Forecasting yields of processing potatoes in different South African environments using the LINTUL model

by

Allan Tatenda Batsirai Machakaire

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Supervisor: Prof. J.M. Steyn

Co-supervisor: Prof. A.J. Haverkort

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DECLARATION

I Allan TB Machakaire, declare that this dissertation, which I hereby submit for the degree MSc (Agric) Agronomy at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

Signed_______________________________

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LIST OF ABBREVIATIONS

ARC	Agricultural Research Council
BK	Brakpan
^{o}C	Degrees celcius
cm	Centimetres
DAE	Days After Emergence
DAP	Days After Planting
df	degrees of freedom
D-index	Dimensionless Index
DM	Dry Matter
DMC	Dry Matter Content
ETo	Reference evapotranspiration
FM	Fresh matter
g	Grams
g $tuber^{-1}$	Grams per tuber
ha	Hectares
HI	Harvest Index
HL	Hans Liebenberg
K	Potassium

kg	Kilograms
L1	Land One
LAI	Leaf Area Index
LINTUL	Light Interception Utilisation
LUE	Light Use Efficiency
m	metres
m^2	square metres
m^3	cubic metres
MAE	Mean Absolute Error
Max	Maximum
Min	Minimum
MJ m^{-2}	Mega Joules per square metre
mm	Millimetres
MSE	Mean Square Error
N	Nitrogen
No	Number
ns	non-significant
P3	Pivot Three
P11	Pivot Eleven

PAR	Photosynthetically Active Radiation
PB	Piet Botha
PSA	Potatoes South Africa
p-value	Probability value
PVX	Potato Virus X
PVY	Potato Virus Y
r	correlation coefficient (Pearson's)
r_s	Spearman's correlation coefficient
R^2	Regression coefficient of determination
RMSE	Root Mean Square Error
RUE	Radiation Use Efficiency
s	significant
SA	South Africa
SM	Steyn Marynick
SPSS	Statistical Package for the Social Sciences
temp	temperature
t ha^{-1}	tonnes per hectare
ton	tonnes
tuber No 10 kg^{-1}	tuber number per 10 kg sample

ABSTRACT

The potato processing industry relies on yield forecasts for production planning and accurate yield forecasting is a challenge. Expected yield forecasts need to be produced as early as eight weeks before harvest and delivery of potatoes to the factory. A simple crop growth model, LINTUL-Potato, was tested to see if it can accurately forecast yields of potato using long term historical and current weather data as well as crop and management input data. This study looked at calibration and validation of the model in different production areas in South Africa. Three different potato varieties were used in the study. The LINTUL-Potato model uses the linear relationship between biomass production and light use efficiency of solar radiation intercepted by the crop's canopy. The model was developed for use in potato production systems and this study focused on adapting the model for use within a yield forecasting system for a potato processing company. The aim of this study was to explore how the LINTUL-Potato model can be used in a yield forecasting system. The hypotheses tested were that a simple model can be used to accurately forecast yields of potato using long term historical and actual weather data, the tuber count and size (mass) of potatoes can be accurately forecasted using a simple model, and that the dry matter content of potato tubers can be forecasted using a simple model. The other objectives of the study were to test the accuracy of the yield forecasts produced, monitor evolution of tuber size distribution for use in forecasting the size composition of the yield and investigate potential use of the model for determining and forecasting dry matter content of tubers.

The LINTUL model used in this study is a simplified version, hence its parameter values needed to be verified through calibration. To find out if the parameterized model worked well, it had to be validated by obtaining and using independent crop, management and weather data. After calibration, the model was then used for yield forecasting using real-time weather data until the sampling date and then using long-term historical weather data until the

expected harvest date. The hypotheses that a simple model can be used to accurately forecast yields of potato using long term historical and actual weather data, and that the tuber count and size (mass) of potatoes can be accurately forecasted using a simple model were accepted and the forecasts produced were reasonably accurate. Results of the model validation showed that accurate forecasts can be produced early in the growing season using current actual weather data up to 65 days after planting and then long term weather data for the remainder of the season up until harvest. LINTUL model performance was evaluated using the r, r_s, R^2, MAE, RMSE and D-index statistical parameters. Validation of the model for the variety Innovator had a r value of 0.80 (R^2 = 0.64) and a strong positive association was observed between the forecasted and observed final yields with r_s = 0.56. Ratios based on the actual and attainable yields were calculated for three different varieties and these were adapted to be used in the forecasting system. The adapted ratios were 0.61 for Innovator, 0.70 for Markies and 0.78 for Pentland Dell. The varietal ratios were used to calculate the actual expected yield from the LINTUL forecasted yield at final harvest.

