfe *et al.* (1983) found a very high correlation between LAD and dry matter production from 94 to 110 DAP. However, Demagante *et al.* (1996) found a low coefficient of determination between relative yield and canopy cover duration for the entire growth period and they attributed that to the confounding effects of variation among the clonal lines in the time to tuber formation. Deblonde and Ledent, (2001) suggest that a moderate drought applied at early stage in the season reduces LAD. The experimental results of this study corroborate the findings by Jefferies (1989), who found that the duration of leaf differed between years indicating that leaf duration was affected by environmental factors other than soil water status.

Table 4.1: Leaf area duration (LAD) and correlation coefficients between LAD versus tuber dry matter yield ( $\text{kg ha}^{-1}$ ) as affected by irrigation water treatments in both spring and autumn planting experiments. Coefficient of determination was calculated by plotting tuber dry matter ( $\text{kg ha}^{-1}$ ) against LAD ( $\text{day m}^2 \text{ m}^{-2}$ ) for each treatment

| Year        | Treatment | LAD ( $\text{day m}^2 \text{ m}^{-2}$ ) | Correlation coefficient between LAD and tuber dry matter yield ( $\text{kg ha}^{-1}$ ) |
|-------------|-----------|---|--|
| Spring 2004 | NNN       | 166                                     | 0.95   |
|             | SNN       | 130                                     | 0.85   |
|             | NSN       | 84                                      | 0.64   |
|             | NNS       | 130                                     | 0.89   |
| Autumn 2005 | NNN       | 281                                     | 0.99   |
|             | SNN       | 147                                     | 0.99   |
|             | NSN       | 145                                     | 0.91   |
|             | NNS       | 225                                     | 0.94   |

Opposed to the control (NNN), all stressed treatments revealed that a reduction in both the rate and the duration of growth of leaves is linked to water stress imposed on potato. However, the severity of the water stress was much greater for NSN in spring 2004, and SNN



and NSN in autumn 2005. Regarding the duration of leaf area, this study has established a linear relationship between leaf area duration (LAD) and yield when the data of all treatments are combined (Figure 4.4). In potato, soil water stress affects the expansion of the crop canopy and the interception of radiation, the coefficient of conversion of radiation into dry matter, partitioning of assimilate into dry matter, and tuber dry matter concentration (Jefferies and Mackerron, 1989). However, SNN attained a deficit of 57 mm and the leaf expansion was maintained relatively high, and increased even more when irrigation was resumed.

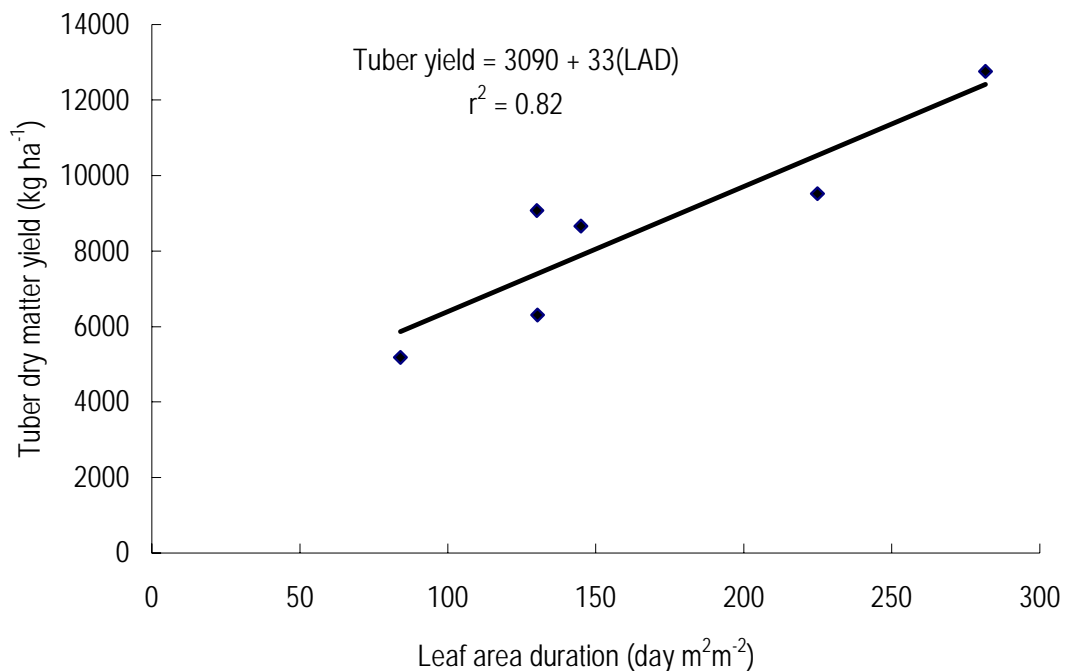


Figure 4.4: The relationship between leaf area duration (LAD) and tuber dry matter yield of all treatments combined (spring 2004 and autumn 2005)

#### 4.3.4. Effect of irrigation regimes on tuber yield

Tuber yields, as affected by different irrigation regimes, are presented in Table 4.2. The treatment fully irrigated throughout the growing season (NNN) gave the highest yields, irrespective of planting season. Table 4.2 shows that irrigation regimes had significant effect on yield in both seasons (spring 2004 and autumn 2005). Amongst the treatments, water stress imposed at tuber initiation until end of tuber bulking stage (NSN) and emergence to tuber initiation stage (SNN) produced the lowest tuber yields. Table 4.2 shows clearly the

sharp decrease in fresh tuber yield in the both years for SNN and NSN. The lowest tuber yield was found in NSN in the both years, but the effect was more pronounced in spring. These results are in agreement with the findings of Costa *et al.* (1997), who contend that water stress imposed during tuberisation severely hindered plant physiological processes and penalized tuber yield. Similarly, in a review of the effect of water stress on potato growth, development, and yield Van Loon (1981) mentioned that water shortage during tuber bulking period decreases yield to a larger extent than drought during other growth stages.

Table 4.2: Influence of irrigation regimes on tuber yield

| Year        | Treatment | Tuber yield (kg ha <sup>-1</sup> ) |
|-------------|-----------|------------------------------------|
| Spring 2004 | SNN       | 22371.3c                           |
|             | NSN       | 17195.7d                           |
|             | NNS       | 44469.3b                           |
|             | NNN       | 47085.3a                           |
| Autumn 2005 | SNN       | 34768c                             |
|             | NSN       | 27716d                             |
|             | NNS       | 41682b                             |
|             | NNN       | 45571a                             |

Values followed by same letter do not differ significantly at P= 0.01 ANOVA summary is presented in Table A1 and A2 of the appendix.

In contrast, a study of Iqbal *et al.* (1999) suggests that water stress imposed at vegetative stage causes the greatest reduction in tuber yield, followed by tuber initiation. Jefferies (1993) noticed that water stress varies in both timing and duration. He further emphasised that both soil moisture status and evaporative demand may play an important role in varying the effect of water stress on plant growth.

#### 4.3.5. Effect of irrigation regimes on tuber size distribution

The potato tuber yield distribution was carried out by grading tubers from field experiments according to the South African regulations for marketable tubers (Theron, 2003) (Table 4.5). Table 4.5 shows that the distribution of tuber sizes varied among different treatments. A high increase marketable ( $\geq 50$  g) tuber yield was obtained in NNN and NNS treatments. In spring planting, marketable tuber yield accounted for about 85% and 83% of the total yield in NNS and NNN, respectively.

Contrary to spring planting, marketable tuber yield was higher in autumn season and accounted for 96 and 95% of the total yield for NNN and NNS, respectively. However, NNS never produced large tubers ( $>250$  g) in both years. The unstressed treatment (NNN) had the largest tuber yield in autumn than in spring. The highest percentage of tuber yield in the smallest tuber sizes was observed in SNN and NSN. In spring planting 62% of tuber yield of SNN were classified as small and baby potatoes, whereas it was 52% in autumn planting. In both years, the treatment most affected by water stress on tuber size distribution was NSN with 69% and 67% of small and babies' potatoes in spring and autumn planting, respectively. In general, spring planting had the lowest tuber size distribution. These results corroborate with those obtained by Steyn (1997). He reports that the decline in yield of large and medium tubers was more pronounced in spring than in autumn. Lynch *et al.* (1995) suggested that differences in marketable yield and tuber size distribution over years within same treatments are likely linked to growing environment and the genetic capacity to capitalize in terms of bulking rate. Potato grown in different seasons (spring and autumn) may produce different tuber size distribution, as suggested by Steyn (1997), due to the differences in vapour pressure deficit that prevail in both seasons, autumn being the most likely to produce larger tubers. Although, few studies are available comparing spring and autumn potato planting data, much has been done to study the effect of deficit irrigation on yield and size of potato.

Fabeiro *et al.* (2001), in an experiment of the effect of deficit irrigation on yield and tuber size, reported that large tubers were obtained in the treatments, which were not stressed at ripening stage. These results corroborate the findings of the present study. In both years, NNS had less large tubers than NNN. Water stress imposed at early stages had a negative effect on the subsequent plant growth, and plants hardly regained the normal growth after irrigation was resumed. Unfortunately, this study did not consider the number of tubers per plant, which would help to substantiate the results of Van Loon (1981), who suggested that

reduction in number of tubers caused by early water stress might increase the proportion of larger tubers. It is clear from the results of this study that potatoes subjected to water stress between vegetative and bulking stages (SNN and NSN) hardly attained a yield with tuber size classified as medium large ( $\geq 170$  -  $\leq 250$  g).

Van Loon's (1981) findings were confirmed by Shock *et al.* (1992). They reported that delaying initial irrigation results in a higher percentage of large sized tubers through its effect in reducing the number of tubers per plants. This is also known to be inversely related to the tuber sizes for healthy plants (Shock *et al.* 1992). Although these studies report that water stress imposed at initial stage of potato has resulted in a higher percentage of large tubers, none of them irrigation water was withheld. All these studies were based on irrigation frequencies where irrigation water was not temporary withheld. This implies that the intensity of water stress was attenuated to some extent. In irrigation, studies where irrigation water was withheld at an early stage resulted in low total tuber yield, accompanied with small tuber sizes (Mackerron and Jefferies, 1987), (Iqbal *et al.*, 1999) and (Hassan *et al.*, 2002). Jefferies (1993) suggested that water stress effect on potato growth and yield varies in both timing and duration.

#### **4.3.6. Effect of irrigation regimes on tuber quality**

Specific gravity was measured by weighing a 2 kg sample of tubers (80 g to 120 g) in air and water. Chip colour was assessed by frying five slices of 1.5 mm thick in vegetable oil for approximately 4 minutes at initial temperature of 190°C. The colour of fried chips was determined according to the method described by Scanlon *et al.* (1994). Chip colour rated between 50 and higher are considered acceptable for processing.

Specific gravity and chip colour of potato tubers, which are important quality criteria for processing potatoes were investigated (Table 4.3). The specific gravity of potato gives an indication of the dry matter content of tubers. The higher the dry matter content, the lower the water content and the higher the specific gravity. Table 4.3 shows that specific gravity varied with season of planting (spring and autumn) and autumn showing higher values and variation between treatments. Specific gravity in the spring planting experiment was not affected by water treatments. On the contrary, the autumn planting experiment did respond to water treatments. Specific gravity was increased in NSN and NNS for autumn planting and the

difference between them was significant at level of 5%. SNN and NNN in autumn planting were not statistically different. These results are in agreement with that of Steyn (1997), who reported that for autumn plantings generally specific gravity (relative density) increased as less water was applied. Similarly, Yuan *et al.* (2003) found that the specific gravity of potatoes tended to decrease as irrigation water increased. Therefore, less irrigation water produced higher specific gravity. In addition, the results of this study are similar to that reported by Shock *et al.* (1992) but not consistent with data reported by Lynch *et al.* (1995) who found that midseason water stress reduced specific gravity. Table 4.3 shows that chip colour results were not affected by irrigation treatments in the autumn planting experiment. However, in the spring planting experiment there was significant differences between treatments, except for NNN and NNS that were not statistically different.

Table 4.3: Tuber size distribution, specific gravity and chip colour as affected by irrigation water treatments in spring and autumn plantings

| Planting year | Treatment | Tuber size grading (%)   |                             |                              |                                |                                      |                 | Specific gravity | Chip colour |
|---------------|-----------|--------------------------|-----------------------------|------------------------------|--------------------------------|--------------------------------------|-----------------|------------------|-------------|
|               |           | Marketable yield (kg/ha) | Babies $\geq 5 - \leq 50$ g | Small $\geq 50 - \leq 100$ g | Medium class                   |                                      | Large $> 250$ g |                  |             |
|               |           |                          |                             |                              | Medium $\geq 100 - \leq 170$ g | Large medium $\geq 170 - \leq 250$ g |                 |                  |             |
| Spring 2004   | SNN       | 22315                    | 23.8                        | 37.9                         | 28.3                           | 10.0                                 | 0.0             | 1.077a           | 48.17c      |
|               | NSN       | 18111                    | 25.7                        | 43.2                         | 31.1                           | 0.0                                  | 0.0             | 1.073a           | 49.63b      |
|               | NNS       | 43698                    | 15.0                        | 31.2                         | 37.7                           | 16.1                                 | 0.0             | 1.074a           | 59.13a      |
|               | NNN       | 45476                    | 16.7                        | 17.5                         | 35.3                           | 15.8                                 | 14.7            | 1.077a           | 59.80a      |
| Autumn 2005   | SNN       | 34166                    | 13.6                        | 38.2                         | 36.2                           | 12.0                                 | 0.0             | 1.077c           | 48.9a       |
|               | NSN       | 27500                    | 18.0                        | 49.2                         | 31.9                           | 0.9                                  | 0.0             | 1.083b           | 49.1a       |
|               | NNS       | 45461                    | 5.3                         | 32.1                         | 38.8                           | 23.8                                 | 0.0             | 1.088a           | 47.9a       |
|               | NNN       | 46370                    | 3.7                         | 16.3                         | 31.0                           | 29.0                                 | 20.0            | 1.078c           | 50.4a       |

Values followed by same letter do not differ significantly at  $p=0.01$

This suggests that treatments in spring experiment responded to irrigation water, as irrigation water increased in NNN and NNS, chip colour improved. However, this trend was not observed for autumn planting where chip colour did not statistically differ between treatments and consistently remained below 50 except in NNN (Table 4.3). Lynch *et al.* (1995) pointed out that fry colour highly correlates with reducing sugars. High temperatures during tuber development enhance the reduction of sugar content (Owings *et al.* 1978). Thus chip colour could be negatively affected in spring planting due to high temperatures that prevail in that season. Inversely to this theory, NNN and NNS in spring planting gave a higher value of chip colour. Steyn (1997) pointed out that the detrimental effect of high temperatures on chip colour can be attenuated by the beneficial effects of regular irrigation. Miller's (1975) cited by Steyn (1997) findings, which state that low temperatures late in the growing period induce higher concentrations of reducing sugars in tubers and the high correlation between reducing sugar content and chip colour found by Lynch *et al.* (1995) substantiate the low values of chip colour obtained in autumn planting. The low values of chip colour obtained in water stressed treatments in both years are in agreement with that of Shock *et al.* (1992) and Lynch *et al.* (1995). They reported that water stress before and during tuber initiation reduced fry colours, but Lynch *et al.* (1995) pointed out that the effect of early and mid-season water stress on fry colour is altered by others factors in the environment in which potato is grown.

#### **4.3.7. Water consumption, irrigation management and soil water profile**

The change in volumetric soil water content over the growing season for the autumn experiment is shown in Figures 4.5a, 4.5b and 4.5c. These Figures provide a good illustration of how the soil water content varied with treatments over the growing season. Irrigation water was applied to refill the soil profile to field capacity every four days and soil water content measurements were taken prior to irrigation. In NNN, plant water availability rarely fell below 50% of the total plant available water content in the top layers (200 and 400 mm). Similarly, at 600 mm soil depth, except small variations, which were observed, soil water content was always above 50% of the total plant available water content. In the water stressed treatments, soil water content decreased when irrigation was withheld. In both years, soil water content was almost depleted to wilting point in the top layers in all water stressed treatments, but remarkable soil water content reduction was recorded for NSN in the top layer (200 mm). After resumption of irrigation in both SNN and NSN treatments, soil water content rose above 50% of the total plant available water content, especially in the top layers

(200 and 400 mm). These results give valuable insight on how plant availability was affected by irrigation treatments. During autumn experiment, in SNN and NSN, there was a noticeable decrease in the water content of the soil. However, for these two treatments, soil water content showed a progressive increase during the final part of the growing season. This trend was also noticeable in NNN, which is an indication of a lower water requirement of the crop during tuber maturation or plant senescence. Figure 4.6c shows that in the bottom layer mostly at 600 mm soil water content was always above 50% of the total plant available water content. Even with water stress imposed at vegetative and tuber initiation stages (SNN and NSN), the soil water content remained above 50% of the total plant available water content in the bottom layer.

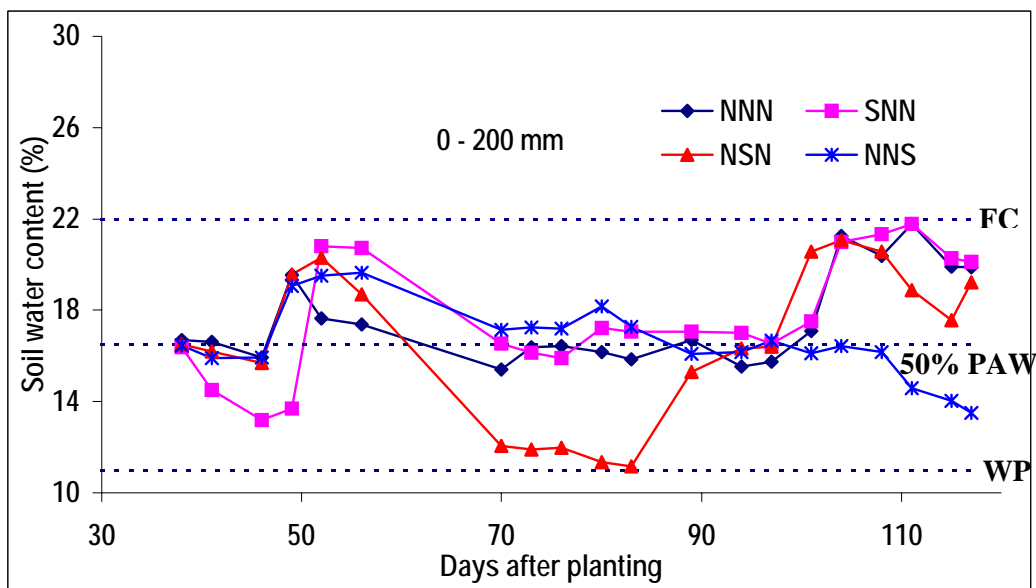


Figure 4.5a: Volumetric soil water content at 200 mm depth for the different irrigation treatments, autumn 2005. The horizontal lines indicate:  
FC = Field Capacity; WP = Wilting Point; PAW = 50% Plant Available Water.



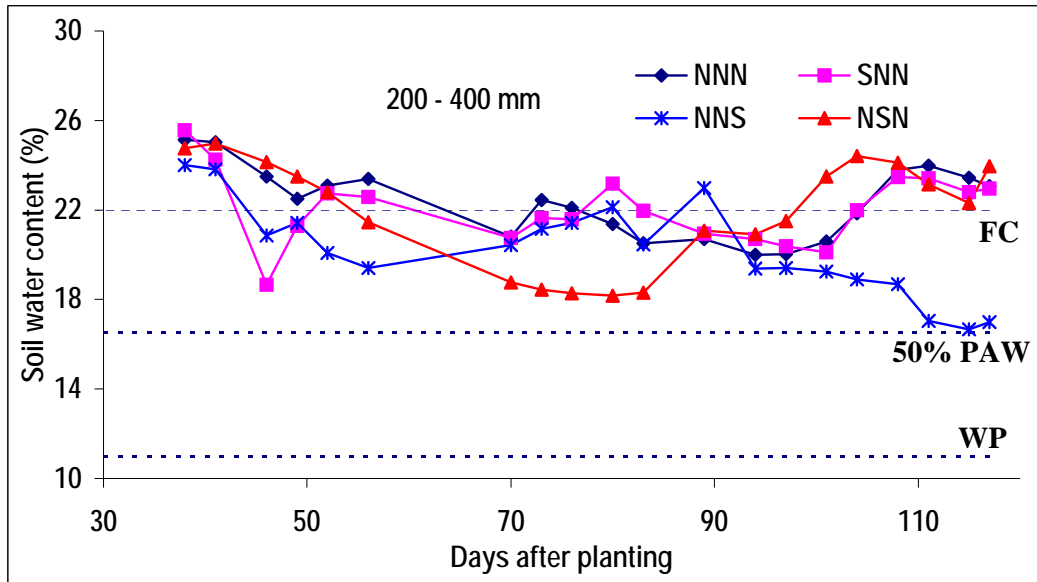


Figure 4.5b: Volumetric soil water content at 400 mm depth for the different irrigation treatments, autumn 2005. The horizontal lines indicate:  
 FC = Field Capacity; WP = Wilting Point; PAW = 50% Plant Available Water

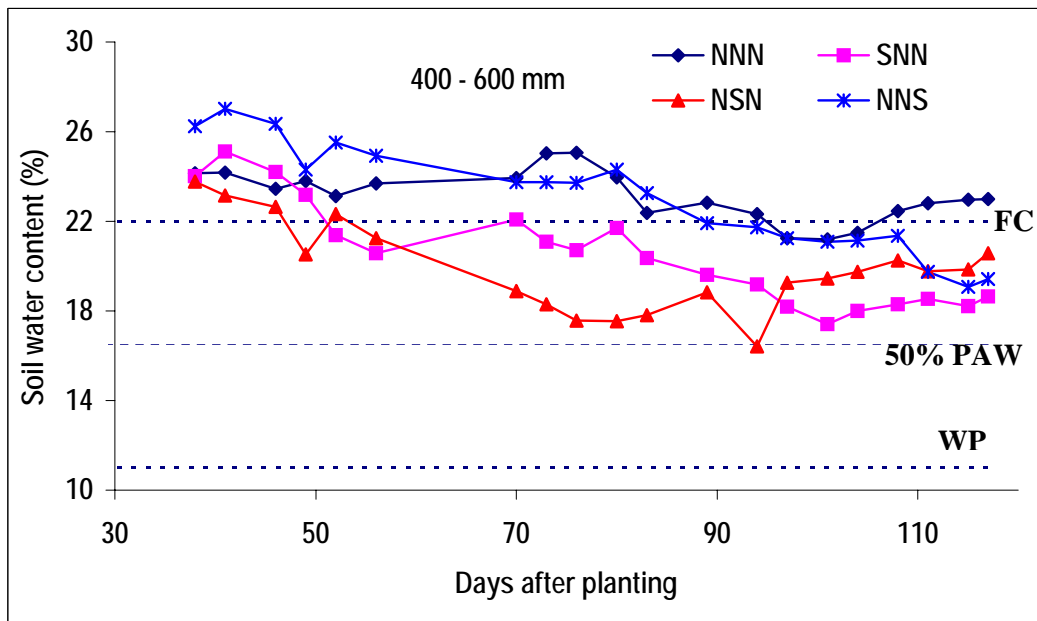


Figure 4.5c: Volumetric soil water content at 600 mm depth for the different irrigation treatments, autumn 2005. The horizontal lines indicate:  
 FC = Field Capacity; WP = Wilting Point; PAW = 50% Plant Available Water

#### 4.3.8. Water use efficiency

Sinclair, Tanner and Bennett (1984) recommended different options to estimate water use efficiency (WUE) and defined WUE as a ratio of total biomass accumulation expressed in carbon dioxide assimilation, total crop biomass or economic yield to water consumed expressed as transpiration, evapotranspiration (ET) or water use. In order to estimate WUE, two approaches were attempted.

- (i) Dividing tuber fresh yield ( $\text{kg ha}^{-1}$ ) by water use expressed as evapotranspiration (mm).

$$\text{WUE} = \frac{\text{Tuber yield}}{\text{ET}} \quad (4.2)$$

Regression analysis between plant water use expressed as transpiration (mm) and yield ( $\text{kg ha}^{-1}$ ) to provide information on the transpirational WUE and the soil evaporation component of ET as suggested by Sinclair *et al.* (1984).

Many potato experiments have been conducted to establish the relationship between water use and potato yield (Tanner, 1981; Trebejo and Midmore, 1990; Costa *et al.* 1997 and Kashyap and Panda, 2003). From these studies, the linear regression coefficient was found to improve when water use (ET) was normalised for the deficit of atmospheric water vapour concentration. However, results obtained using this approach are controversial, since the method of calculating vapour pressure deficit (VPD) leads to differences, and therefore the predictions of biomass become unreliable (Steduto and Albrizio, 2005).

Tanner (1981) advises the use of a daytime saturation deficit (when the main daily transpiration occurs) for VPD calculation. Tanner and Sinclair (1983) suggest that VPD should be estimated using temperatures taken at canopy level. In the absence of canopy temperatures, Steduto and Albrizio (2005) propose replacing the VP gradient at canopy level that represents the driving force of the transpiration, by the VPD of the air which is assumed to be similar to that of canopy. Since the temperatures at canopy level in water stressed treatments are expected to be different to that of the air, in the regression analyses for this study, only the unstressed treatment (NNN) was considered.

The crop transpiration ( $T$ ) was taken from SWB (Annandale *et al.*, 1999) simulation model as this is accurately estimated. SWB uses a daily saturation deficit at minimum and maximum temperatures to estimate VPD. Thereafter the daily  $T/VPD$  was accumulated for each dry matter-sampling interval as recommended by Tanner (1981).

Total water use data for potato during the spring and autumn experiments are shown in Table 4.4. In well irrigated plots (NNN), total water use during the crop season varied from 360 mm in the autumn to 579 mm in spring. Irrigation water in SNN plots was reduced by 19% and 23% in spring and autumn seasons respectively.

The total water received in spring and autumn for the treatments where irrigation water was withheld at tuber initiation (NSN) ranged from 432 to 268 mm, respectively. NNS is the treatment that received the lowest amount of water applied in both spring and autumn plantings. In spring, NNS received 30% less water than NNN and during autumn NNS received 28% less than NNN. In the water stressed treatments, water use was less in both spring and autumn seasons. The WUE varied with irrigation treatments (Table 4.4) and planting time. The autumn season generally had higher WUE values than spring. In subtropical climates, potato is normally grown in a double cropping system (Levy, Livesku and Zaag, 1986). Relatively few studies are available in the literature to compare the performance of potato in both seasons. The most recent studies are those of Steyn (1997), Trabejo and Midmore (1990), Fahem and Haverkort (1988), and Levy *et al.* (1986). Results from these studies are in agreement with the findings of this study. In the unstressed treatment (NNN) for autumn planting, water use efficiency accounted for about 127 kg ha<sup>-1</sup>mm<sup>-1</sup> (fresh mass). Similar values were also reported by Steyn (1997) and Trabejo and Midmore (1990). Contrary to autumn planting, WUE in NNN for the spring planting yielded a substantially lower value of 81 mm, compared to 94 mm obtained by Steyn (1997).

The low value of WUE in NNN obtained in spring could be attributed to the fact that the experiment was conducted under a rain shelter and bearing in mind that this could increase temperatures during nights when the shelter was closed. Towards flowering and tuber bulking in summer, rainfall was often imminent, which dictated closing of the rain shelter for the whole night to avoid rainfall interference with the water stressed treatments. Lynch *et al.*

(1995) suggested that the use of shelters to enable the imposition of water stress modifies the micro-environment.

Well watered treatments (NNN) probably responded to this micro-environment change by developing more above ground biomass (Figure 4.1). Van Dam *et al.* (1996) reported that onset of tuber growth and onset of tuber bulking were delayed by higher temperature, however, the delay was more pronounced for a temperature greater than 23°C. Even though temperatures under the rain shelter were not recorded during the experiment, it was evident that high temperatures were responsible for the low yield in NNN and therefore low WUE. This was confirmed by a similar experiment conducted nearby in an open field (data not presented here) which did not show any particular response to high temperature.

For a proper comparison among experiments carried out in different years or locations, Tanner and Sinclair (1983) recommend to normalise transpiration (T) or evapotranspiration (ET) for evaporative demand of the atmosphere. Estimates of water use efficiency based upon regression analyses and the relationship between tuber dry matter increase versus both cumulative transpiration and cumulative transpiration normalised for VPD are presented in Figure 4.6. As recommended by Tanner and Sinclair (1983) tuber dry mass represents the dependent variable (Y-axis) and the independent variable (X-axis) is represented by the amount of water transpired by the crop. The slope represents transpirational water use efficiency in  $\text{kg ha}^{-1}\text{mm}^{-1}$ . Apart from the slope of the NNN in autumn, which shows a high value of  $74.5 \text{ kg ha}^{-1}\text{mm}^{-1}$ , Figure 4.6 shows a range of slopes with no distinctive trend.

As expected, when the cumulative transpiration was normalised for VPD (Tanner and Sinclair, 1983), the value of the slopes for NNN treatment were comparable:  $42 \text{ kg ha}^{-1}\text{mm}^{-1}$  for spring and  $46 \text{ kg ha}^{-1}\text{mm}^{-1}$  for autumn (Figure 4.6). Transpirational water use efficiency was higher in autumn than in spring. Sinclair *et al.* (1984) suggest that crop growth under conditions when VPD is minimal, would improve water use efficiency directly. These results are in the range of 38 to  $63 \text{ kg ha}^{-1}\text{mm}^{-1}$  reported for potato by Tanner (1981) but much higher than that found by Trebejo and Midmore (1990)  $26 \text{ kg ha}^{-1}\text{mm}^{-1}$  in summer and  $15 \text{ kg ha}^{-1}\text{mm}^{-1}$  in winter. Gregory and Simmonds (1992) discussed the reasons of differences in transpirational WUE in potato, yet it is suggested to be a conservative parameter for many crops (Tanner and Sinclair, 1983). One of the reasons for differences in transpirational water

use in potato is likely to be linked to the uncertainties of calculating VPD and sensitivity of potato to drought (Gregory and Simmonds, 1992).

Table 4.4: Crop water use efficiencies ( $\text{kg ha}^{-1}\text{mm}^{-1}$ ) of potato crop under different irrigation regimes during spring 2004 and autumn 2005

| Planting period | Treatments | Tuber fresh yield ( $\text{kg ha}^{-1}$ ) | Total water use (mm) | Water use efficiency ( $\text{kg ha}^{-1} \text{mm}^{-1}$ ) |
|-----------------|------------|---|----------------------|---|
| Spring 2004     | NNN        | 47085                                     | 579                  | 81  |
|                 | SNN        | 22372                                     | 472                  | 39  |
|                 | NSN        | 17196                                     | 432                  | 47  |
|                 | NNS        | 44469                                     | 405                  | 110   |
| Autumn 2005     | NNN        | 45571                                     | 360                  | 127   |
|                 | SNN        | 34769                                     | 276                  | 126   |
|                 | NSN        | 27716                                     | 268                  | 103   |
|                 | NNS        | 41682                                     | 259                  | 161   |

Tanner (1981) points out that the value of transpirational water use efficiency depends very much on how VPD is calculated and proposes using an integrated VPD for a day time transpiration period rather than the mean saturation deficit. When potato is exposed to a large atmospheric demand for water, even in wet soil, stomatal closure and partial wilting may occur (Gregory and Simmonds, 1992). Therefore, this could affect the transpirational water use efficiency by altering the conservative parameter for many crops as suggested by (Tanner and Sinclair, 1983).

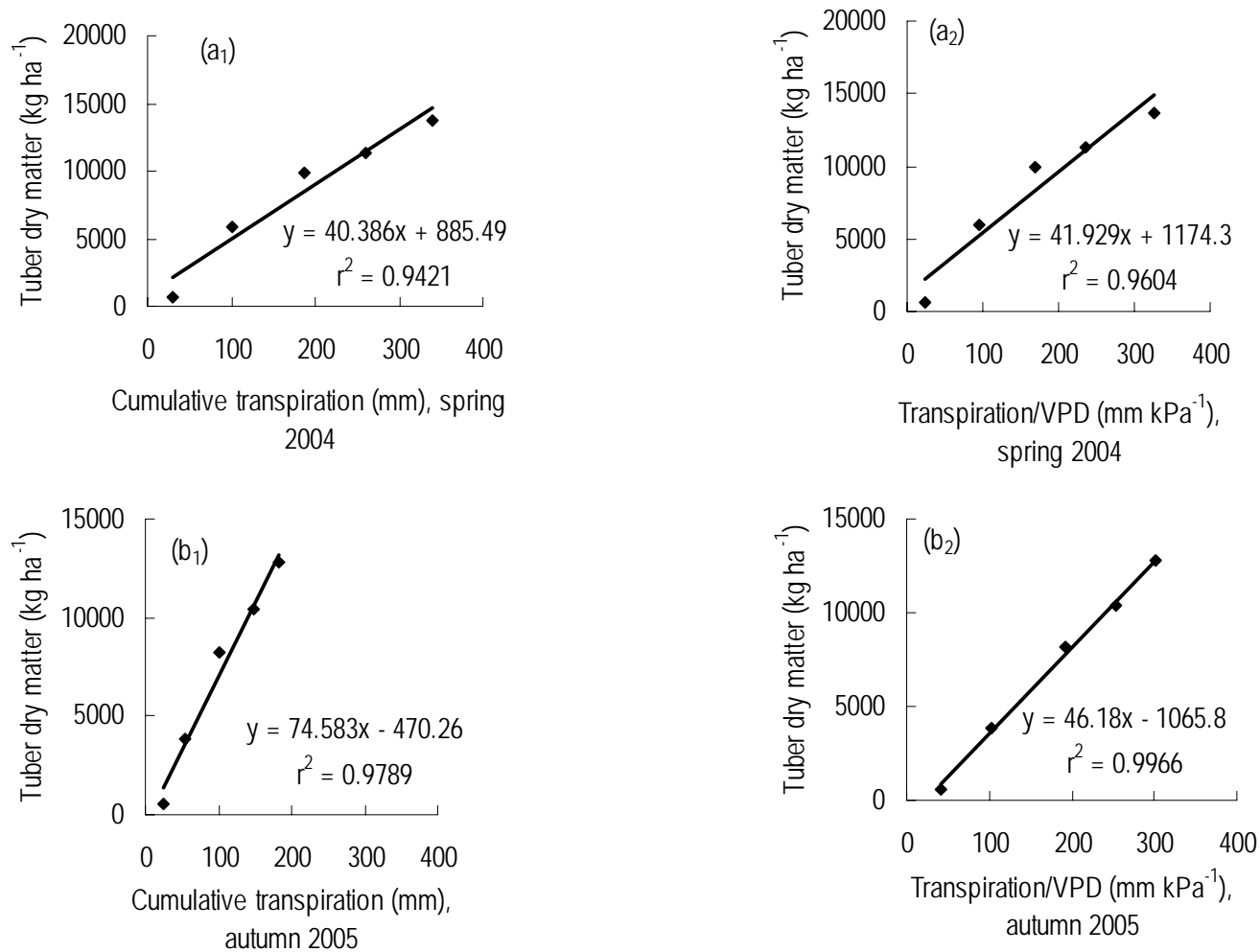


Figure 4.6: Relation of measured tuber dry matter accumulation to cumulative transpiration and cumulative transpiration normalised to vapour pressure deficit for both spring 2004 and autumn 2005 experiments for unstressed treatment (NNN).

## CHAPTER 5

### MODEL CALIBRATION AND VALIDATION

#### 5.1. Model description

SWB (Soil Water Balance) is a generic crop growth and irrigation scheduling model which simulates the soil water balance, crop growth, development and yield using a mechanistic approach. In addition, SWB includes the option of an FAO type crop factor model to calculate the soil water balance. The model is subdivided into three units, namely, the weather, soil and crop units, and are described in detail by Annandale *et al.* (1999). In this study, only a brief outline of the model is given.

The weather unit of SWB calculates the Penman-Monteith grass reference daily evaporation (ET<sub>o</sub>) as recommended by FAO (Smith *et al.* 1998).

The soil water budget in SWB comprises precipitation, irrigation, interception, runoff, water infiltration, crop transpiration and evaporation, water distribution in the profile and deep percolation. For actual field simulations, irrigation and rainfall are inputs and the other components of the soil water balance are calculated. Water distribution is simulated using either a cascading or finite difference approach. This study used the cascading approach, which calculates soil water content of horizontal soil layers by distributing water among soil layers. The model distributes water from rainfall, irrigation and drainage by filling soil layers to saturation, starting from the top of the profile and moving downwards. The soil profile is divided into as many as 11 horizontal, homogenous layers with user-specified properties to ensure a realistic simulation of water distribution in the soil.

In the SWB model partitioning into potential crop transpiration and potential soil evaporation is determined by canopy radiant interception from simulated leaf area. Water availability in the soil profile determines the actual transpiration and soil evaporation. This water availability is influenced by plant water uptake, which also depends on root density that characterises the water supply capabilities of the soil root system.

The model considers that a crop is water stressed if the ratio of actual to potential transpiration is less than the specified stress index (Annandale, Campbell and Olivier, 2000).

The simulation of crop phenology is based on thermal time using the algorithm developed by Monteith (1977) which considers that plant development rate increases as a linear function of average temperature between a base and an optimal temperature as follows:

$$\text{GDD} = \sum \left( \frac{T_x - T_n}{2} \right) - T_b \quad (5.1)$$

where,

GDD is growing day degrees,  $T_x$  is maximum temperature in °C,  $T_n$  is minimum temperature in °C, and  $T_b$  is base temperature in °C.

The crop unit of SWB calculates dry matter accumulation based on both crop transpiration limited (Tanner and Sinclair, 1983) (Eq. 5.2) and radiation limited (Monteith, 1977) (Eq. 5.3) conditions. The model calculates both the transpiration limited and radiation limited dry matter accumulation (DM) in  $\text{kg m}^{-2}$  on daily basis, and chooses the lesser of the two.

$$\text{DM} = \text{DWR}(T / \text{VPD}) \quad (5.2)$$

where,

DWR is the dry matter water ratio (Pa), VPD is vapour pressure deficit in Pa, and T is transpiration in  $\text{kg m}^{-2}$ .

$$\text{DM} = E_c T_f \text{FI}_{\text{transp}} R_s \quad (5.3)$$

Where,

$E_c$  is radiation conversion efficiency ( $\text{kg MJ}^{-1}$ );  $T_f$  is a dimensionless temperature factor for radiation limited crop growth.

Where,

FI is fraction of incident solar radiation intercepted by the green, transpiring canopy and  $R_s$  is total solar radiation in  $\text{MJ m}^{-2} \text{day}^{-1}$ .



$$T_f = (T_{\text{avg}} - T_b) / (T_{\text{lo}} - T_b) \quad (5.4)$$

Where,  $T_{\text{lo}}$  is temperature of optimum light limited growth ( $^{\circ}\text{C}$ ) and  $T_{\text{avg}}$  is average air temperature. The upper limit of  $T_f$  is set at 1, when  $T_{\text{avg}} > T_{\text{lo}}$

In SWB, the LAI is calculated as a function of biomass accumulation partitioned to the canopy (Eq. 5.5). A partitioning coefficient known as leaf - stem partitioning factor controls the ratio of biomass allocated to leaves and stems.

$$\text{LAI} = \frac{\text{SLA} * \text{CDM}}{(1 + p\text{CDM})} \quad (5.5)$$

where, SLA is specific leaf area or leaf area per unit dry mass of leaves ( $\text{m}^2 \text{kg}^{-1}$ ), CDM is canopy dry matter and represents total dry mass ( $\text{kg m}^{-2}$ ) of stems and leaves, and  $p$  is a partition coefficient ( $\text{m}^2 \text{kg}^{-1}$ ).

## 5.2. Model parameterisation and calibration

Governing equations for the SWB model and calculation procedures for the key parameters in those equations are detailed in Annandale *et al.* (1999). In SWB, potato crop parameters were previously determined separately for both the spring and autumn seasons (Steyn, 1997). This approach was proved by Steyn (1997) to fairly simulate the development, growth and yield of the potato crop. However, when the model was evaluated for spring potato with crop parameters for autumn potato, the model resulted in inaccurate simulation results (Steyn, 1997). This poor performance was attributed to the failure of the model to take into account the effect of photoperiod and high temperatures on assimilate distribution and development (Steyn, 1997). Photoperiod governs the time of tuber initiation and the length of the growing season in potatoes crop (Kooman and Haverkort, 1995). Potato partitions assimilates among leaves, stems, tubers and roots through controls on initiation and growth of various organs (Ewing *et al.* 1990).

Steyn (1997) suggested that SWB performance in simulating potato growth, development and yield could be enhanced by adapting it (SWB) to simulate the effect of photoperiod and high temperatures. Therefore, one set of crop parameters for both spring and autumn plantings that

could be used to accurately simulate potato development, growth as well as soil water balance could possibly be obtained.

In this study, the model was validated using data from two experiments conducted during spring 2004 and autumn 2005 seasons. The results from this validation process show that the model fairly simulates potato crop growth variables such as LAI, TDM, HDM, FI and the soil water deficit (Appendix B). This led to a new calibration of the model using the experimental data obtained in spring 2004 and autumn 2005 (Table 5.1). The simulation results are presented in Figures 5.1a and b, and in Figures 5.2a and b, and in Appendix A. Excellent agreement between observed and predicted leaf area index (LAI) and fractional interception (FI) for the spring 2004 and autumn 2005 experiments are evident in Figures 5.1a and b. However, the simulation of total dry matter and tuber dry matter in both the spring 2004 and autumn 2005 under predicted the observed data, especially during tuber bulking of the growing season and over estimated towards the end of the growing season (Figures 5.1a and b). These Figures, however, illustrate that predicted total dry matter and tuber dry mass changes with time are close to observed values for both the spring 2004 and autumn 2005 experiments. Thus, the model accurately predicted the development and growth of potato for the spring and autumn experiments. Soil water deficit simulation results for both the spring 2004 and autumn 2005 experiments were always underestimated by the model throughout the season (Figures 5.1a and 5.2a).