For tuber size distribution, the average tuber mass 10 kg^{-1} sample at final harvest correlated well (r = 0.87) and a strong positive association was observed (r_s = 0.60). The average tuber No 10 kg^{-1} sample was forecasted with lower accuracy (R^2 of 0.56) but correlated well with r = 0.75. A strong positive association was also observed (r_s = 0.64). A T-test was also used to compare the forecasted and observed fresh tuber yield, tuber No 10 kg^{-1} and average tuber mass 10 kg^{-1} at final harvest. The results showed non-significant differences for fresh tuber yield, average tuber count and average tuber mass per 10 kg at final harvest at the 5% significance level. The hypothesis that the dry matter content of potato tubers can be forecasted using a simple model was rejected. The dry matter composition of tubers was influenced by a number of external factors and forecasting was not possible in this study and requires a further study.

It was also concluded that the model can be used to produce different types of forecasts which can be used to run comparisons of expected performance of current cropping seasons with the historical average. The model is also a valuable management tool as its results can be used in strategic decision making such as when to plant, how much to plant and where to plant. It can be easily adapted for different production areas. However, the quality of weather and crop input data will influence its accuracy level.

INTRODUCTION

Crop production is significantly affected by environmental factors such as weather conditions which influence growth and development, causing large intra-seasonal variability in yield. The interaction between the weather and the spatial variability of soil properties also causes spatial yield variability (Basso *et al*., 2013). Yield estimation is an important part of the planning process for the potato processing industry and has been a challenge for many years (Iritani, 1963). This information can aid in decision making for supply strategies. Huge losses can be incurred if forecasting is not accurate due to loss of production time. Hence yield forecasting is important in improving efficiency at factory and limiting periods of over or under supply to the factory. Strategically, yield estimation is used to determine whether the estimated tonnes will meet the needs of the factory, or if contracts will be met. Various methods are being used for forecasting expected yields in potato crops, usually with low accuracy levels. The challenge in the processing industry is that management usually asks for models that are predictive, whereas research wants models that are explanatory (Spitters, 1989). Crop growth models which have generally been developed as a simplified representation of the agricultural cropping system (Bouman *et al*., 1996) are capable of accurately predicting crop yield. Spitters (1989) described how crop models can also be used for yield forecasting by the processing industry for predicting and planning the supply of raw product. The main objective of any yield forecast should be to give a precise and scientifically sound forecast of the crops' yield as early as possible in the growing season by considering weather effects, as well as the effects of crop management and soil characteristics.

Accurate potato growth and yield prediction is a challenge for the potato processing and crop growth simulation models could be useful to improve yield forecasts. LINTUL is an example of such a model that has been successfully calibrated and validated for different potato production environments around the world (Haverkort, 1986; Kooman and Haverkort, 1995; Caldiz and Struik, 1999; Caldiz et al., 2001; Caldiz et al., 2002; Franke et al., 2011; Molahlehi et al., 2013; Svubure et al., 2015). The LINTUL model has also been used on an experimental basis to make forecasts of expected yields and tuber sizes of processing potatoes in different production areas of South Africa. However, in this study the model was tested out for the first time as a practical management tool for yield forecasts on a commercial scale. More detail on the LINTUL model is provided in section 1.6 on p23.

Usually crop models only predict what yield to expect when a crop is harvested, but seldomly have the ability to also forecast quality. When growers know the production potential for their areas, they can be challenged to improve their production practices in order to achieve better yields.

The development of crop models started about 50 years ago with the pioneering work of researchers at Wageningen in the Netherlands. Over the years, models of varying levels of complexity have been developed aimed at different production situations. Potato production is one area of agriculture that has used crop models to explain the underlying physiological processes explicitly. The application of crop models has enabled researchers, scientists and growers to understand the performance of crops and fill in some of the gaps in knowledge (Haverkort, 2007).

When crop growth modelling started, the primary aim was about increasing our knowledge in crop growth processes by understanding the mechanisms through a synthesis of knowledge expressed using mathematical equations. Use of crop models has been found to be beneficial in various areas of agricultural research and education (Spitters, 1989; Marcelis *et al*., 1998; Haverkort, 2007). Simulation models are powerful tools for testing our understanding of crop performance by comparing simulation results and experimental observations (Bouman *et al*., 1996). Use of crop models has been demonstrated to be of help when trying to understand the physiological basis of yield formation under various production situations (Van Ittersum *et al*., 2003) and they can be used to quantify the relative importance of crop characteristics, such as physiological and morphological traits, and environmental characteristics. Models can be used to systematically explore the production potential of agricultural crops such as potatoes in historical or predicted future weather conditions. Estimation of potential tuber yields in various regions can be considerably improved by use of dynamic dry matter allocation as in the LINTUL Potato model (Kooman and Haverkort, 1995).