Table 5.1: Crop parameters of potato (cv. BP1) determined from 2004 spring and 2005 autumn field data and the literature to calibrate the SWB model

| Parameter   | Autumn<br>2005 | Spring<br>2004 | Units                             | Source                      |
|---|----------------|----------------|-----------------------------------|-----------------------------|
| Canopy extinction coefficient (Kc)                    | 0.55           | 0.55           | -                                 | Data                        |
| Dry matter: water ratio (DWR)                         | 6.4            | 5.8            | Pa                                | Data                        |
| Radiation use efficiency (RUE)                        | 0.0018         | 0.002          | kg MJ <sup>-1</sup>               | Data                        |
| Base temperature (T <sub>b</sub> )                    | 2              | 2              | °C                                | Kooman <i>et al.</i> (1996) |
| Light limited temperature                             | 28             | 28             | °C                                | Kooman <i>et al.</i> (1996) |
| Optimum temperature                                   | 22             | 22             | °C                                | Data                        |
| Thermal time: emergence                               | 406            | 362            | day degree                        | Data                        |
| Thermal time: reproductive phase                      | 750            | 742            | day degree                        | Data                        |
| Thermal time: maturity                                | 1717           | 2439           | day degree                        | Data                        |
| Thermal time: transition                              | 450            | 560            | day degree                        | Data                        |
| Thermal time: leaf senescence                         | 900            | 1350           | day degree                        | Data                        |
| Leaf water potential at maximum<br>transpiration rate | -550           | -550           | kPa                               | Steyn (1997)                |
| Maximum transpiration rate                            | 7.5            | 7.5            | mm day <sup>-1</sup>              | Data                        |
| Specific leaf area                                    | 22             | 22             | m <sup>2</sup> kg <sup>-1</sup>   | Data                        |
| Leaf stem partitioning factor                         | 2              | 2              | m <sup>2</sup> kg <sup>-1</sup>   | Data                        |
| Total dry matter at emergence                         | 0.005          | 0.005          | kg m <sup>-2</sup>                | Steyn (1997)                |
| Root fraction   | 0.1            | 0.1            | -                                 | Steyn (1997)                |
| Stem translocation                                    | 0.45           | 0.45           | -                                 | Steyn (1997)                |
| Root growth rate                                      | 3              | 4              | m <sup>2</sup> kg <sup>-0.5</sup> | Steyn (1997)                |
| Maximum canopy height                                 | 0.7            | 0.7            | m                                 | Data                        |



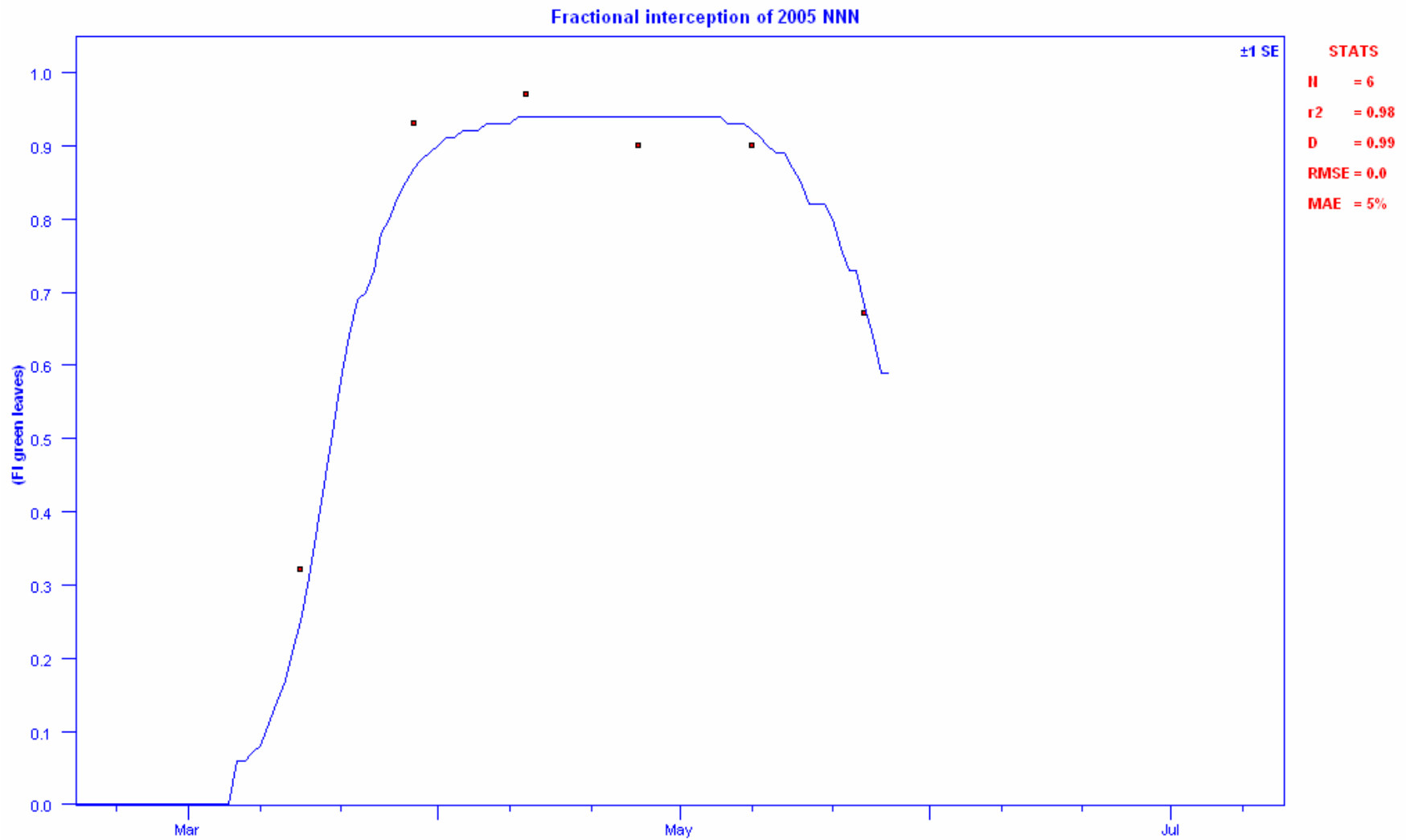


Figure 5.1b: Simulated (lines) and observed values (points) of FI for PAR for 2005 autumn planting (unstressed treatment, NNN)

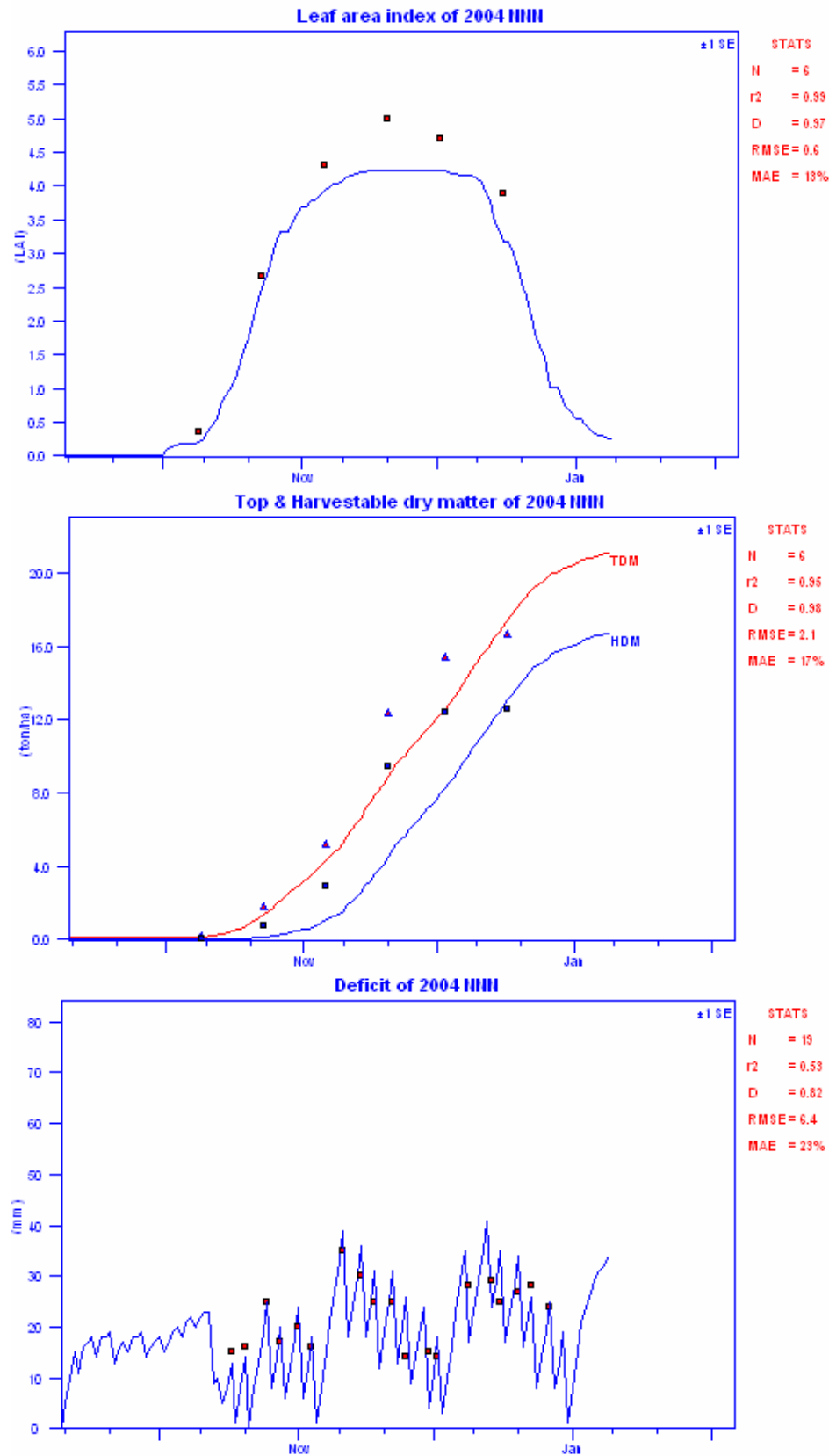


Figure 5.2a: Simulated (lines) and observed values (points) of LAI, TDM, HDM and soil water deficit for 2004 spring planting (unstressed treatment, NNN)

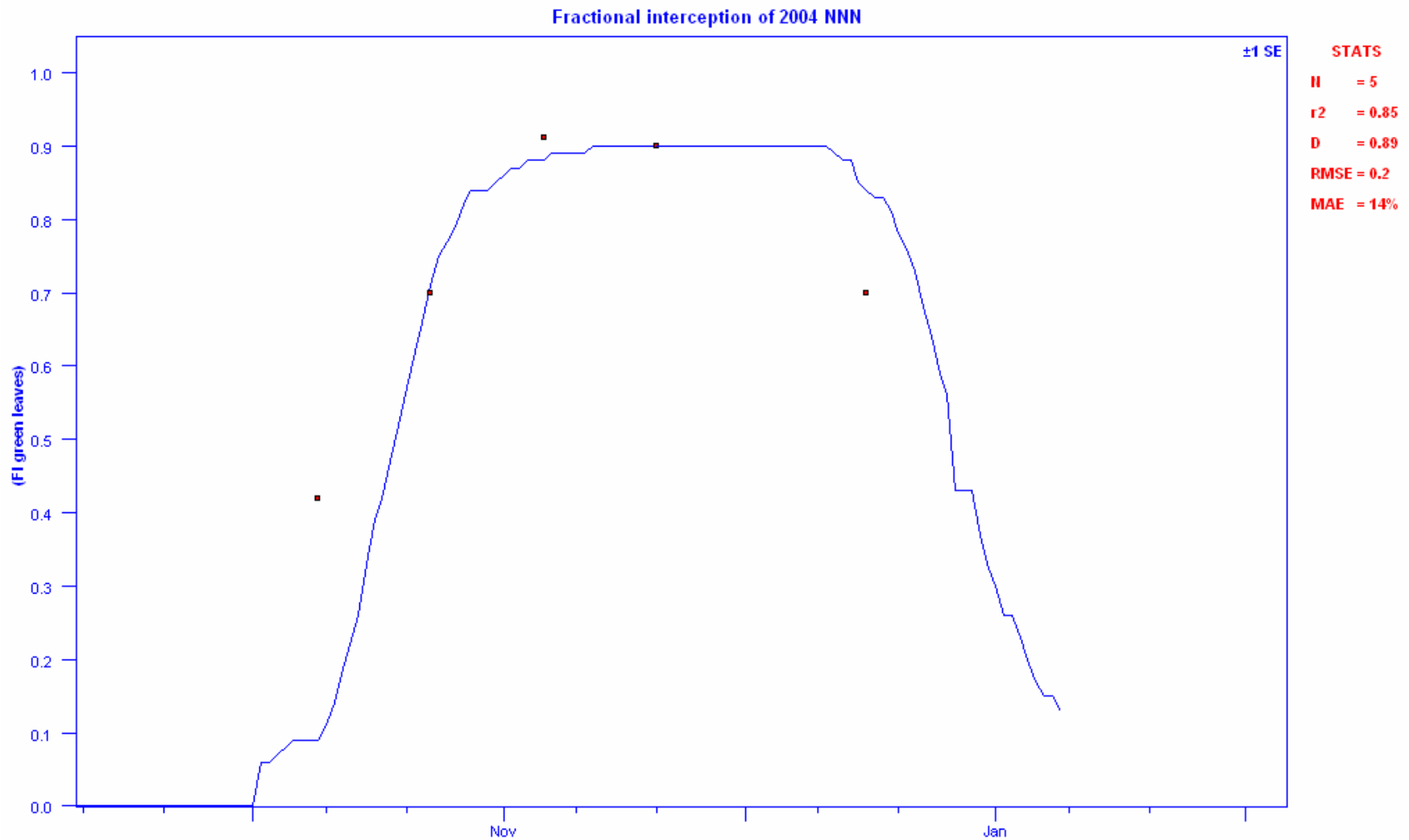


Figure 5.2b: Simulated (lines) and observed values (points) of FI for 2004 spring planting (unstressed treatment, NNN)

### 5.3. Model evaluation

The model evaluation was carried out using independent data sets from the spring and autumn 2000 seasons (unpublished data). Since there was no soil water deficit data available, simulated results of this parameter were not evaluated in this study. The accuracy of the model simulations were assessed based on five validation statistics recommended by De Jager (1994). In this evaluation, the indicators of performance are root mean square error (RMSE), mean absolute error expressed as a percentage of the mean of the measured values (MAE), coefficient of determination ( $r^2$ ) and the Willmott index of agreement (D) that takes on values from 0 to 1, with an index of 1 indicating perfect agreement (Willmott, 1982). Model performance is shown with simulation results presented as figures, and Table 5.2 shows reliability criteria as recommended by De Jager (1994).

Table 5.2: Reliability criteria for model evaluation as recommended by De Jager (1994)

| Statistical parameter   | Reliability criteria |
|---|----------------------|
| Root of the mean square error (RMSE)  | -                    |
| Mean absolute error expressed as a percentage of the mean of the measured values (MAE in %) | < 20                 |
| Coefficient of determination ( $r^2$ )  | > 0.8                |
| Willmott index of agreement (D)   | > 0.8                |

Simulation results are presented in Figures 5.3a and b and 5.4a and b. Total crop dry matter and tuber dry matter simulations were in general reasonably close to the measured values for the autumn 2000 season, as well as for spring 2000. According to De Jager's (1994) reliability criteria (Table 5.2), the model accurately predicted the leaf area index as well as fractional interception for both the spring and autumn seasons (Figures 5.3 and 5.4.).



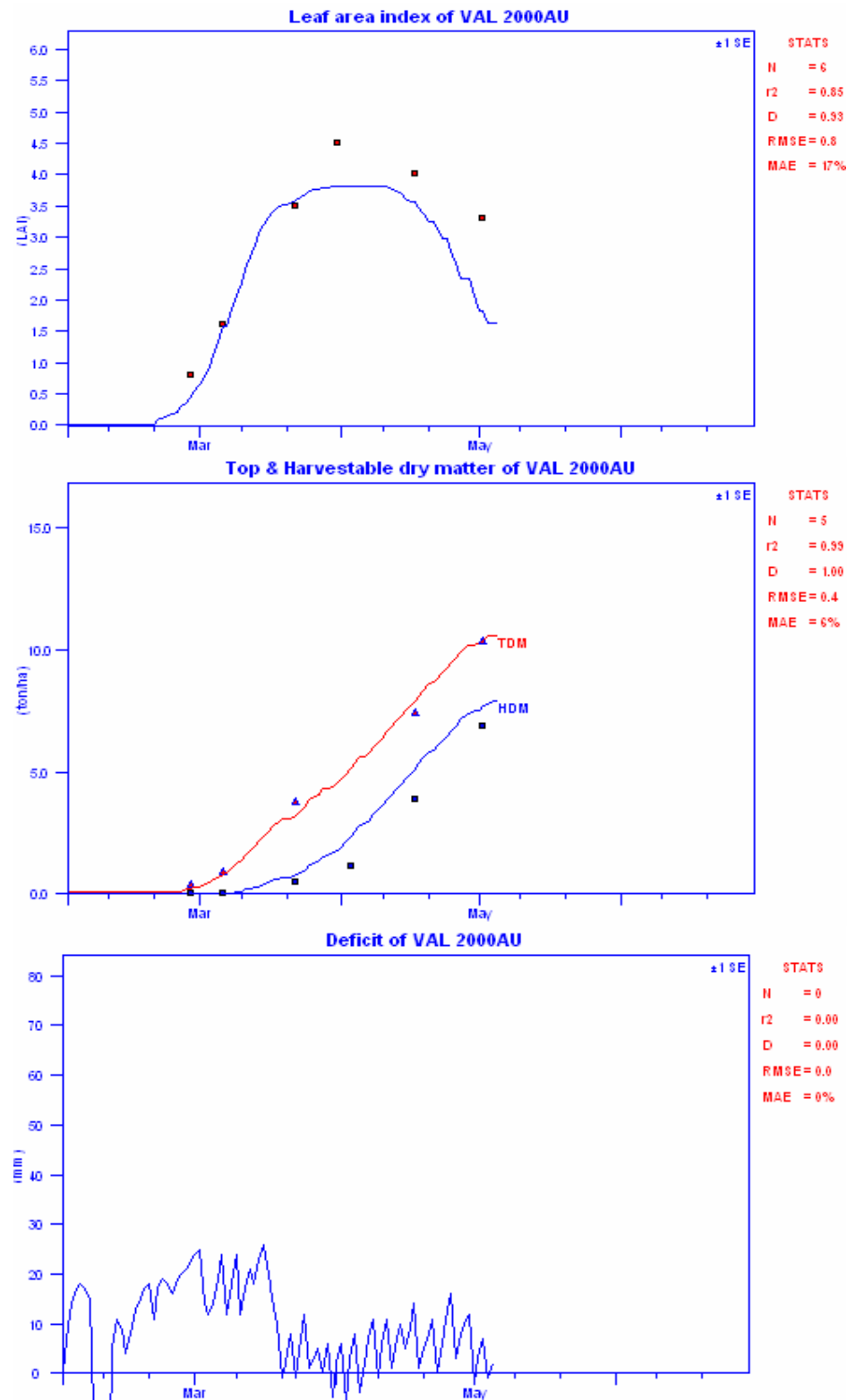


Figure 5.3a: Simulated (line) and observed values of LAI, TDM, HDM and water deficit for autumn 2000 season (independent data used for the evaluation of the performance of the model). VAL stands for validation and AU stands for autumn season

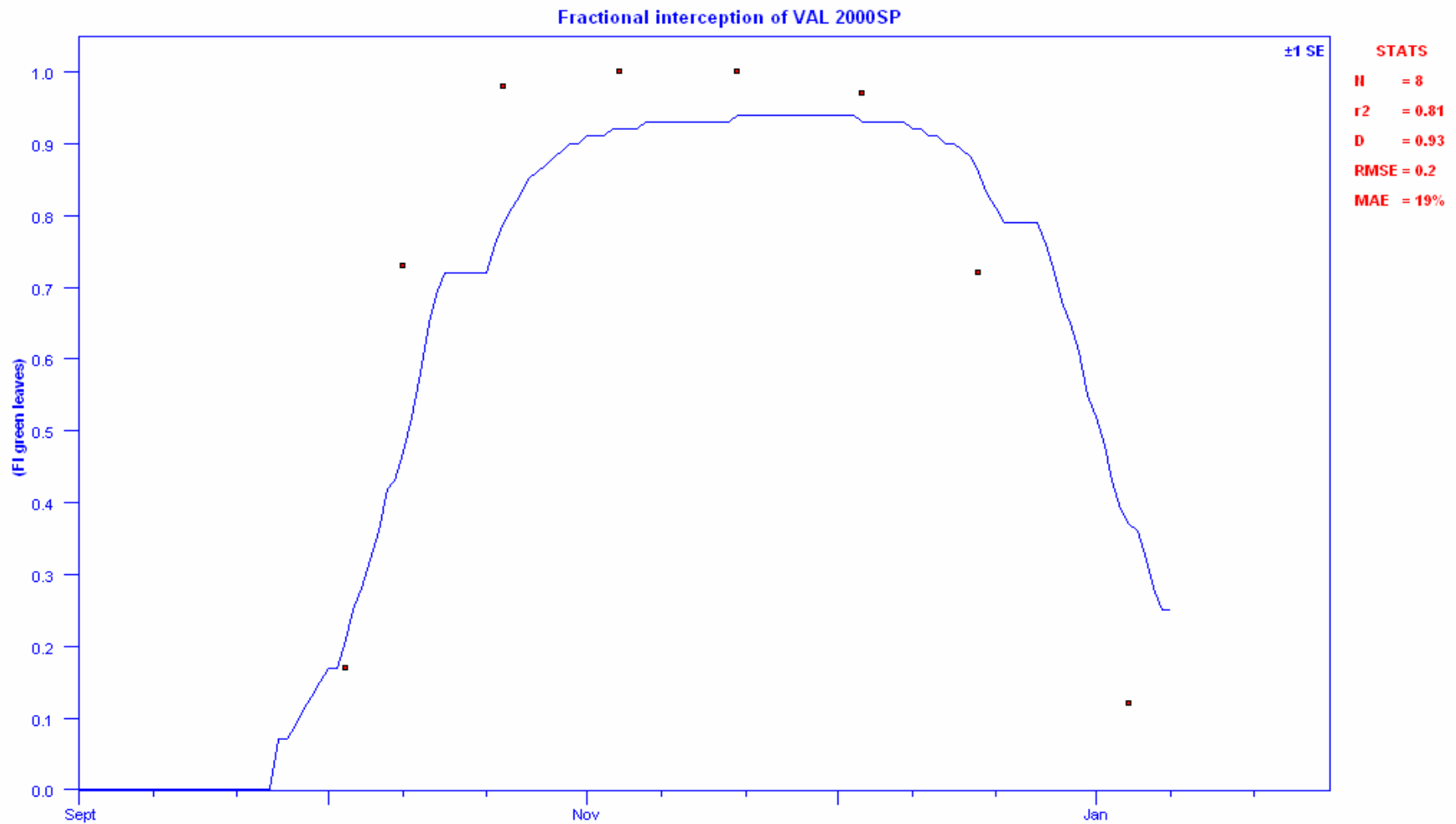


Figure 5.3b: Simulated (line) and observed values of FI for spring 2000 season (independent data used for the evaluation of the performance of the model). VAL stands for validation and AU stands for autumn season

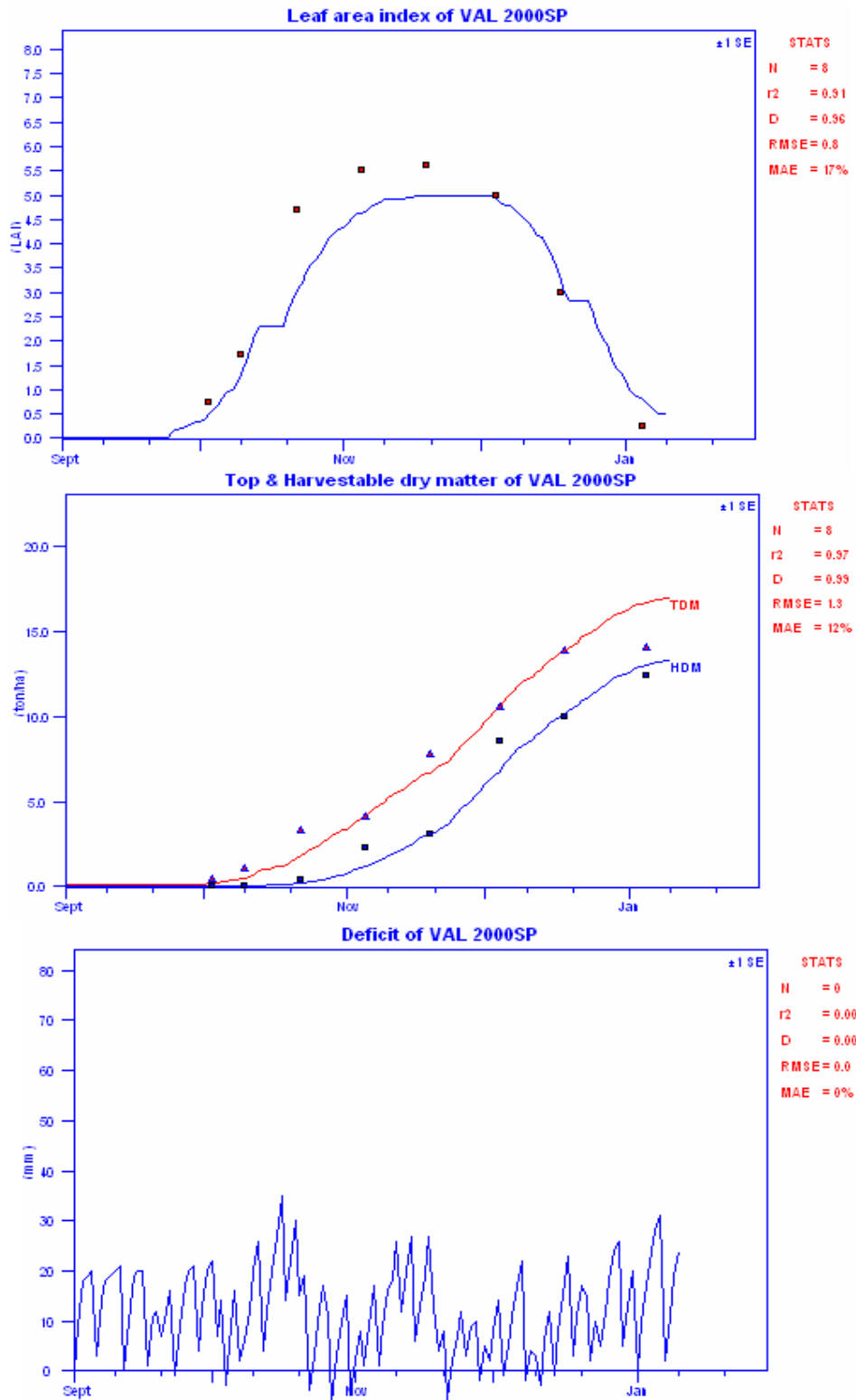


Figure 5.4a: Simulated (line) and observed values of LAI, TDM, HDM and water deficit for spring 2000 season (independent data used for the evaluation of the performance of the model). VAL stands for validation and SP stands for spring season

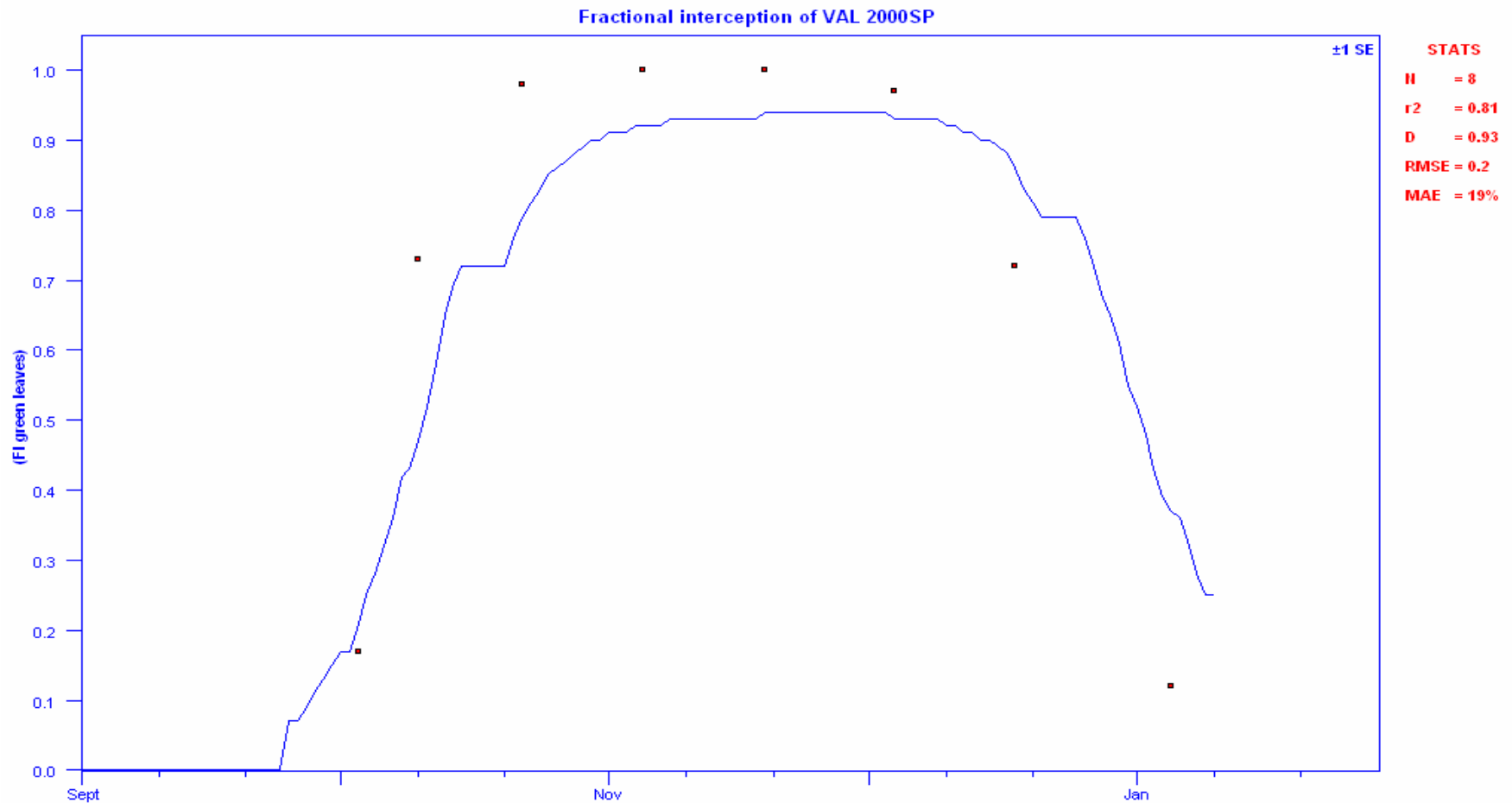


Figure 5.4b: Simulated (line) and observed values of FI for spring 2000 season (independent data used for the evaluation of the performance of the model). VAL stands for validation and AU stands for autumn season

## CHAPTER 6

### ESTIMATION OF THERMAL TIME FOR TUBER INITIATION

#### 6.1. Introduction

In potato crop modelling, photoperiod is an important feature in areas where it varies greatly at time of planting. Photoperiod governs the timing of tuber initiation and the length of the growing season (Kooman and Haverkort, 1996). Potato partitions assimilates among leaves, stems, tubers and roots through controls on initiation and growth of various organs (Ewing *et al.*, 1990). As suggested by Ewing *et al.* (1990) photoperiod and temperature play a dominant role in the control of this partitioning. Manrique, Hodges and Johnson (1990), Kooman and Haverkort (1995), and Wheeler and Tibbitts (1997) showed that under optimal conditions, phenological development of potato is most influenced by both temperature and photoperiod. The effect of photoperiod is closely associated with temperature through their influence on development (Van Dam *et al.*, 1996). These authors pointed out that short days hasten tuber initiation, whereas long days postpone it.

In potato crop models like POTATO (Ng and Loomis, 1984) and SUBSTOR (Ritchie *et al.* 1995), the time of tuber initiation is a function of cultivar response to both temperature and photoperiodicity. In these models, the time of flowering is not simulated. On the contrary, SWB estimates the time of flowering from thermal time in order to correctly simulate assimilate partitioning in a wide variety of crops. In fact, potato tuber initiation occurs much earlier than flowering (Kabat *et al.*, 1995). Since SWB is a generic crop model it assumes the time of tuber initiation to be a surrogate for the time of flowering, as this is when assimilates begin to be partitioned not only to vegetative above ground structures, but also to tubers.

SWB calculates thermal time using an algorithm developed by Monteith (1977) which considers that plant development rate increases as a linear function of average temperature between a base and an optimal temperature.

However, for potato, a non linear dependence of development on temperature was suggested (Sands, Hackett and Nix, 1979). Manrique and Hodges (1989) used the non linear

temperature response function developed by Sands *et al.* (1979) and found it adequate in describing the thermal time required for tuber initiation. Since SWB is a generic model, the linear relationship between development and temperature is convenient because it must apply not only to potato but also to other crops. Gayler *et al.* (2002) suggested that generic models may require modifications of a single process formulation where divergences in physiological and ecological principles between crop classes such as cereals and root crops may occur.

Currently, SWB simulates potato growth and development using different sets of parameters developed for spring and autumn planting. This approach was shown to be reasonable by Steyn (1997) and this study (section 5.2) to simulate the development, growth and yield of potato reasonably well. However, there are clearly shortcomings in the mechanistic description of potato growth and development, and the challenge is to get one set of parameters for both spring and autumn planting that could be used to simulate potato development, growth, yield as well as soil water balance. As suggested by Steyn (1997), SWB model performance in simulating potato development, growth and yield could possibly be enhanced by adapting it (SWB) to simulate the effect of photoperiod and high temperatures on development and growth.

## 6.2. Materials and methods

To find a convenient and reasonably accurate method to compute thermal or photo thermal time required for tuber initiation, a comparison of different calculation approaches was made. This involved the following methods:

**Method 1:** Daily thermal time was computed using the SWB (Annandale *et al.*, 1999) approach, which considers that plant development proceeds as a linear function of average temperature, between a base and an optimal temperature as follows:

$$\text{GDD} = \sum \frac{T_x + T_n}{2} - T_b \quad (6.1)$$

Where,

GDD is the growing degree days ( $^{\circ}\text{Cd}$ ),  $T_x$  is maximum temperature,  $T_n$  minimum temperature and  $T_b$  is base temperature below which there is no more growth and development. Tuber initiation occurs when  $\Sigma\text{GDD}$  reaches a certain critical value.

**Method 2:** This method uses the SUBSTOR approach (Ritchie *et al.*, 1995) to compute thermal time required for tuber initiation. In SUBSTOR, thermal time for tuber initiation is computed as a function of a relative temperature factor and photoperiod. The relative temperature factor for tuber initiation (RTFTI) is calculated as shown in Equation 6.2. For convenience, parameter names used in SUBSTOR were not changed for this study. In Equation 6.2, the mean temperature (TEMPM) is more heavily weighted towards the minimum temperature (Eq. 6.3), as tuber initiation is more dependent on minimum than maximum temperature (Ritchie *et al.*, 1995).

$$\text{RTFTI} = \begin{cases} 1 - (1/36)(10 - \text{TEMPM})^2 & ; 4 < \text{TEMPM} < 10 \\ 1 & ; 10 \leq \text{TEMPM} < \text{TC} \\ 1 - (1/64)(\text{TEMPM} - \text{TC})^2 & ; \text{TC} \leq \text{TEMPM} < \text{TC} + 8 \end{cases} \quad (6.2)$$

Where,

RTFTI is a relative temperature factor for tuber initiation,

$$\text{TEMPM} = 0.25 * T_x + 0.75 * T_n \quad (6.3)$$

and  $T_x$  is maximum temperature,  $T_n$  minimum temperature and TC is a critical temperature above which the growth and development are affected to some degree (Figure 6).

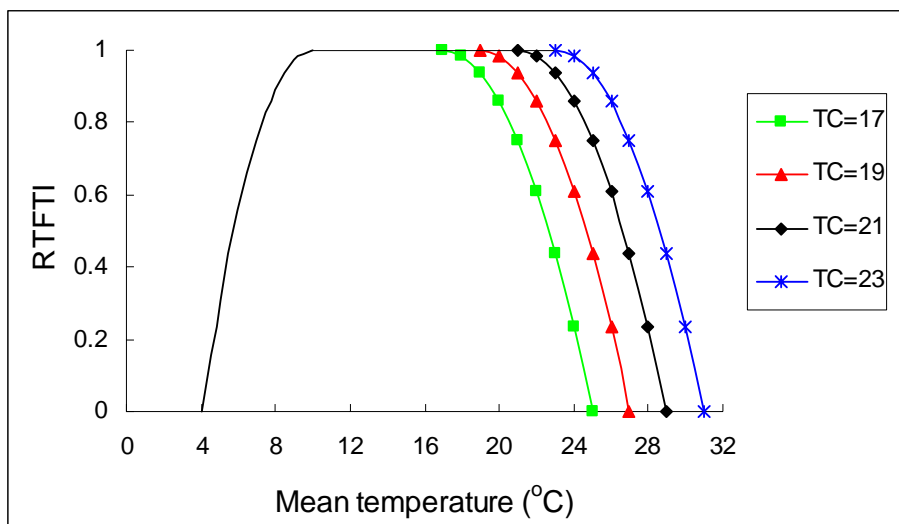


Figure 6: The influence of critical temperature (TC) on relative temperature for tuber initiation (RTFTI)

In SUBSTOR, time of initiation is a function of temperature and photoperiodicity. To integrate the photoperiod effect as a modifier of tuber induction, a photoperiod factor for tuber initiation (RDLFTI) was introduced and is calculated as follows:

$$\text{RDLFTI} = \begin{cases} 1 & ; \text{PHPER} \leq 12 \\ (1 - P2) + P2/144 (24 - \text{PHPER})^2 & ; \text{PHPER} > 12 \end{cases} \quad (6.4)$$

Where,

RDLFTI is a relative day length factor for tuber initiation,

PHPER is photoperiod (h) calculated using equations developed by Campbell and Norman (1998), and P2 is a dimensionless parameter, which is an input genetic coefficient for cultivar sensitivity to photoperiod (Figure 7).



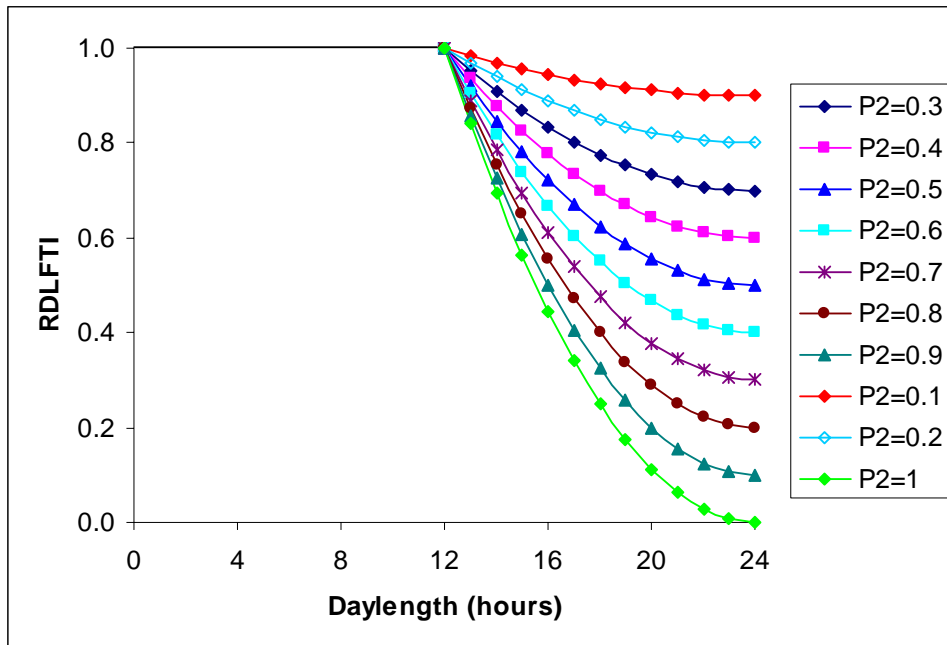


Figure 7: Relationship between relative day length factor for tuber initiation (RDLFTI) and cultivar sensitivity to photoperiod (P2).

Under optimal plant growth conditions, RDLFTI is used to calculate the tuber induction index (TII) each day after emergence as a function of the relative temperature factor for tuber (RTFTI) as follows:

$$CTII = RDLFTI * RTFTI \quad (6.5)$$

where,

TII is tuber induction index,

CTII is cumulative tuber induction index.

**Method 3:** In this method, thermal time for tuber initiation was computed using the standard SWB approach combined with a relative photoperiod factor for tuber initiation as follows:

$$GDD = \sum \left( \frac{T_x + T_n}{2} - T_b \right) * RDLFTI \quad (6.6)$$

**Method 4:** Thermal time in this method was computed using SWB approach combined with photoperiod factor and temperature factor as follows:

$$\text{GDD} = \sum \left( \frac{T_x + T_n}{2} - T_b \right) * \text{RDLFTI} * \text{RTFTI} \quad (6.7)$$

**Method 5:** This method computed thermal time with SWB approach, except that the mean temperature was calculated according to Equation 6.3.

**Method 6:** This method computed thermal time using the weighted mean temperature developed in SUBSTOR model and combined with a relative photoperiod factor for tuber initiation as follows:

$$\text{TEMPM} = (0.25 * T_x + 0.75 * T_n) * \text{RDLFTI} \quad (6.8)$$

**Method 7:** This method computed daily thermal time for tuber initiation using a mean weighted temperature and relative temperature for tuber initiation factor and relative photoperiod factor for tuber initiation as follows:

$$\text{TEMPM} = (0.25 * T_x + 0.75 * T_n) * \text{RDLFTI} * \text{RTFTI} \quad (6.9)$$

### 6.2.1. Day length calculation

Day length used is civil day length, which includes periods when the sun is 6°C below the horizon, an angle of sun at twilights. Calculations are based on the formulas developed by Campbell and Norman (1998):

$$\cos \psi = \sin \beta = \sin \phi \sin \delta + \cos \phi \cos \delta \cos [15(t - t_0)] \quad (6.10)$$

where,

$\cos \psi$  is zenith angle (radians) of the sun which depends on the time of day, the latitude of the site, and the time of the year.  $\phi$  is the latitude,  $\delta$  is solar declination,  $t$  is time, and  $t_0$  is the time of the solar noon calculated as follows:

$$to = 12 - LC - ET \quad (6.11)$$

where, LC is the longitude correction and ET is the equation of time and is calculated as follows:

$$ET = \frac{-104.7 \sin f + 596.2 \sin 2f + 4.3 \sin 3f - 12.7 \sin 4f - 429.3 \cos f - 2.0 \cos 2f + 19.3 \cos 3f}{3600} \quad (6.12)$$

where  $f = 279.575 + 0.9856J$  in degrees.