In modelling crop growth, all the events that determine and influence the development and growth of the crop are schematically structured, and the cause and effect relationships quantified. These events are mainly determined by the Genotype, Environment and Management (Haverkort, 2007).

Crop growth models could be used to investigate the effects of management options such as planting dates, population density, irrigation timing and frequency, and fertiliser applications in different environmental conditions (Franke et al.,2011; Molahlehi et al., 2013; Svubvure et al., 2015). In some cases results from these studies have stimulated field experiments to test the outcomes predicted in the simulations (ten Berge *et al*., 1994). Lately, researchers have begun to apply the results of crop models to tactical decision making, using knowledge based systems such as decision support systems. Franke *et al*. (2011) in developing environmental principles, criteria, indicators and norms for potato production in South Africa through field surveys and modelling, used a potato growth model parameterized for Sandveld conditions. Some of the indicators assessed in their survey, such as the efficiencies of land and water, were benchmarked against the results of the LINTUL potato growth model. The model was then used to simulate potential and water limited yield of potatoes and scenarios were simulated with 18 years of weather data, giving an insight into the way seasonal weather conditions impact on land and water use efficiencies. The model showed that the month of planting in the Sandveld had a strong impact on the potential yields and the effect of planting date on actual yields followed the trend observed in the simulated potential yields.

Approaches to plant growth modelling vary in detail and complexity according to the objectives of the researcher (Johnson *et al*., 1986). Crop growth models therefore vary widely in their aims and complexity. At one end of the range of models are those which attempt a synthesis of physiological and biochemical factors to calculate the growth of a plant and those which use sophisticated models of canopy architecture and light penetration to describe photosynthesis by a crop. At the other end are simple regression models which attempt to relate yield to a very few environmental variables by a simple algebraic or even arithmetic relationship. Regression models have generally been found to be rather crude under conditions with constraints such as diseases and drought (Spiertz *et al*., 1984). The empirical models that describe the development of potato crops and their actual yields under contrasting conditions and predict crop performance under other conditions by inter- and extrapolation have the advantage of being relatively simple. They, however, do not explain changes physiologically, but rather mechanically (Haverkort and Harris, 1987). Crop models can be used to explore the potential production and optimum timing of production for any area with minimum time and expense.

It has been widely assumed that for a model to be usefully accurate it must be detailed and mechanistic, incorporating descriptions of the processes involved in plant growth, their interactions and any known feedback processes. By limiting the application of the model to a specific geographical region, the number of environmental inputs required to run the model is effectively reduced (Griffin *et al*., 1993). Mechanistic models enable predicting growth rates and yields under a variety of environmental and management conditions. This may be used as a tool for the farmer to assist in his decisions on management operations such as scheduling irrigation, fertilizer applications and crop protection, or to be used in process control such as climate control in greenhouses.

Problem statement

Accurate potato growth and yield prediction, which is important for planning purposes, is a huge challenge for the potato processing industry and crop growth simulation models such as LINTUL could be useful to improve yield forecasts.

Hypotheses

- A simple crop model can be used to accurately forecast potato yields using real-time current and long term historical weather data.
- The tuber count and size (mass) of potatoes can be accurately forecasted using a simple model.
- The dry matter content of potato tubers can be forecasted using a simple model.

Purpose and Objectives

The purpose of this study was to evaluate the LINTUL-POTATO crop growth model for use in a yield forecasting system for potatoes, using long term historical and actual weather data.

Other objectives included:

- Determining the accuracy of the yield forecasts.

- Monitoring the evolution of tuber size distribution at each sampling event for use in forecasting the size distribution of the yield at harvest.
- Investigating potential use of the model for determining and forecasting dry matter content of tubers at harvest.