Solar declination ranges from  $+ 23.45^\circ$  at summer solstice to  $- 23.45^\circ$  winter solstice and is calculated as follows:

$$\sin \delta = 0.39785 \sin[278.97 + 0.9856J + 1.9165 \sin(356.6 + 0.9856J)] \quad (6.13)$$

Where,  $\delta$  is solar declination (degrees),  $J$  is the day of the year  $J = 1$  with at January 1.

The half-day ( $h_s$ ) length, which is the time (in degrees) from sunrise to solar noon, is calculated as follows:

$$h_s = \cos^{-1} \left( \frac{\cos \psi - \sin \phi \sin \delta}{\cos \phi \cos \delta} \right) \quad (6.14)$$

where,

$\cos \psi = 96$  the twilight are included at sunrise and sunset when the sun is  $6^\circ$  below the horizon,  $h_s$  is half day in degrees,  $\phi$  is latitude and  $\delta$  is solar declination. Day length in hours is twice the half-day length in degrees divided by  $15^\circ\text{C/hr}$  ( $2 * h_s / 15$ ).

### 6.2.2. Data collection and processing

For data collection, a methodology developed by Manrique and Hodges (1989) was used. In this methodology, days to tuber initiation are used for each method from planting to tuber initiation to compute thermal time. A minor modification was made to this methodology. The onset of tuber initiation is calculated from the time of plant emergence, rather than to

time of planting. This was suggested by O'Brien *et al.* (1998), as emergence always precedes tuber initiation and the interval from planting to emergence can be extremely variable. Similarly, Sands *et al.* (1979) suggested that the period between planting and emergence depends greatly on management practice, thus the emergence should be treated as the beginning of the calculation of phenological development. As expected, the time between planting and emergence in the data sets used in this study varied widely. Therefore, the estimation of development after emergence was used to avoid any discrepancy between the data sets.

Manrique and Hodges (1989) define tuber initiation as the time when 50% of plants had at least one tuber of 1 cm or larger in diameter. They suggest sampling every two to three days after full emergence. However, in this study, the time of tuber initiation was only assessed every two weeks. This implies that the exact time of tuber initiation could be missed since under good growing conditions a tuber of 1 cm or larger in diameter can be produced within one week as suggested by O'Brien *et al.* (1998).

Since the observed day of tuber initiation may have been missed due to lack of an appropriate frequency of sampling, this study adopted a method estimating the date of onset of tuber initiation by back extrapolation of tuber bulking lines to zero, as suggested by Sands *et al.* (1979).

In this method, the time of tuber initiation corresponds with the time obtained by extrapolation of yield curves back to zero yield (Sands *et al.*, 1979).

### **6.2.3. Method evaluation**

This study used an approach developed by Manrique and Hodges (1989) to assess the degree of variability associated with each method (section 6.2.1) in computing thermal time for tuber initiation. Days to tuber initiation were used to calculate thermal time for each method from emergence to tuber initiation for each season. The coefficient of variation and the standard deviation of the thermal time for each season were computed (Table 6.2). This was done to assess the degree of variability associated with each method. The assumption is that if thermal time required for tuber initiation for a given season is computed correctly then it should be relatively constant for different seasons (spring and autumn). In addition, this

study used graphics to estimate error in days to initiate tubers if a threshold value of thermal time required for tuber initiation is to be fixed.

### **6.3. Results and discussion**

#### **6.3.1. Estimation of the time of tuber initiation**

The estimation of tuber initiation was carried out for five data sets and the results are presented in Table 6.1. Here, it is evident that the time of tuber initiation varied with season. In spring plantings, the time between emergence and tuber initiation was the longest and this varied with planting season. The trial carried out in spring 2000 took 23 days after emergence to initiate tubers, whereas the experiment conducted in spring 2004 took only 19 days (Table 6.1). In autumn 1999, the stage between emergence and tuber initiation lasted 22 days and in autumn 2005 and 2000 it lasted only 18 and 19 days, respectively (Table 6.1). Firman *et al.* (1991) suggested that in many cultivars tuber initiation occurs 2-3 weeks after emergence within a wide range of temperatures and photoperiods. This is in agreement with the results of this study.

As suggested by Manrique *et al.* (1990), Kooman and Haverkort (1995), and Wheeler and Tibbitts (1997) short days which prevail early in spring plantings (Figure 6.1a) should induce tuber initiation faster than in autumn plantings, since in autumn emergence and the tuber initiation period coincide with relatively long days. However, Table 6.1 shows that autumn planting time in most cases has a shorter period between emergence and tuber initiation than spring plantings although temperatures and day lengths corresponding to that period were higher in autumn than in spring plantings (Figures 6.1a and b). This implies that there were factors other than photoperiod and temperature that also influenced tuber induction in these experiments. These variations in time to tuber initiation could be attributed to the differences in management practices applied to the experiments. Data from spring 2000 and autumn 2000 and 1999 were derived from a well-managed commercial farm where more nitrogen could have been applied. As suggested by Vos (1995) an increased nitrogen dose in potato will lengthen the period between emergence and tuber initiation. Both 2004 and 2005 trials were conducted at the experimental farm where nitrogen and water were applied according to plant requirements and weeds, pests and diseases were strictly controlled. However, these experiments were conducted under a mobile rain shelter to avoid the interference of rainfall

with treatments under water stress. During the period between emergence and tuber initiation rainfall often occurred in the spring planting.

On some nights, the rain shelter was closed to avoid any interference of rainfall with water stressed treatments, as the rain shelter was not automated. It is known that rain shelters modify the micro environment by increasing temperature, especially during night and by limiting solar radiation in the day time (Lynch *et al.*, 1995). It is suspected that these warmer conditions caused by the rain shelter when it covered the crops at night could have altered the normal course of tuber induction. Van Dam *et al.* (1996) reported that onset of tuber initiation and onset of tuber bulking are delayed by higher temperatures and the effect of temperatures above 23°C is especially pronounced. Minimum temperatures greater than 18°C at night and maximum temperatures greater than 28°C during the day are considered to be higher for potato growth and development (Midmore, 1992).

Table 6.1: Time in days, to tuber initiation, as influenced by planting date and season (spring and autumn). DAP stands for days after planting and DAE stands for days after emergence.

| Planting season | Planting date    | Emergence (DAP) | Tuber initiation (DAE) |
|-----------------|------------------|-----------------|------------------------|
| Spring          | 31 August 2000   | 21              | 23                     |
|                 | 9 September 2004 | 23              | 19                     |
| Autumn          | 22 February 1999 | 17              | 22                     |
|                 | 1 February 2000  | 19              | 19                     |
|                 | 15 February 2005 | 17              | 18                     |

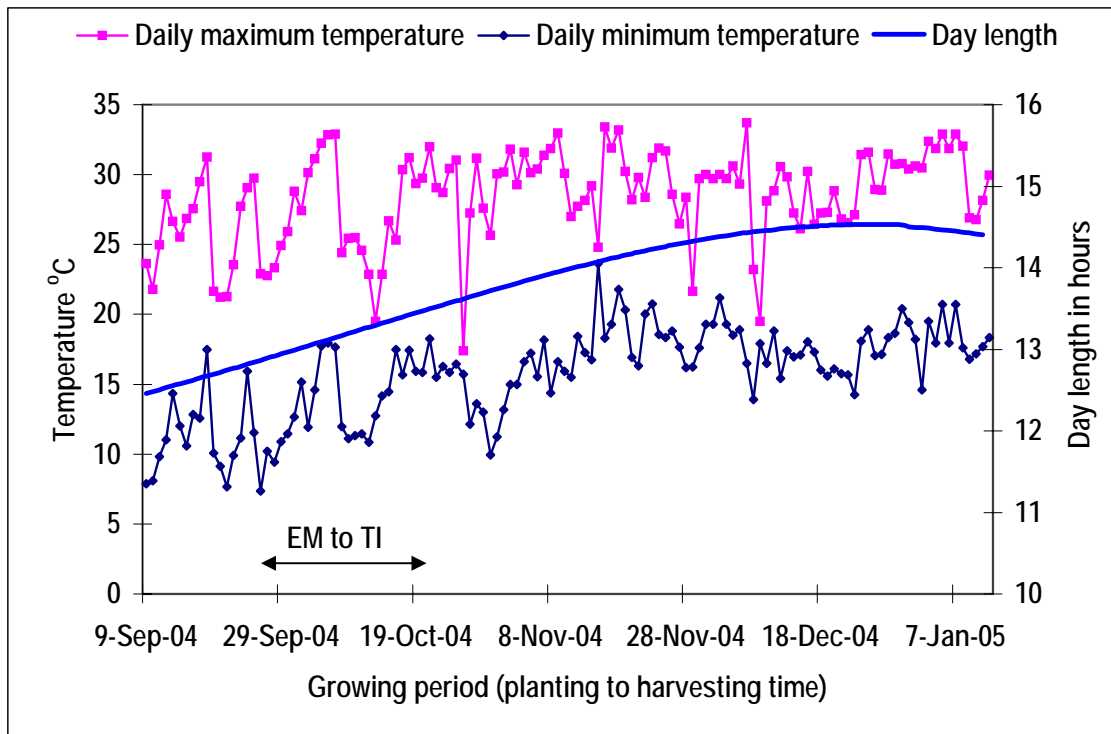


Figure 6.1a: Daily values of day length and daily minimum and maximum temperatures for the spring 2004 season. EM stands for emergence time and TI stands for tuber initiation time

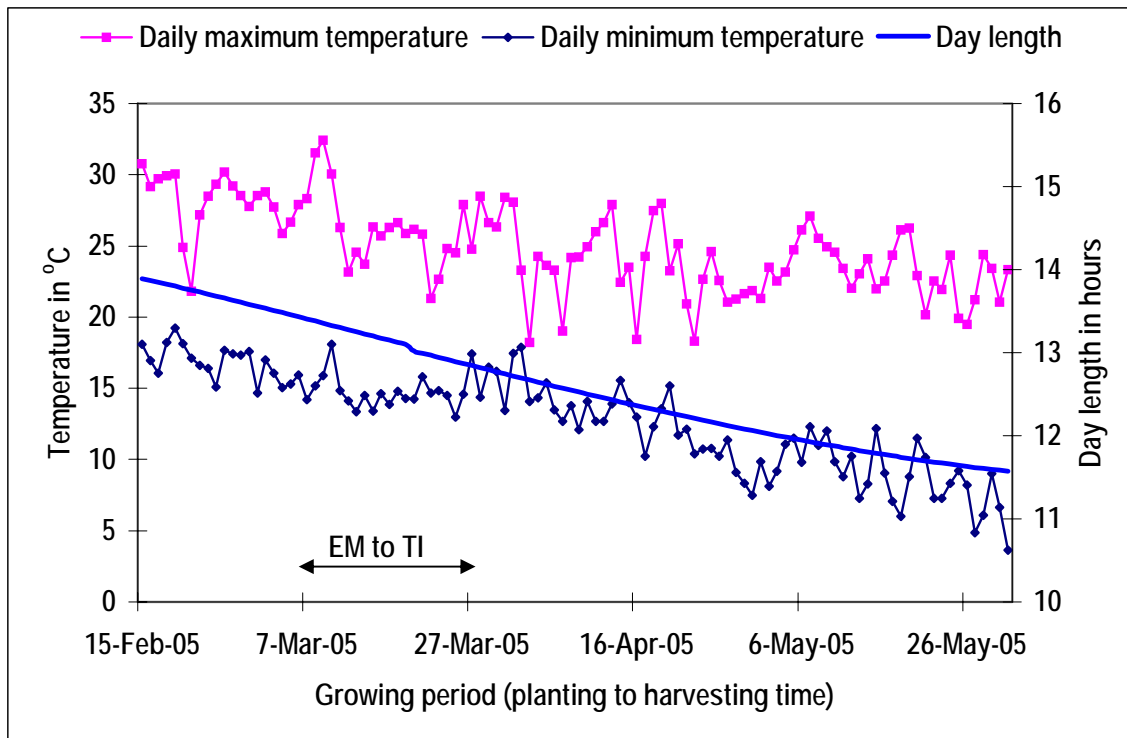


Figure 6.1b: Daily values of day length and daily minimum and maximum temperatures for the autumn 2005 season. EM stands for emergence time and TI stands for tuber initiation time

Initiation of tubers has been established to lead to a preferential partitioning of assimilates to the tubers (Ewing, 1992 and Kooman, 1995) and is regarded as a key developmental stage in the crop's life, having profound implications for subsequent growth and development (O'Brien *et al.*, 1998). In temperate climate with photoperiods ranging from 12 to 17 hours with similar temperatures and daily amounts of incident radiation during initiation, O'Brien *et al.* (1998) found no differences in interval between the time of plant emergence and onset of tuber initiation in three cultivars, namely, Desiree, Maris Piper and Estima. However, in tropical environment these varieties were reported by Demagante and Vander Zaag (1988b) to be sensitive to photoperiod ranging from 12 to 16 hours. O'Brien *et al.* (1998) attributed the variation in effects of photoperiod in both temperate and tropical environments to the differences in temperature between the two sites as the combinations of high temperatures and long photoperiods have been shown to be particularly inhibitory to tuber formation. This indicates that photoperiod effects on potato growth in sub-tropical regions could significantly alter the duration of tuber initiation, while it could be stable in temperate regions.



Table 6.1 shows a small variation of the duration between emergence and tuber initiation in different seasons. This small variation could be attributed to the fact that the potato growing season in South Africa (Pretoria) in spring 2004 and autumn 2005 experiences minimum and maximum temperatures which are acceptable for the growth of potato crops (Figures 6.1a and b). More importantly, in Pretoria, emergence and tuberisation take place under relatively cool temperatures (Figures 6.1a and b). In spring, planting time is organised towards the end of August or early in September when temperatures are cool (Figure 6.1a). In autumn planting, relative high temperatures are expected early in the planting time but decrease with the growing season so that the phase between emergence and tuber initiation coincides with cool temperatures favourable for potato growth (Figure 6.1b). Consequently, potato grown in this period may escape the early autumn and late spring high temperatures. However, autumn planting experiences short day lengths towards tuber initiation, which may hasten the time of tuber initiation before the plant canopy can attain maximum size. As a result, most assimilates are partitioned to the storage organs (tubers) causing either a reduction in the growth rate or cessation in growth of foliage and roots (O'Brien *et al.* 1998 and Kooman *et al.*, 1996). Kooman *et al.* (1996) found that in climates with short days, the duration of the period between full emergence and tuber initiation was reduced, whereas climates with long days, tuber initiation was delayed and leaf growth was prolonged as a result.

### **6.3.2. Estimation of photothermal time for tuber initiation**

Thermal time required to reach tuber initiation was computed using seven methods. The results from these methods were compared for five data sets and are presented in Table 6.2 and in Figures 6.2 to 6.9. Cumulative thermal time from emergence to tuber initiation computed with the SWB method corrected by a relative day length factor (RDLFTI) among data sets ranged from 344 to 376 day degrees, with a coefficient of variation of 3.8%. Cumulative thermal time for tuber initiation varied widely in all methods, which were corrected by both a relative day length factor and a relative temperature factor (Table 6.2 and Figures 6.4 and 6.7.). In these methods, when the relative temperature factor was introduced in the calculation, cumulative thermal time among data sets varied widely. For the SWB method corrected by relative day length factor (RDLFTI) and relative temperature factor (RTFTI), cumulative thermal time for tuber initiation ranged from 252 to 376 day degrees, with a coefficient of variation of 14.7%. For the weighted mean temperature method

corrected by relative day length factor (RDLFTI) and relative temperature factor (RTFTI) as well, cumulative thermal time for initiation ranged from 220 to 356 day degrees, with a coefficient of variation of 16.7%.

The SWB method corrected by relative day length factor used to compute thermal time for tuber initiation in different data sets has the smallest standard deviation and coefficient of variation values. The results from this method suggest that the time of onset of tuber initiation can be estimated from thermal time with an accuracy of  $\pm 1$  day and a threshold value of thermal time required for onset of tuber initiation in both spring and autumn was found to be 352 degree days. This strongly suggests that SWB method corrected by the relative day length factor is the appropriate method for computing thermal time from emergence to tuber initiation. The fact that thermal time requirements in both spring and autumn for the entire data set get close (Figure 8.3) when SWB method corrected by the relative day length factor is used, substantiates the need of improving SWB model, which fails to simulate potato tuber induction.

Squire (1995) suggested that the literature provides evidence about the linear relationship between temperature and development rate for stages of sprouting and leaf initiation of potato. Thus, the main justification for usage of thermal time that is common in models of development and leaf expansion of potato. However, Squire (1995) pointed out that there is little evidence that the rate of expansion of the canopy has a linear relationship with temperature. Similarly, Squire (1995) suggested that there is much less justification for relating the time of tuber initiation to thermal time.

The ability of this method (SWB corrected by day length factor) to estimate thermal for potato grown at different sites, and under different regimes of temperature and day length (spring and autumn), implies that the method must be capturing the physiological characteristic of the crop. If the day length factor could be integrated into SWB, it appears that the model will better simulate potato development and one set of crop parameters for spring and autumn planting would be possible. The poor simulation results of total dry matter and harvestable dry matter early in the growing season (Figure 5.2a) suggest that the model should be improved by allowing it to simulate the start of tuber initiation. Kooman (1995) highlighted that a later commencement of tuber growth leads to an extension of crop growth. He explained the cause of this as a result of a combination of prolonged leaf growth and

slower leaf senescence, which explains a considerable part of the variation in yield. In SWB, dry matter partitioning is mechanistically simulated. It uses a partitioning parameter as an input to control the fraction of dry matter partitioned to different plant organs (leaf and stem). If data that are used to determine the leaf stem partitioning factor are accurate, then SWB will correctly simulate dry matter allocated to different plants organs. In this study, the model gives a perfect match between measured and simulated values of total dry matter and harvestable dry matter at the beginning of the growing season (Figures 5.2a and b and 5.3a), but towards the end of the exponential tuber bulking stage (50 - 65 DAP) simulation results start deteriorating and cause the final yield not to be accurately simulated. Regel and Sands (1983) found that the dependence of yield on day length was explained by the effect of day length on the time at which tuber growth commences rather than on tuber development and on yield or tuber bulking rate as suggested by the literature. Based on the results by Kooman *et al.* (1996), potential and actual tuber dry matter production of potato is mainly determined by the length of the growth period. High average temperature during the growing season and short day lengths at emergence shorten the duration of potato growth. It was also suggested that day length plays a major role in the partitioning of assimilates and evidently, it affects tuber growth as well as tuber initiation (Kooman and Haverkort, 1995; Wheeler and Tibbitts, 1997).

Table 6.2: Thermal time required from emergence to tuber initiation, estimated using different methods<sup>1</sup>, namely, SWB, SWB\*RDLFTI, SWB\*RDLFTI\*RTFTI, TEMPM, TEMPM\*RDLFTI, TEMPM\*RDLFTI\*RTFTI, and SUBSTOR for BP1 cultivar grown during autumn and spring seasons

| Season | Year | SWB  | SWB*RDLFTI | SWB*RDLFTI*RTFTI | TEMPM | TEMPM*RDLFTI | TEMPM*RDLFTI*RTFTI | SUBSTOR |
|--------|------|------|------------|------------------|-------|--------------|--------------------|---------|
| Autumn | 2005 | 355  | 345        | 331              | 338   | 328          | 314                | 17      |
|        | 2000 | 399  | 376        | 376              | 378   | 356          | 356                | 16      |
|        | 1999 | 381  | 348        | 347              | 349   | 319          | 318                | 15      |
| Spring | 2004 | 362  | 344        | 301              | 338   | 321          | 296                | 15      |
|        | 2000 | 425  | 348        | 252              | 371   | 304          | 220                | 16      |
| Mean   |      | 384  | 352        | 321              | 355   | 326          | 301                | 15.8    |
| SD     |      | 28.5 | 13.4       | 47.3             | 18.7  | 19.1         | 50.7               | 0.8     |
| CV     |      | 7.4  | 3.8        | 14.7             | 5.3   | 5.9          | 16.7               | 5.2     |

SD = Standard deviation.

CV = Coefficient of variation.

<sup>1</sup>See Materials and method section for equations and symbols employed to compute thermal time.