CHAPTER 1: LITERATURE REVIEW

1.1 The Potato processing industry

The use of potatoes as a raw material by the processing industry to produce French fries or frozen chips, crisps and flakes is increasing. World potato production was estimated at 363,383,667 tons in 2013 with Africa contributing 29,731,211 tons, which was 8% of the total production. Of the total production in Africa, South Africa produced 2,252,000 tons which was 7.6% of the total (faostat.fao.org). As of 2013, the potato processing industry in South Africa used 20% of the total volume of potatoes produced in the country (www.potatoes.co.za)

Growers who produce potatoes for processing normally aim to get high yields and quality at the lowest costs. When proper varieties are grown under suitable conditions and supplied with adequate amounts of inputs, high yields can be achieved. However, high yields do not necessarily lead to the best quality because recovery at the factory mainly depends on high DMC, uniform and relatively large tuber sizes. A number of factors determine the acceptability of tubers for processing with the most important being tuber size, DMC and low level of defects (Nelson *et al.*, 1988; Caldiz, 2015, Personal communication). The processing industry has to produce a high quality product on a cost effective basis and has therefore set strict requirements for tuber length, DMC, flesh colour, injuries and defects amongst other things. The quality of potato tubers is influenced by various external factors such as weather, crop management, soil type, variety, harvesting and storage.

DMC of potato tubers is an important quality criterion influencing their suitability for potato processing (Ifenkwe and Allen, 1978). A high DMC will improve the processing efficiency and quality of the finished product. If DMC is too low, French fries or crisps will be too soft or too wet. More energy will also be required in processing as more water must be evaporated.

A high DMC will also result in a lower fat content in the finished product thereby lowering processing costs and also producing a healthier product for the consumers (Haverkort et al., 2002). If the DMC is too high, French fries will be too hard and dry and the crisps too brittle. The texture of the processed potato is also partly determined by the DMC. Dry matter requirements are therefore determined by the end product with French fries preferring 20 – 24%, crisps 22 – 24% and flakes higher than 21% DMC.

Size and shape of tubers are an important external characteristic as they influence the appearance of the product and also wastage during peeling. Most processors prefer yield in the size grade between 40 – 70 mm tuber diameter. French fry producers prefer long tubers with sizes greater than 50mm, whilst round tubers with a size range of 40 – 60 mm are preferred for crisp production (Haverkort et al. 2002).

Internal and external qualities of varieties also plays an important role in determining the suitability of potatoes for the processing industry. Some of the important properties and qualities of varieties are DMC, tuber shape, shallowness of eyes and size of tubers.

1.2 The evolution of crop simulation models

Crop simulation models have been described by Hogenboom *et al*. (2004) as being computerised representations of crop growth, development and yield, simulated as functions of soil conditions, weather and management practices through mathematical equations. Models can be used to systematically explore production potential of crops in past or future predicted weather conditions. For the potato crop (*Solanum tuberosum*) that is growing under optimal conditions, simple models have been developed. Hackett *et al*. (1979) presented an empirical regression model which could be used for predicting commercial yields of potatoes. The model was found to work well in a given location but could not be applied over a broad area as its parameters were highly influenced by the environmental and cultivar differences. A model for predicting yields of potato focussing on the management of water and transpiration was developed by Feddes *et al*. (1984). Ng and Loomis (1984) developed the model “POTATO” for simulating potato growth and yield, which included a high level for physiological and morphological processes. MacKerron and Waister (1985) developed a potato growth model for yield, which was based on the time between planting, emergence and leaf expansion rate that was temperature dependent and the radiation use efficiency (RUE).

Fishman *et al*. (1985) simulated growth of potato at the plant community level using a model which considered fertilisation, irrigation and timing of harvest as being the main control factors. A simple whole plant level model for potato growth was developed by Johnson *et al*. (1986) and it accumulated and partitioned dry matter into leaves, stems, roots and tubers. The daily growth rate in the model is calculated from a function of the gross solar radiation, the amount that the crop intercepts, the temperature and water status of the soil. Haverkort and Harris (1987) developed a model describing the growth and yield of a potato crop grown under conditions in tropical highland where temperatures and levels of solar radiation are usually higher than in temperate climates. The model was dependent on a conversion coefficient for temperature and radiation and was considered as being an improved version of the model that was presented by MacKerron and Waister (1985). Jefferies and Heilbronn (1991) further developed the model of MacKerron and Waister (1985) so that it included the effect of water stress in constraining yield.

De Wit and others at Wageningen were some of the pioneers in developing and applying crop models in the 1960s as shown in Fig.1.1 (Bouman *et al*., 1996; Van Ittersum *et al*., 2003). The aim of their models was mainly to better understand the growth of crops based on the underlying physiological processes (Van Ittersum *et al*., 2003). Other scientists at Wageningen also became involved in developing crop models in the 1980s. Van Keulen *et al*. (1982) developed SUCROS, a generic model for potential production situations, which was also further developed by Laar *et al*. (1997). This model formed the foundation of later models to be developed such as WOFOST as shown in Fig.1.1 (Van Diepen et al., 1989). Plant growth models relating the growth of plants and environmental factors dynamically were suggested to be used in order to improve crop yield potential analysis and losses induced by pests (Johnson *et al.*, 1986). If these models are well developed, the expectation is that they will predict well the expected actual yield of a crop that is free from pests and under differing environmental conditions. If they are also combined with sub-models of pest population they can be used in determining the actual yield lost under pest pressures of varying levels in different environmental conditions and they can therefore be used as an aid in management decision making. Kadaja and Tooming (2004) also presented a potato production process model (POMOD) which was based on the maximum plant productivity principle and the concept of reference yields. Fig 1.1 shows how some of the main models in the “School of de Wit” have evolved over the years.

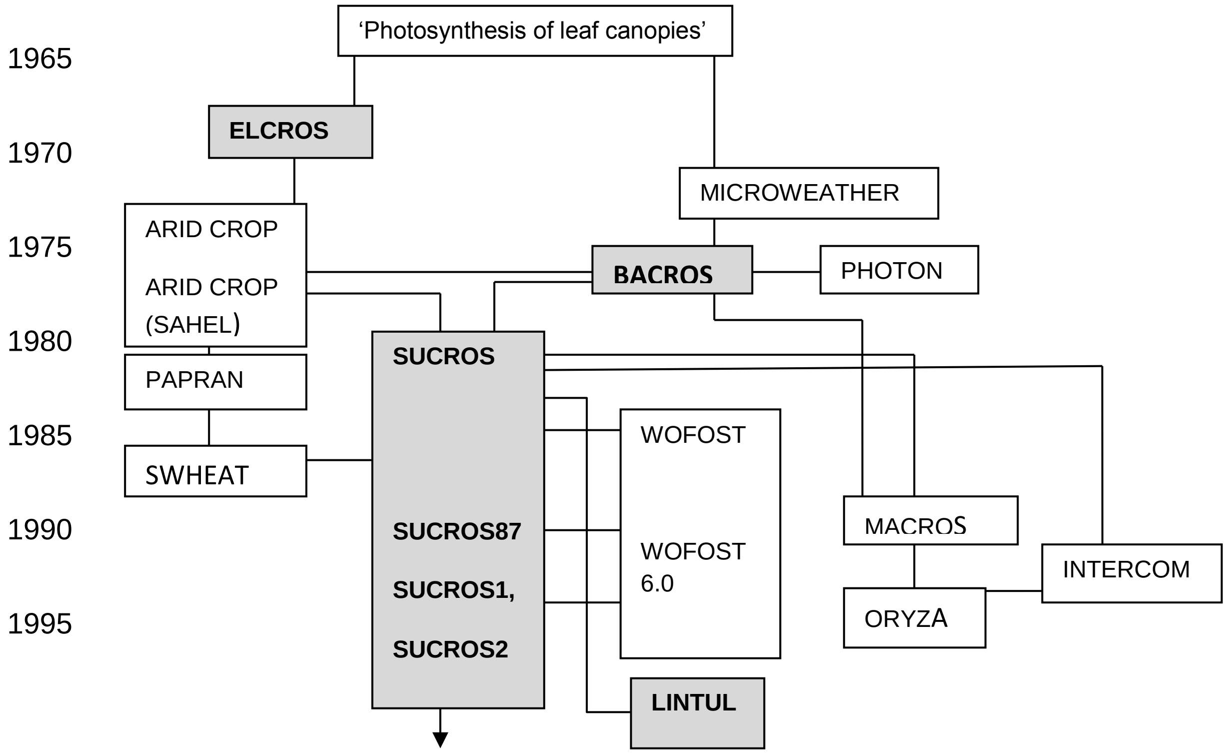

FIG.1.1: School of de Wit models (Adapted from Bouman *et al*., 1996).

The demand for decision support that is strategic, forecasting of yields, land zoning and explorative scenario studies has also played a role in the development of models (Bouman *et al*., 1996; Van Ittersum *et al*., 2003).