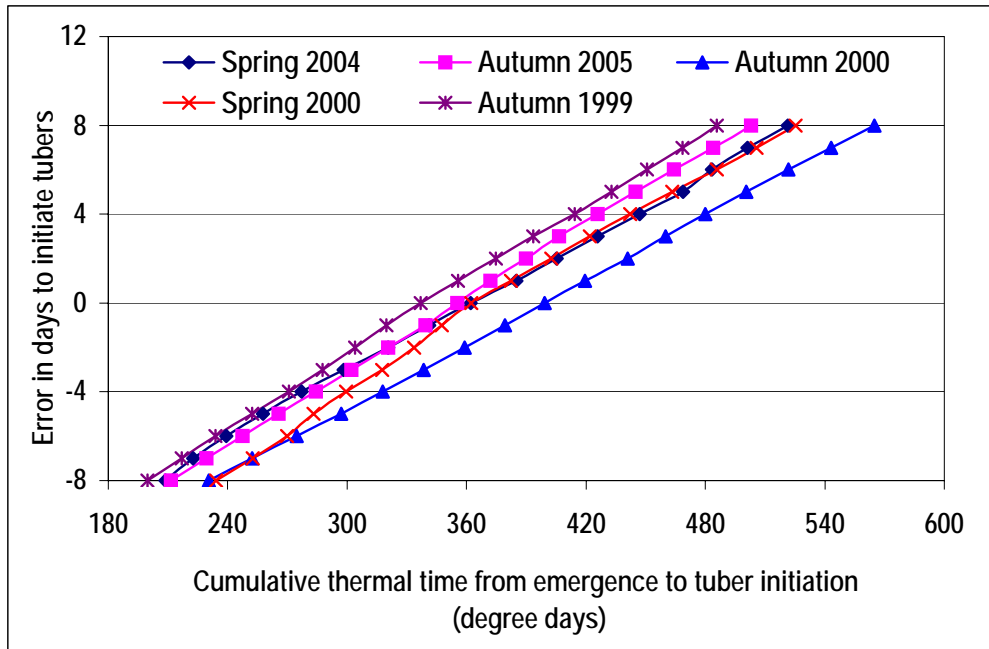


Figure 6.2: Cumulative thermal time for tuber initiation computed from emergence using the SWB method for five data sets of potato grown in both spring and autumn seasons

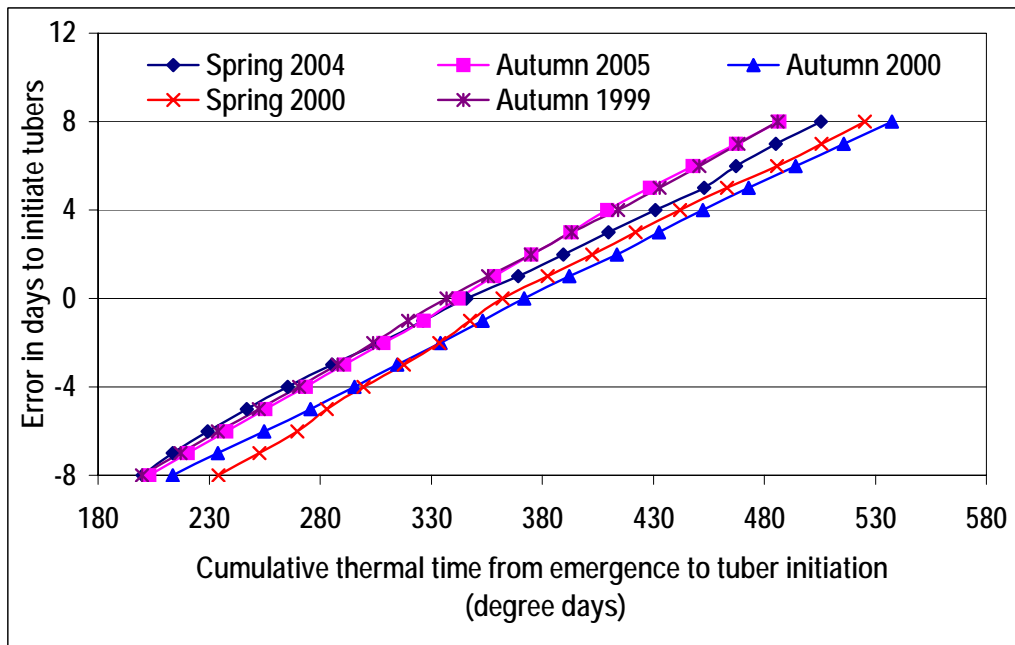


Figure 6.3: Cumulative thermal time for tuber initiation computed from emergence using SWB method corrected by relative day length factor for five data sets of potato grown in both spring and autumn seasons

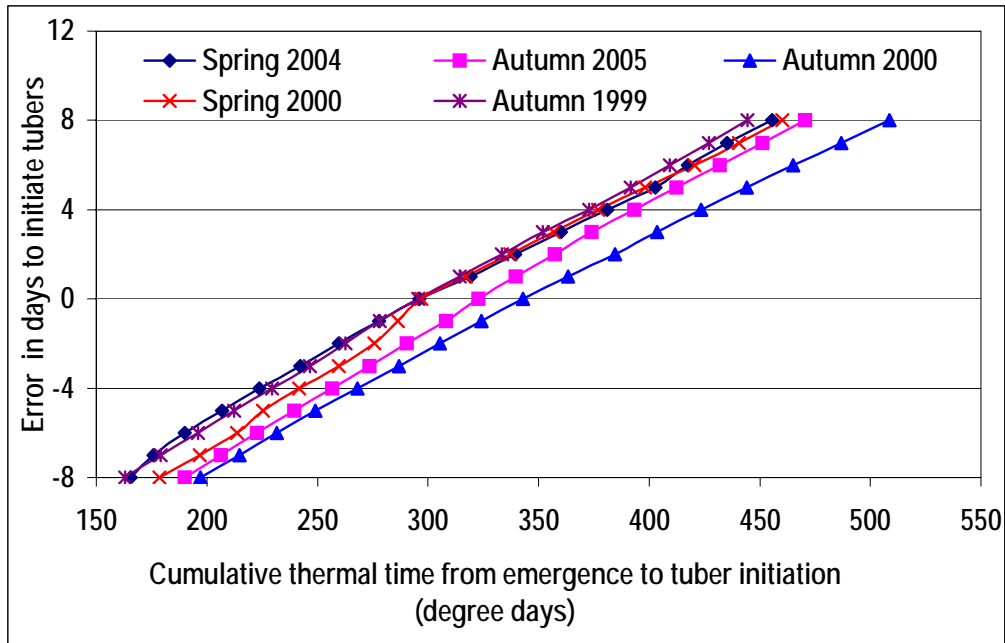


Figure 6.4: Cumulative thermal time for tuber initiation computed from emergence using SWB method corrected by relative day length factor and relative temperature factor for five data sets of potato grown in both spring and autumn seasons

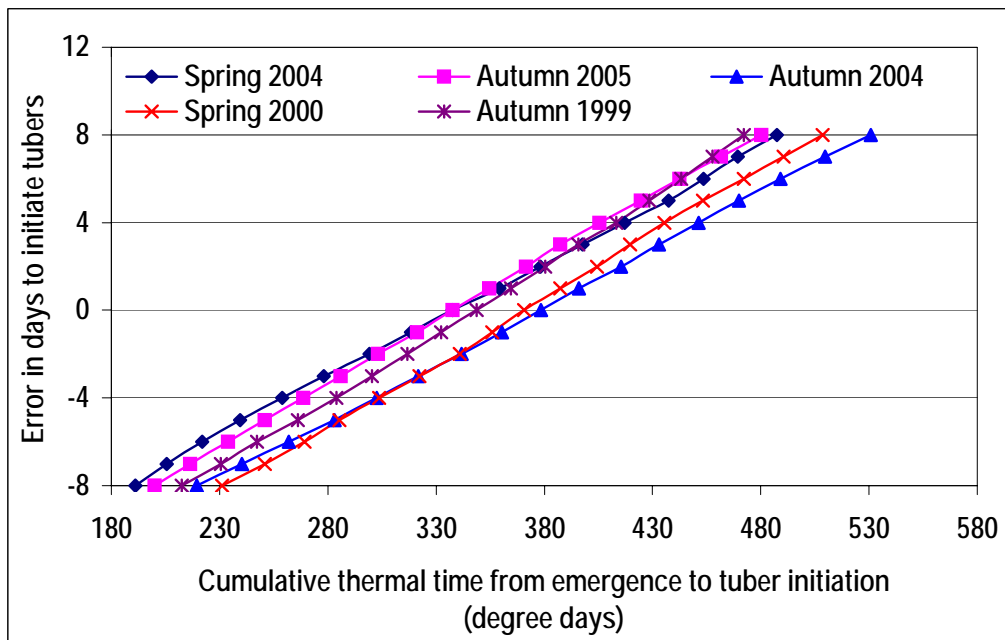


Figure 6.5: Cumulative thermal time for tuber initiation computed from emergence using weighted mean temperature (TEMPM) method for five data sets of potato grown in both spring and autumn seasons

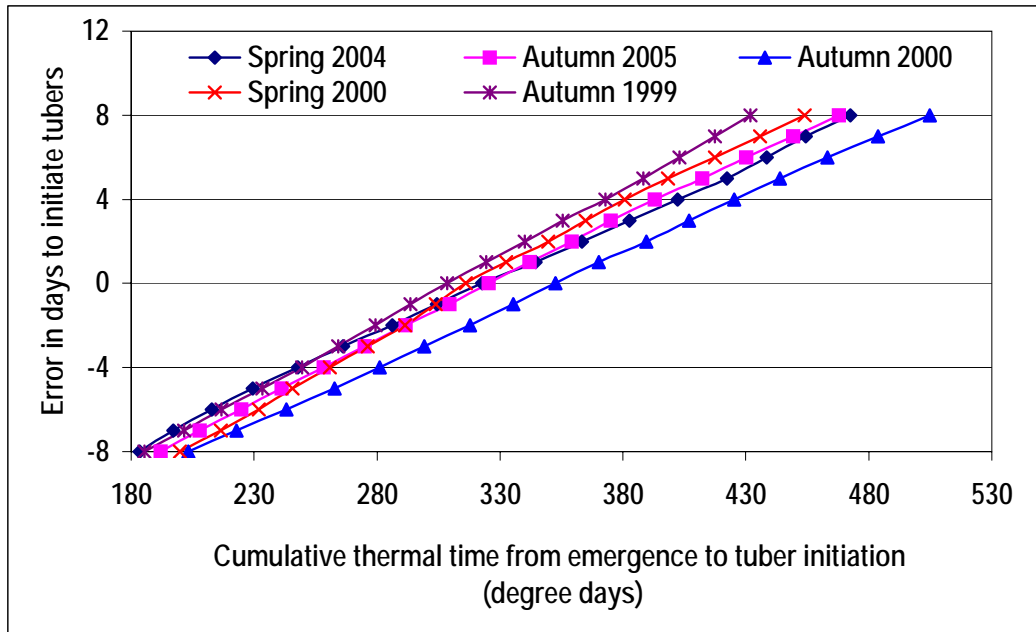


Figure 6.6: Cumulative thermal time for tuber initiation computed from emergence using weighted mean temperature (TEMPM) method corrected by relative day length factor for five data sets of potato grown in both spring and autumn seasons

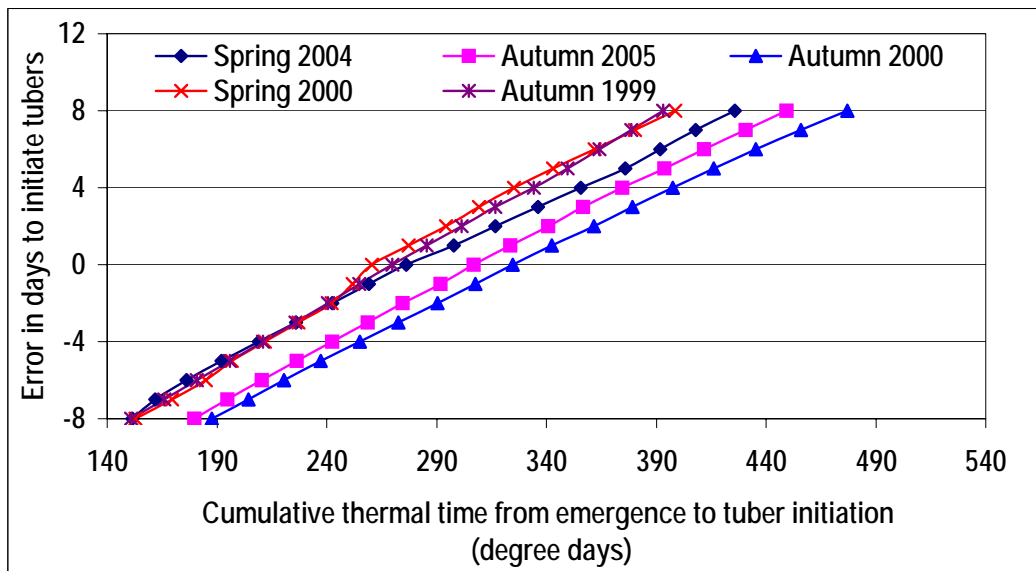


Figure 6.7: Cumulative thermal time for tuber initiation computed from emergence using weighted mean temperature (TEMPM) method corrected by relative day length factor and relative temperature factor for five data sets of potato grown in both spring and autumn seasons

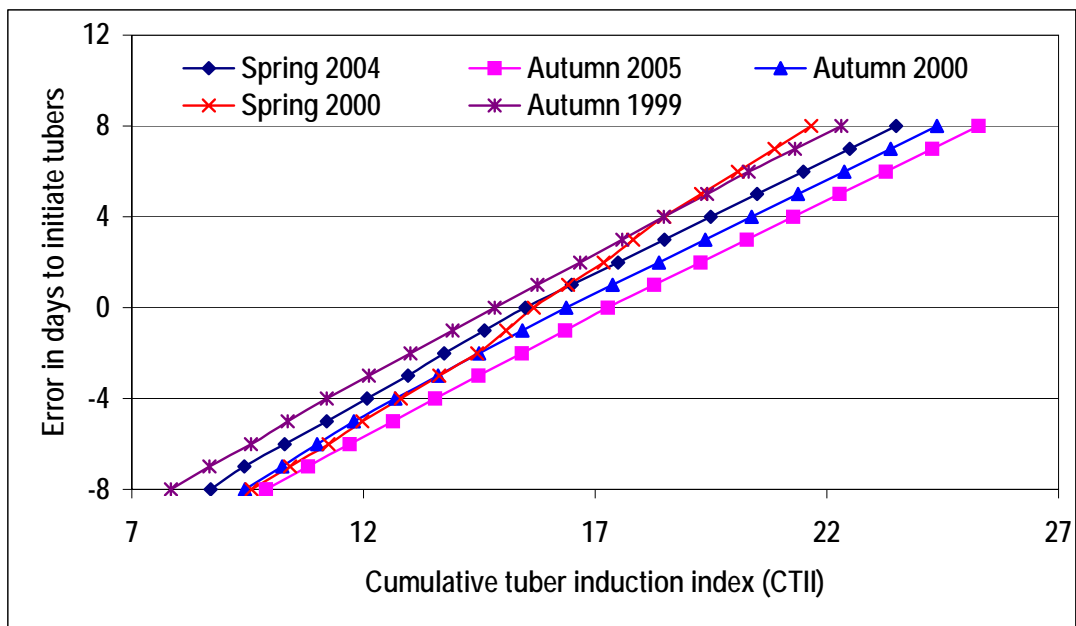


Figure 6.8: Cumulative thermal time for tuber initiation computed from emergence using SUBSTOR method for five data sets of potato grown in both spring and autumn seasons



## CHAPTER 7

### CONCLUSIONS AND RECOMMENDATIONS

#### 7.1. Conclusions

To determine and quantify the effect of water stress on potato growth and development under a subtropical climate, two experiments (spring and autumn seasons) were carried out. The results from these experiments show that water stress imposed at tuber initiation until the end of tuber bulking is the most detrimental to biomass and tuber production. This suggests that water stress at tuber initiation should be avoided if high tuber yield is the target.

The treatment fully irrigated throughout the growing season (NNN) gave the highest tuber yields, irrespective of planting season. In all treatments, marketable tuber yield was higher in autumn than spring. Specific gravity of tubers varied with season of planting (spring and autumn) and autumn had higher values.

The water use efficiency varied with irrigation treatments and planting time. The autumn experiment had generally higher values than for spring. However, water use efficiency values of unstressed treatments corrected for vapour pressure deficit (VPD) in both spring and autumn seasons were comparable ( $42 \text{ kg ha}^{-1} \text{ mm}^{-1} \text{ Pa}^{-1}$  for spring and  $46 \text{ kg ha}^{-1} \text{ mm}^{-1} \text{ Pa}^{-1}$  for autumn). In autumn planting, the trends of the water use efficiency showed that water stressed treatments had higher values than the unstressed treatment. This implies that in autumn seasons good tuber yield can still be achieved if water stress is well managed.

The calibration of the model showed an excellent agreement between observed and predicted leaf area index (LAI) and fractional interception (FI) for both autumn and spring experiments. Simulation results of total and tuber dry matter for both autumn and spring under predicted observed data, especially during tuber bulking in the season. SWB estimated soil water deficit fairly well throughout the season for both spring and autumn experiments.

The model evaluation was carried out using independent data sets from spring and autumn seasons (spring and autumn 2000). Total dry matter and tuber dry matter simulations were

close to the measured throughout the growing season. The model satisfactorily simulated leaf area index and fractional interception.

With regard to thermal time required for tuber initiation, the SWB method corrected by a relative day length factor appeared to better estimate thermal time for tuber initiation in all the data sets. The results of this method show that cumulative thermal time required for tuber initiation in all the data sets ranged from 344 to 376-degree days with a coefficient of variation of 3.8%. This strongly suggests that the SWB method corrected by the relative day length factor is an appropriate method for computing thermal time from emergence to tuber initiation. The coefficient of variation and standard deviation for this method are smaller than the coefficient of variation and standard deviation of the other methods. SWB method corrected by relative day length factor suggests that the time of tuber initiation can be estimated from its thermal time within two days.

The photothermal time at which tuber initiation commences appeared not to be affected by planting season since variation of the duration between emergence and tuber initiation in different seasons was small. This small variation could be attributed to the fact that the potato growing season in South Africa (Pretoria) in spring 2004 and autumn 2005 experiences minimum and maximum temperatures which are acceptable for the growth of potato. In Pretoria, emergence and tuberisation take place under relatively cool temperatures late in September and also early in April when temperatures are relatively cool. Consequently, potato grown in this period may escape the early autumn and late spring high temperatures. However, autumn planting experiences an abrupt change of day lengths from long days to short days towards tuber initiation. This rapid change of day length may change the crop physiology and affect the subsequent normal course of plant growth.

## **7.2. Recommendations**

This study showed that the most sensitive stage of potato crop to water stress is tuber initiation to tuber bulking. Therefore, any kind of water stress should be strictly avoided at tuber initiation and bulking stages. Apart from the treatment that water stressed from tuber initiation until the end of tuber bulking (NSN), water use efficiency was found to improve with water stress in the autumn season. However, water use efficiency for spring planting

showed a large variation between treatments. As spring results on water use efficiency are not conclusive, more studies should be conducted to further investigate water use efficiency.

Given the results from this study, there are indications that the SWB model would improve the simulation results of total dry matter, tuber dry matter and soil water deficits if a photoperiod factor is taken into account. The method that correctly estimates photothermal time required for tuber initiation at any time of planting suggested by this study should serve as basis for the future modification of the model. The fact that the model is in excellent agreement with measured values of total and harvestable dry matter at the beginning of tuber initiation and this deteriorates later at the end of the growing season, is an indication that the model fails to simulate the size of the canopy and its duration. Modification of the model by integrating photoperiod factor as an additional modifier of tuber induction would improve the model simulation results.

This study covered only a limited range of environments and compared a limited number of data sets from one location. Therefore, variation in duration of the period between emergence and tuber initiation could not be assessed for a wide range of planting dates. In South Africa, planting time varies with regions. In some regions, potato is planted when temperatures are low and day lengths are short, while in other regions the crop is planted when temperatures are high and day lengths long. Consequently, a study comparing a wide range of environments should be conducted to further verify the effect of day length on the time of tuber initiation. The effect of day length on the time of tuber initiation in subtropical climates was found to be more important than in temperate climates because of the combination of day lengths and high temperatures that prevail in subtropical climates. In addition, to correctly determine the onset of tuber initiation, sampling should be carried out every two to three days from the date of full emergence. This will allow accurate determination of the actual time of tuber initiation commencement.

## SUMMARY

A study was initiated to examine the relations between potato growth and water use for improved irrigation management by means of a mechanistic soil water balance model, calibrate and evaluate the model for potato under full irrigation and deficit irrigation conditions and ultimately provide valuable insight into photoperiod and its effect on potato growth and development.

To accomplish the above objectives, data from experiments carried out both in spring and autumn under different water regimes were collected to re-parameterise and re-calibrate the model. The model was then validated against 2000 spring and autumn data on phenological dates, tuber dry mass, total dry mass, LAI and FI. Root mean square error (RMSE), mean of the measured values (MAE) and coefficient of determination ( $r^2$ ) were used to analyse the degree of confidence between simulated and observed values.

Results obtained from irrigation treatments based on water stress imposed at vegetative stage (SNN), tuber initiation and tuber bulking stages (NSN), maturity stage (NNS) and from an unstressed treatment (NNN), showed that the potato crop is very sensitive to water stress. Water deficit imposed from tuber initiation to tuber bulking stage appeared to cause a more dramatic response in terms of LAI, TDM and HDM. In general, water stress, which was varied in both timing and duration, influenced soil water status resulting in different levels of water stress among treatments. Contrary to the autumn planting experiment, LAI and TDM in SNN for spring planting attained values equivalent to that of unstressed treatment (NNN). For the spring planting top growth of SNN was vigorously stimulated after irrigation was resumed and attained a high above ground biomass, but this did not influence its final tuber yield. Top growth was suggested to be stimulated vigorously if plants are re-watered after a period of drought and high temperatures (Van Loon, 1981). This could therefore prolong the duration of leaf for such a crop, compared to crops without second growth.