Model development still continues to this day, with more efforts being focused towards obtaining a full understanding of crop performance under varying conditions. Models mainly similar in philosophy but of differing levels of complexity are being developed because of research goals and priorities that keep changing (Johnson *et al*., 1986). Oerke *et al*. (1994) found that potential production is seldom achieved under field conditions, with only a fraction of the calculated potential ranging from 5 – 60% for country average yields being generally obtained (Van Ittersum *et al*., 2003). For potato farmers in the Sandveld region of South

Africa, and other well-managed systems, actual yields are typically about 50 - 70% of the potential yields (Franke *et al*., 2011). If the potential yield can be simulated for a given environment, the yield gap between potential and actual yield can be quantified. Farmers can then be challenged to improve their production practices so as to increase their yields. Estimation of potential tuber yields in various regions can be improved considerably by use of the LINTUL Potato model for dynamic dry matter allocation (Kooman and Haverkort, 1995).

1.3 Growth factors and production levels of potato

Penning de Vries (1983) proposed classifying of the agricultural production system into four different production situations. The first, production situation 1, represented potential yield. It assumed that growth occurred under conditions where water and nutrient supply was adequate and the growth rate was solely determined by the weather conditions, in particular temperature and solar radiation (Kadaja and Tooming, 2004). Production situation 2 was water limited and growth was limited by inadequate supply of water in a part of the growing season, but with nutrients being in adequate supply. Production situation 3 was nitrogen limited and growth was limited by nitrogen shortage in some part of the growing season, and in the other part of the season by water or weather conditions. The fourth production situation was nutrient limited and a shortage of phosphorous or other minerals limited growth in some part of the season, and by nitrogen, water or weather conditions in the rest of the season.

A new classification was, however, introduced by Rabbinge (1993) who grouped the production levels into potential, attainable and actual yield. Yield of potato crops is influenced by various factors which can be grouped into three distinguishing groups to get a hierarchy of the production levels as shown in Fig.1.2 (Bouman *et al*., 1996; Van Ittersum *et* *al*, 2003). The first group are the yield or growth defining factors temperature, radiation intensity, crop growth characteristics and atmospheric carbon dioxide concentration, which determine the potential yield and the grower has little control over. They determine the maximum production possible and influencing them can only be achieved through decisions such as planting date, planting population or breeding. This potential yield is only achieved if the crop is provided with an optimum supply of nutrients and water, and protected completely from pests, diseases, weeds and any other factors that might reduce growth.

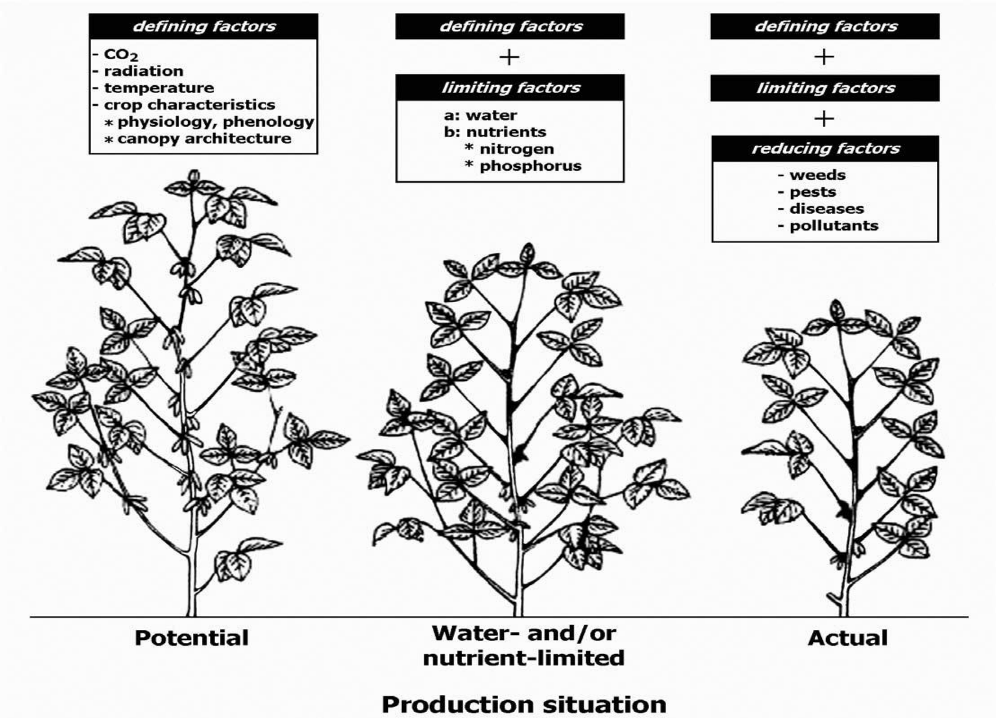

FIG.1.2: Hierarchy showing the influence of growth factors on production levels in a production situation (Van Ittersum *et al*., 2003).