The treatment fully irrigated throughout the growing season (NNN) gave the highest yields, irrespective of planting season. Among the treatments, water stress imposed at tuber initiation and tuber bulking stages (NSN) produced the lowest tuber yields, followed by the treatment stressed during the vegetative stage (SNN).

Distribution of tuber sizes varied among treatments, with a high increase in total and marketable ( $\geq 50$  g) tuber yield obtained in NNN and NNS treatments. In all treatments, marketable tuber yield was higher in autumn than in spring. The smallest tuber sizes were observed in SNN and NSN. SNN had 62% of tuber yield classified as small and babies in the spring planting and 52% in autumn. In both years, the treatment most affected by water stress on tuber size distribution was NSN, with 69% of the total yield classified as small and babies' in spring and 67% in autumn.

Specific gravity of tubers varied with of planting (spring and autumn), with autumn showing higher values and variation between treatments. Specific gravity of tubers was not affected by water treatments in spring. In autumn planting specific gravity of tubers was high in NSN and NNS.

Chip colour results were not affected by irrigation treatments in the autumn planting experiment. However, in the spring planting there were highly significant differences between treatments, except for NNN and NNS that were not statistically different.

The water use efficiency varied with irrigation treatments and planting time. Autumn experiment had generally higher values than spring.

Plant water availability rarely fell below 50% of the total plant available water content in the top layers (200 and 400 mm) in unstressed treatment (NNN). However, at 600 mm soil depth, except small variations, which were observed, soil water content was always above 50% of the total plant available water content. In the water stressed treatments, soil water content decreased when irrigation was withheld. In both years, soil water content was almost depleted to wilting point in the top layers in all water stressed treatments, but remarkable soil water content reduction was recorded for NSN in the top layer (200 mm). After resumption of irrigation in both SNN and NSN treatments, soil water content rose above 50% of the total plant available water content, especially in the top layers (200 and 400 mm). These results give valuable insight into how plant availability was affected by irrigation treatments. In SNN and NSN, there was a noticeable decrease in the water content of the soil. However, for these two treatments, soil water content showed a progressive increase during the final part of the growing season. This trend was also noticeable in NNN, which is an indication of a lower water requirement of the crop during tuber maturation or plant senescence.

SWB calibration showed an excellent agreement between observed and predicted leaf area index (LAI) and fraction interception (FI) for both autumn and spring experiments. However, the simulation results of total and tuber dry matter for both autumn and spring under predicted observed data, especially during tuber bulking. Regarding soil water deficit, the model fairly estimated it throughout the season for both spring and autumn experiments. The model evaluation was carried out, using independent data sets of the spring 2000 and autumn seasons. Total dry matter mass and tuber dry matter mass simulations were close to the measured values throughout the growing season.

The estimation of tuber initiation onset was carried out for five data sets and the results showed that the time of tuber initiation varied with planting season. In spring planting, the time between emergence and tuber initiation was the longest and varied with planting year. Autumn planting time in most cases has a shorter period between emergence and tuber initiation than spring plantings, although temperatures and day lengths corresponding to that period were higher in autumn than in spring planting. This implies that factors other than photoperiod and temperature influenced the onset of tuber induction in these experiments.

Thermal time required to reach tuber initiation stage was computed using seven methods. Cumulative thermal time computed with the SWB method corrected for relative day length factor (RDLFTI) indicated that 344 and 376-degree days are required for the onset of tuber initiation. The SWB method corrected by relative day length factor used to compute thermal time for tuber initiation in different data sets had the smallest standard deviation (13.4) and coefficient of variation (3.8 %) values. This strongly suggests that the SWB method corrected by the relative day length factor is the appropriate method for computing thermal time from emergence to tuber initiation.

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## Appendix A

### Calibration results of water stressed treatments during autumn 2005

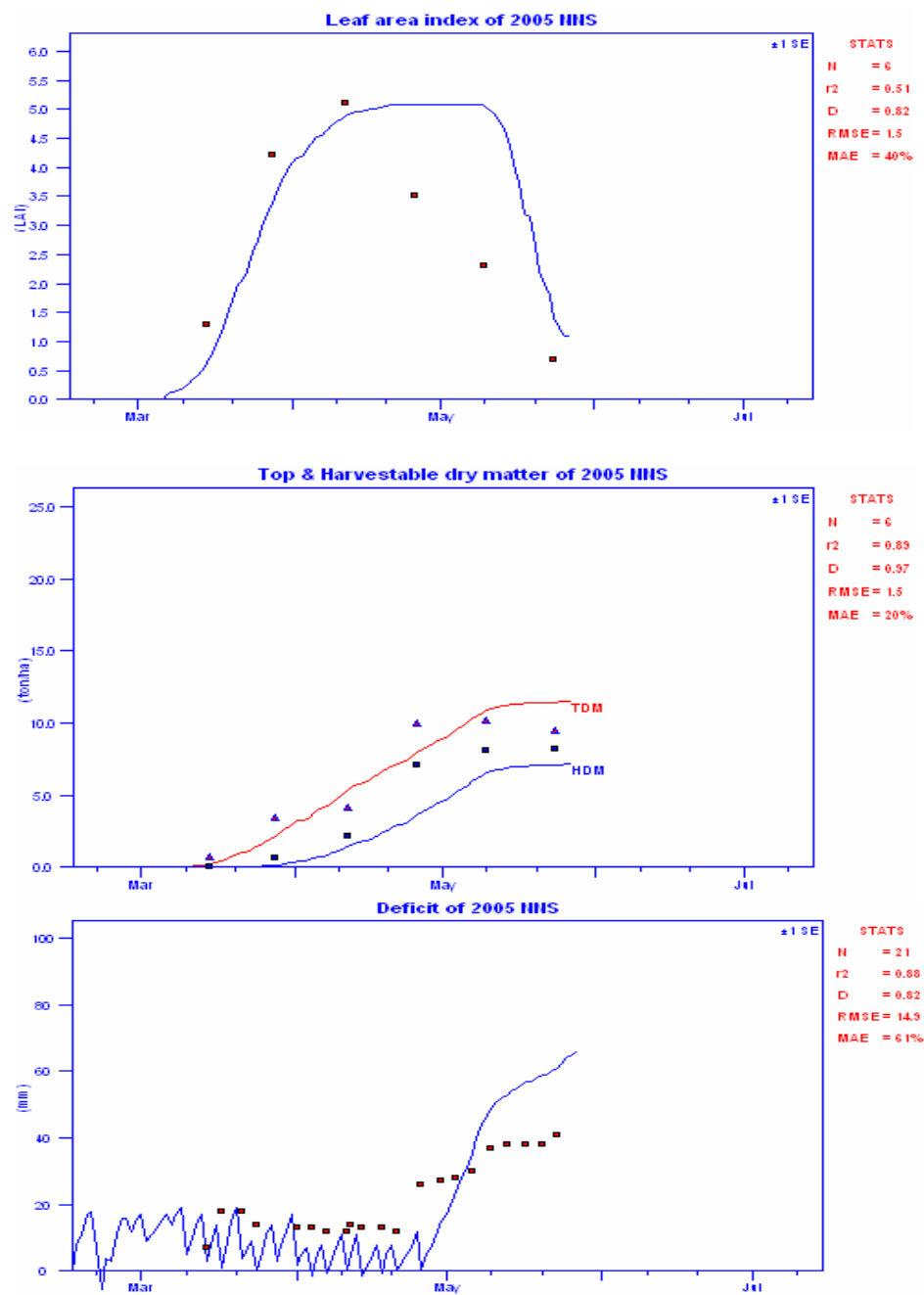


Figure A.1a: Calibration results of LAI, TDM, HDM and water deficit during spring 2005 season (NNS). Simulated (line) and observed values (points)

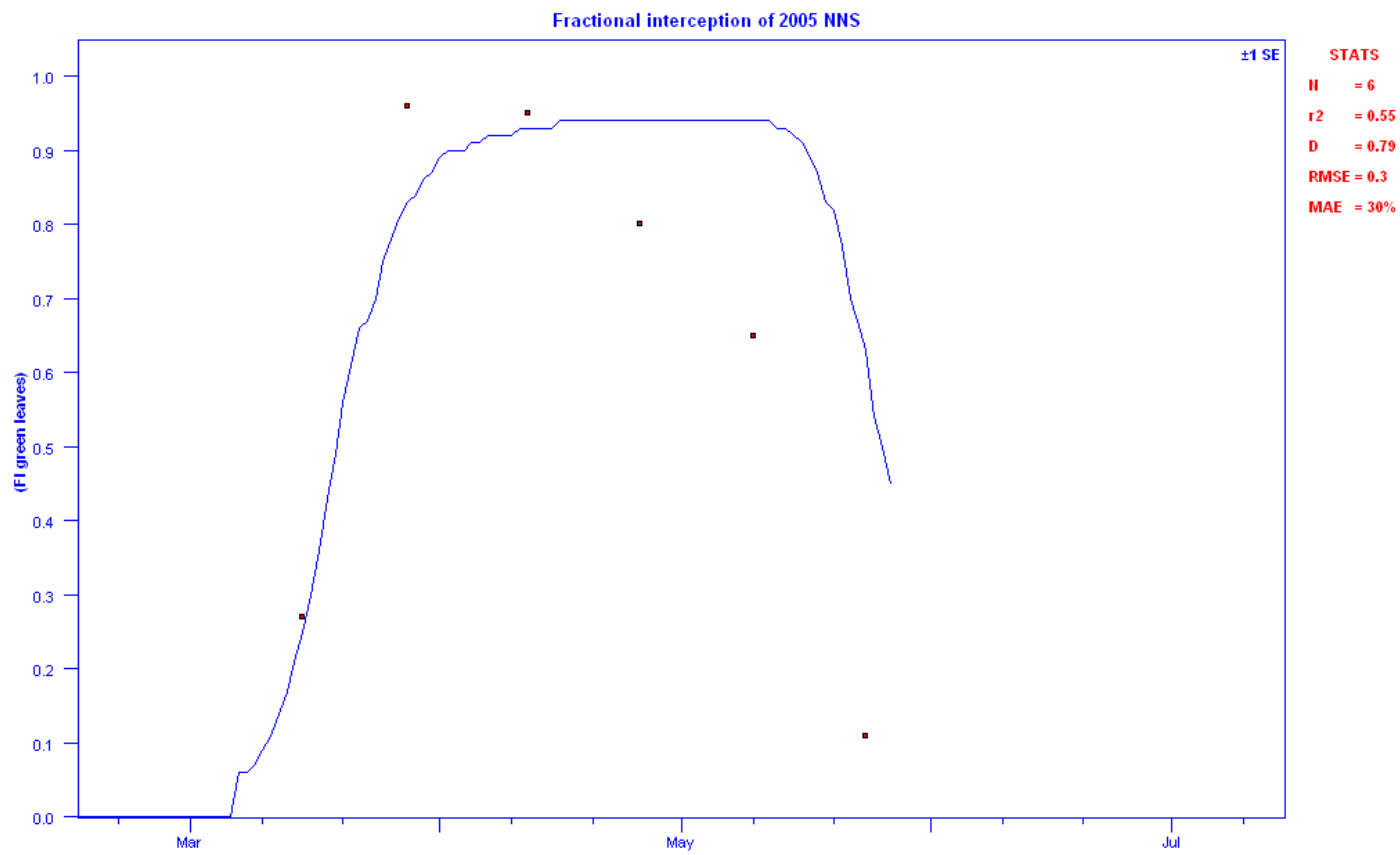


Figure A.1b: Calibration results of FI during 2005 autumn planting (NNS). Simulated (lines) and observed values (points)

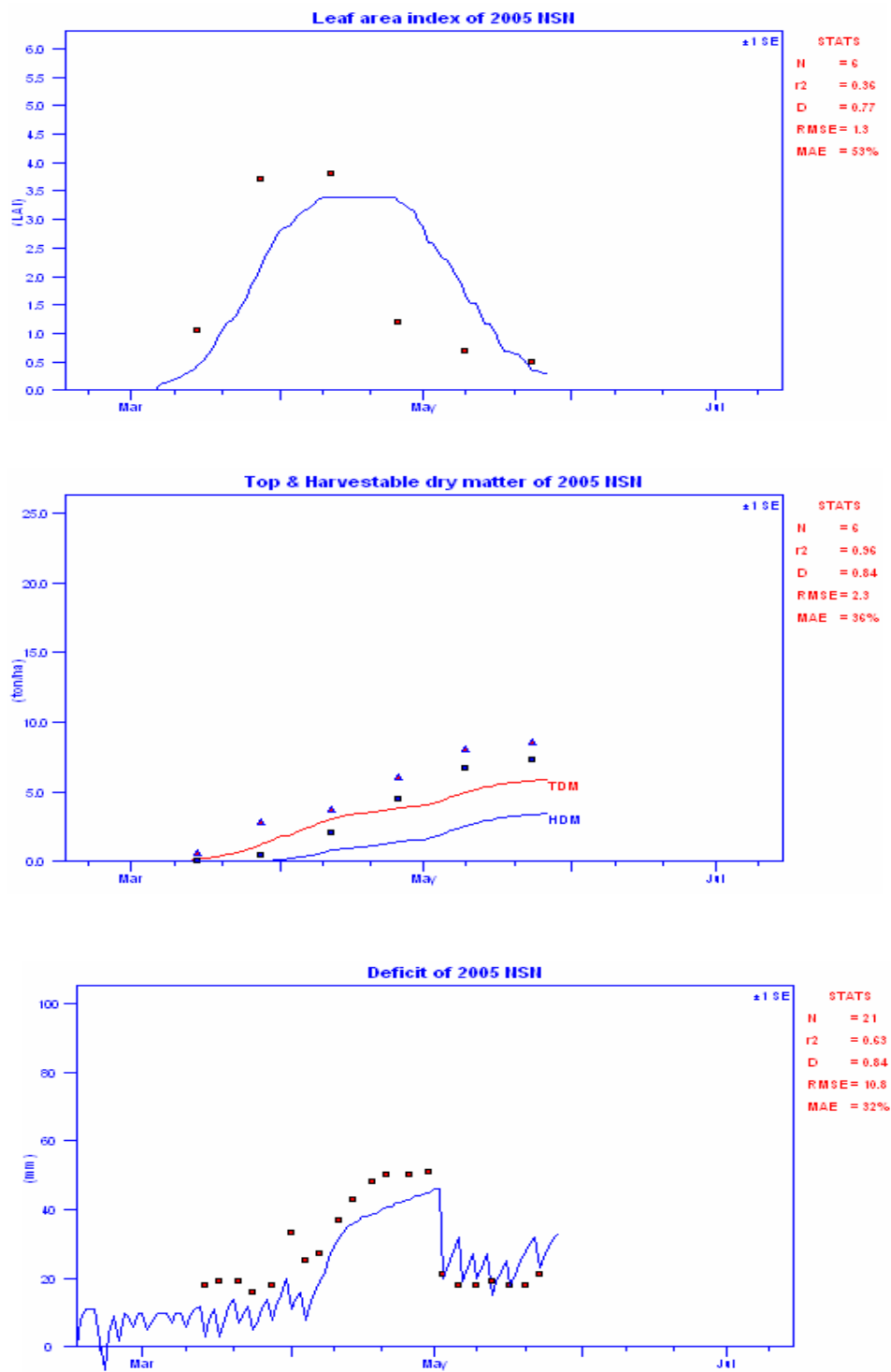


Figure A.2a: Calibration results of LAI, TDM, HDM and water deficit during spring 2005 season (NSN). Simulated (line) and observed values (points)

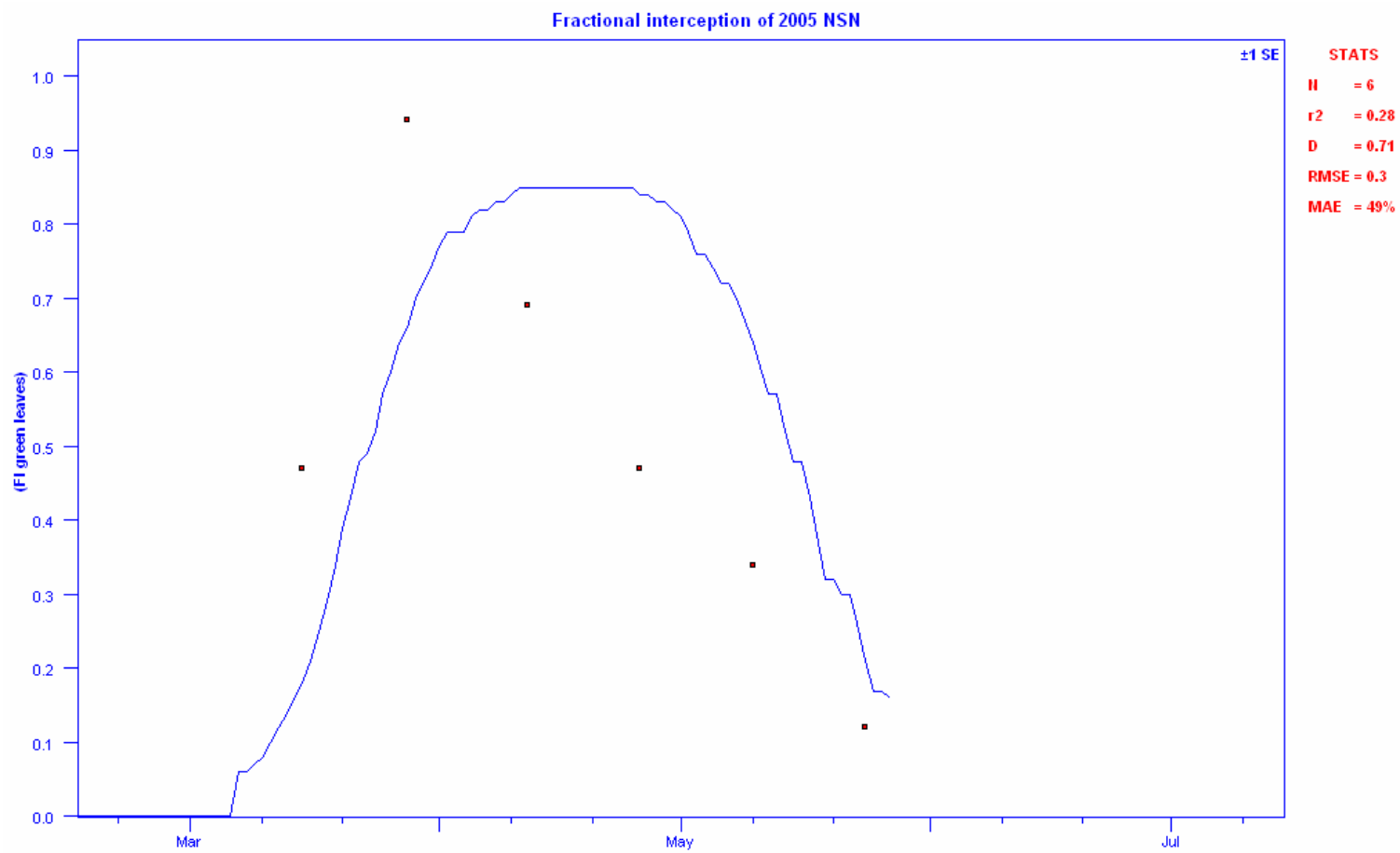


Figure A.2b: Calibration results of FI during 2005 autumn planting (NSN). Simulated (lines) and observed values (points)

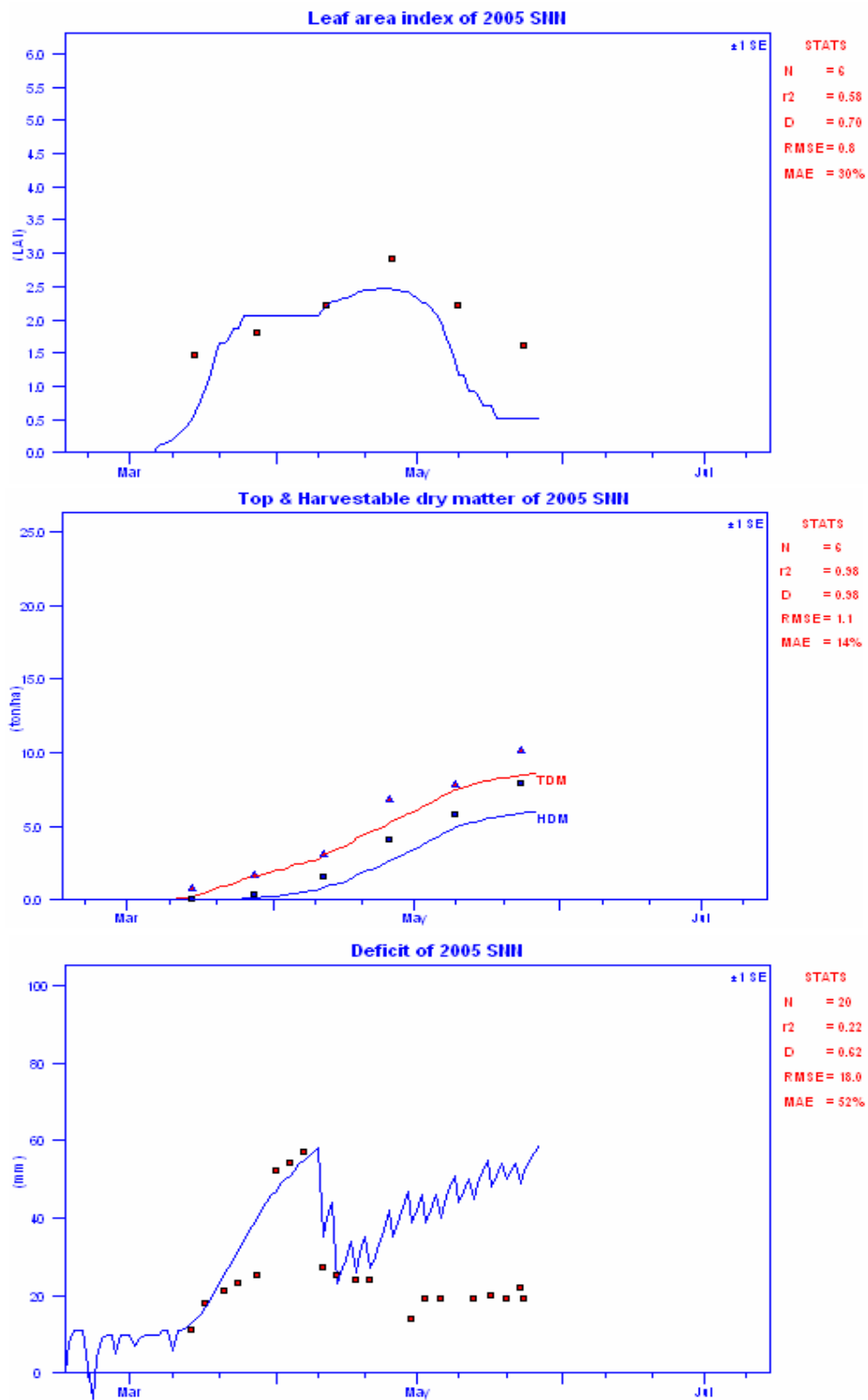


Figure A.3a: Calibration results of LAI, TDM and HDM for SNN treatment during spring 2005. Simulated (line) and observed (point)

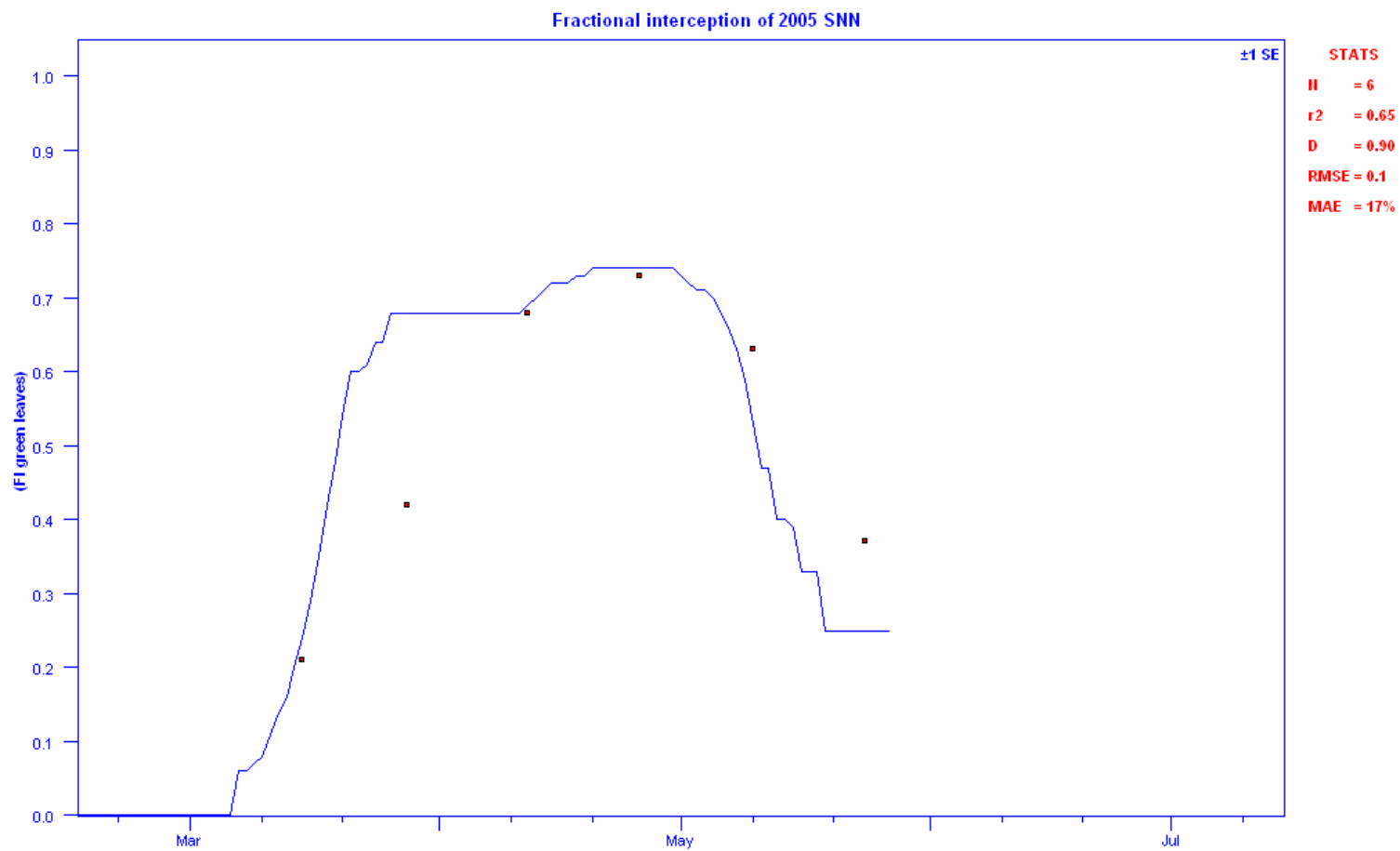


Figure A.3b: Calibration results of FI for 2005 autumn planting (SNN). Simulated (lines) and observed values (points)

## APPENDIX B

### Validation results of independent data from spring 2004 and autumn 2005

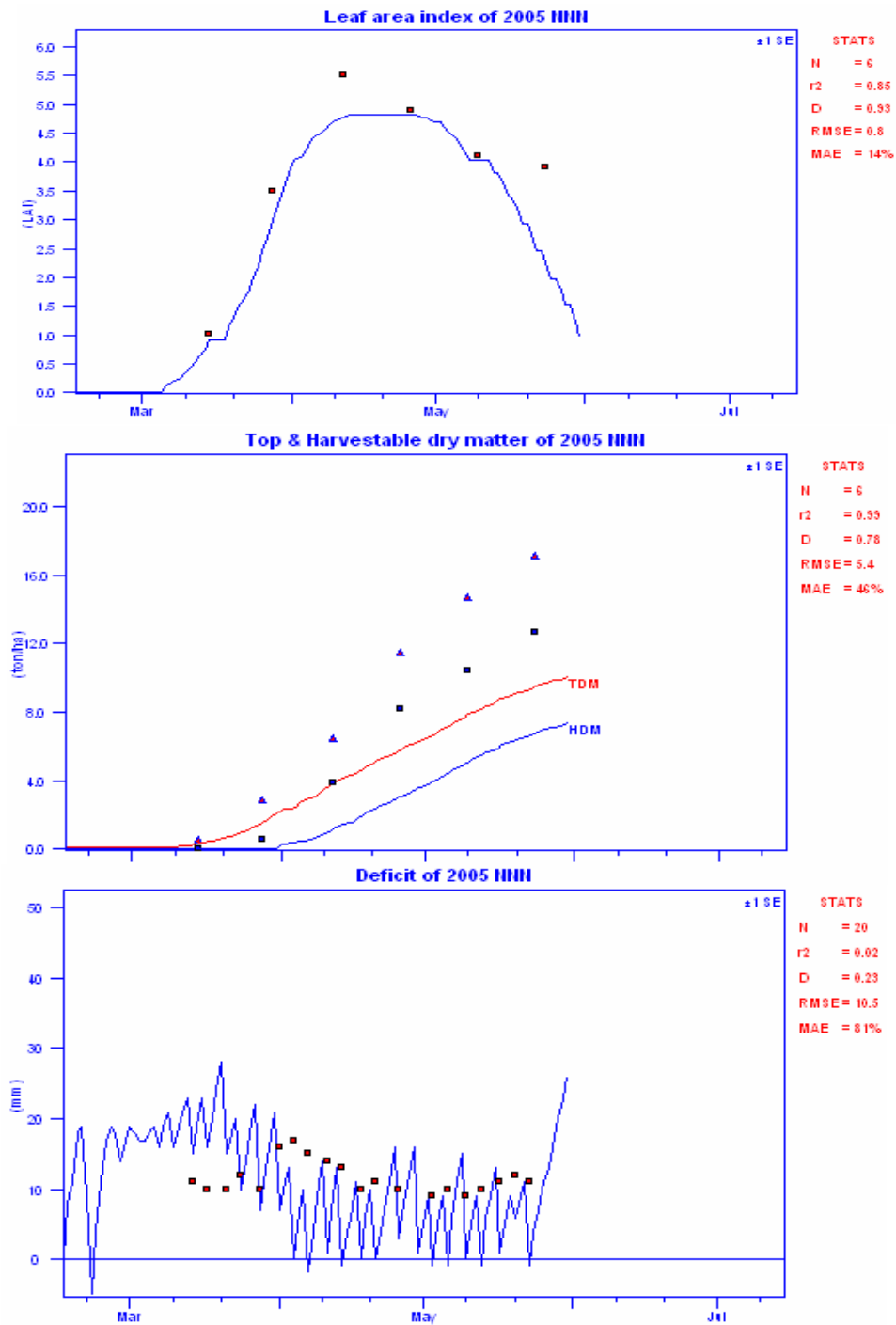


Figure B.1a: Simulation results of LAI, TDM, HDM and soil water deficit obtained using independent data from autumn 2005. Simulated (line) and observed (point)



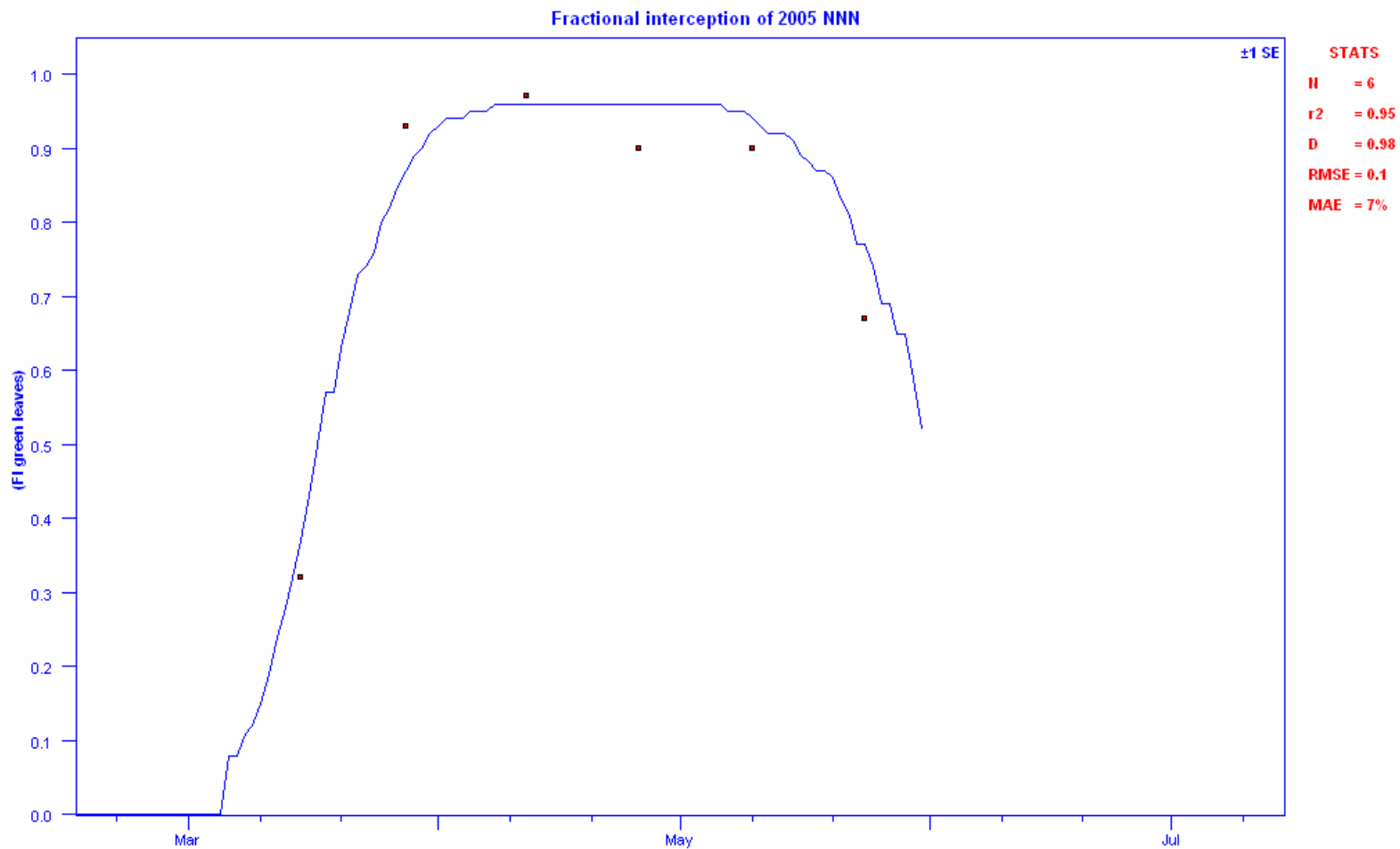


Figure B.1b: Simulation results of FI obtained using independent data from autumn 2005. Simulated (line) and observed (point)

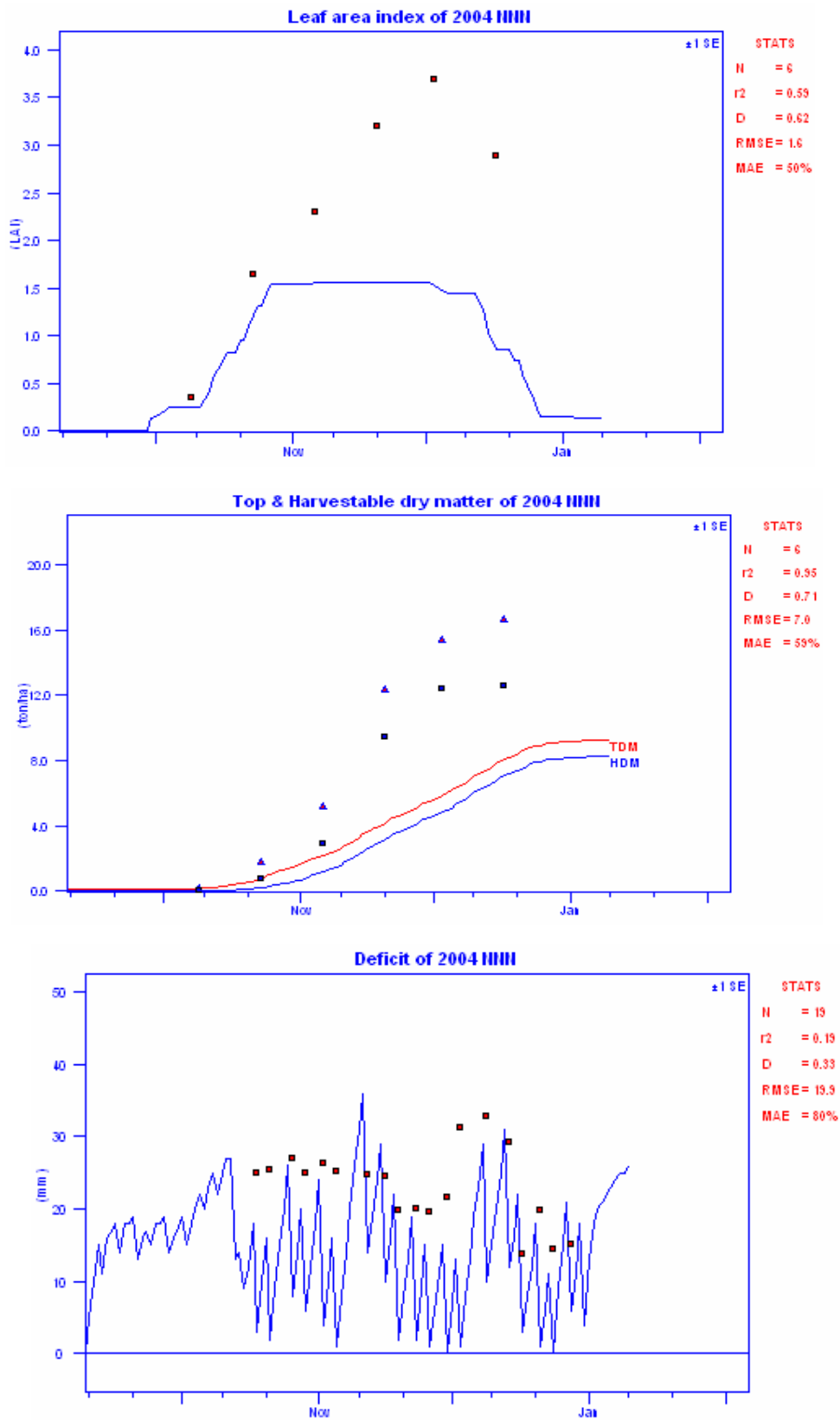


Figure B.2a: Simulation results of LAI, TDM, HDM and soil water deficit obtained using independent data from autumn 2004. Simulated (line) and observed (point)

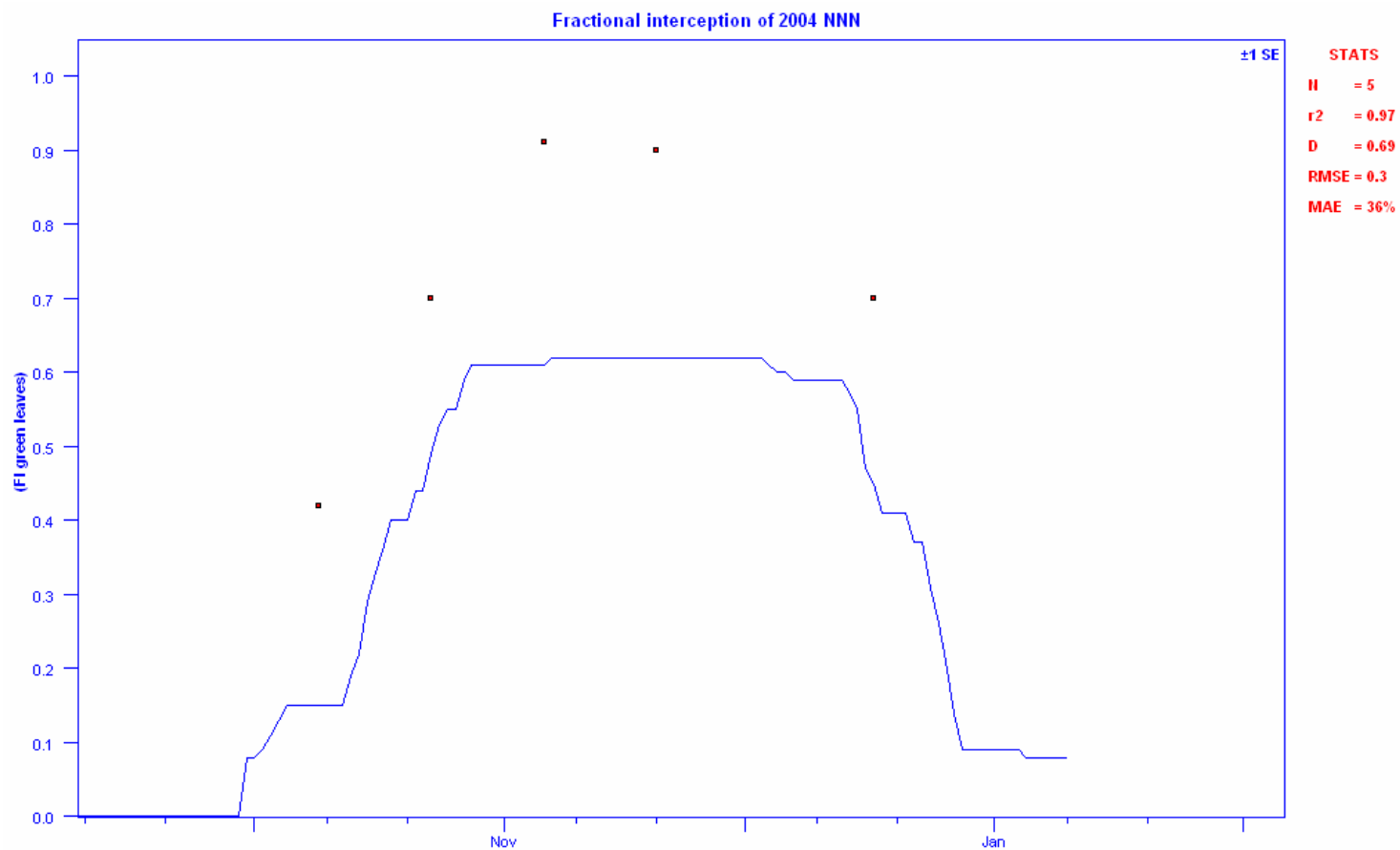


Figure B.2b: Simulation results of FI obtained using independent data from autumn 2004. Simulated (line) and observed (point)