The second group takes into account water and nutrients, which are considered as the yield or growth limiting factors and the grower can influence them. The grower can control water and nutrients through management and implementation of yield increasing measures in order to improve yield towards the potential. The third group takes into account the yield or growth reducing factors of pests, diseases, weeds, pollutants and active ingredient toxicity, which the grower can influence through implementing yield and crop protection measures. Yield reducing factors lead to competition for resources and reduction in foliage and photosynthetic rate (Haverkort, 2007). Other factors that also affect yield and cause variability are the variation in the types of soils, soil preparation as well as soil compaction, which can restrict the penetration of roots and impede water movement within the soil (Bouman *et al*., 1996). For use in yield forecasting, there is therefore need for a model that includes the yield limiting factors so as to reduce the large deviation of results from field data (Bouman *et al*., 1996; Van Ittersum *et al*., 2003). The actual production attained usually results from a combination of the factors limiting and reducing growth. Kadaja and Tooming (2004) also presented the concept of reference yields which allows a step by step study of the production process. It starts from the higher level yields and also allows the relative importance of factors in the different groups to be compared.

For the potato crop to attain high yields and quality, it depends on an adequate amount and regular supply of water. Drought and heat cause stress to the crop which may result in adverse effects on growth and yield. The relative sensitivity of the potato crop to water stress has been shown in many irrigation experiments (Fabeiro *et al*., 2001). The efficiency of photosynthesis of the plant is reduced by water stress at all growth stages, with the most drastic effect on yield being due to drought during tuber initiation and bulking (MacKerron and Jefferies, 1986). In most arid and semi-arid areas the overall rainfall is low and erratic, usually making irrigation necessary for economically acceptable yields to be achieved. Water stress will reduce crop canopy development, biomass production and ultimately the yield. In previous studies, limitations in soil water availability have been shown to cause crops to mature early, growth of plants to be reduced, together with tuber yield, tuber numbers per plant and their size and quality (MacKerron and Jefferies, 1986; Ojala *et al.*, 1990).

Decreased water content has also shown to alter the dry matter assimilation and increase sucrose levels after a heat or drought stress resulting in translucent sugar ends. Sucrose is a non- reducing sugar that may further breakdown during the Maillard reaction into glucose and fructose. These reducing sugars are undesirable as they cause problems in processing potatoes by causing dark brown colouration in fried products.

Research has shown that when water and nutrients are in adequate supply, rate of dry matter accumulation by arable crops is proportional to the solar energy quantity which they intercept (Monteith and Moss, 1977; Spitters, 1987; Kooman and Haverkort, 1995). Commercial crops of potato that are well grown have been found to intercept maximum radiation of around 95 to 98%. To convert the tuber dry matter yield to fresh tuber yield, an estimation of the tubers' dry matter concentration is required (MacKerron and Waister, 1985). Most researchers working on model development have estimated this dry matter content to be around 20% (Mackerron and Waister, 1985; Kooman and Haverkort, 1995; Franke *et al*., 2011; Haverkort *et al*., 2013). Experiments on how cultivars differ in their conversion efficiencies showed that a linear relationship exists between the total dry matter yield and the integral of the solar radiation that is intercepted for the greater part of the growing season. Temperature can however, strongly influence the photosynthesis rate.

In order to simulate yield potential for any given field, the minimum set of input data required varies by model but usually includes the daily maximum and minimum air temperatures, solar radiation, rainfall, sowing date, depth of seed placement, date of emergence, the genotype-specific photo thermal phenological development coefficients for the cultivar to be simulated, and plant density (Lobell *et al*., 2009).

1.4 Potato growth stages

Potato crops are mainly grown in the vegetative phase of their life cycles with planting done from seed tubers which are either planted un-sprouted or sprouted. In South Africa and other parts of the world, tubers are also being planted as cut seed pieces. Potato plants can also be produced from true seed but this is uncommon under commercial production and is mostly used in plant breeding. The growth of potatoes can be divided into the five (5) stages as shown in Figure 1.3. The time at which these stages occur and the length they will last can vary depending upon the availability of soil water and temperature amongst other factors which also include cultivar differences.

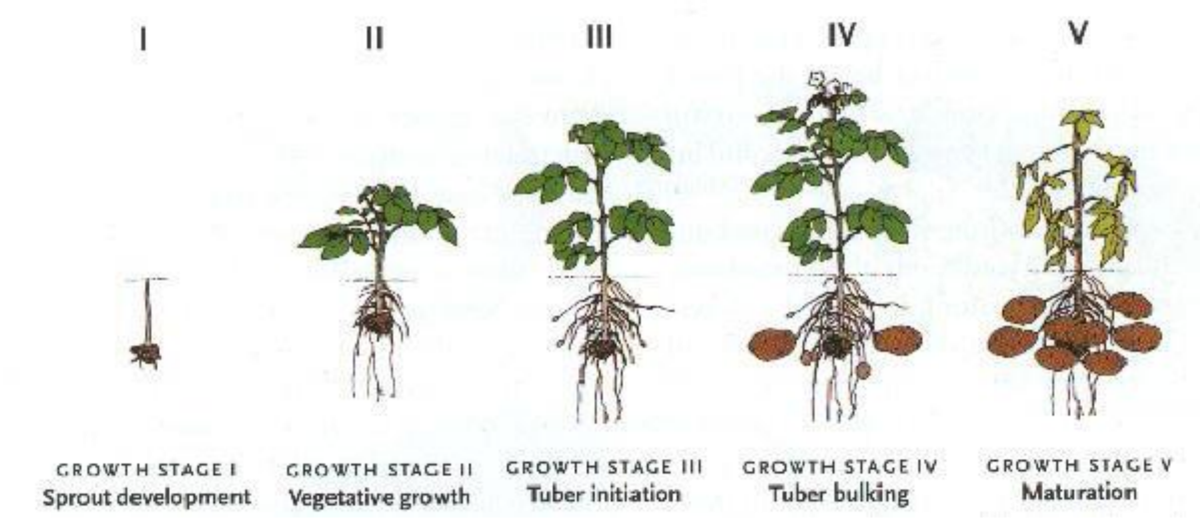

FIG.1.3: Potato growth stages (Adapted from Johnson, 2008)

An example of the development of the potato crop's total fresh matter (FM) and DM yield through these stages is shown in Fig 1.4.

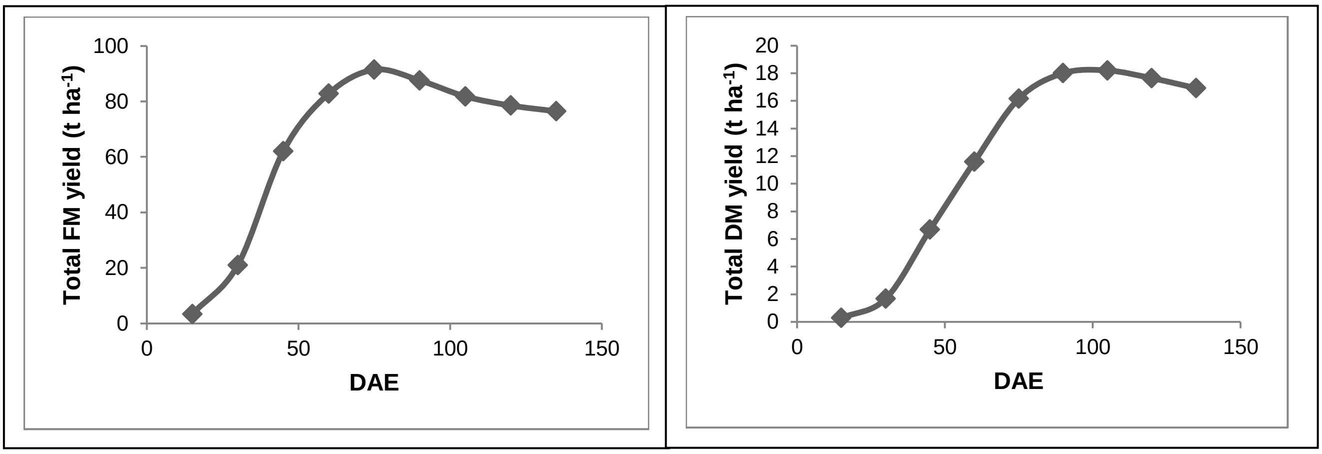

FIG.1.4: Total FM and DM yield over time (Adapted from Kolbe & Stephan-Beckman, 1997).

After tuber initiation, the fresh matter and dry matter yield increase exponentially. Thereafter, there is a long period of nearly linear growth, which is followed by a decreasing rate and finally an end to growth, as shown in Fig 1.4.

1.4.1 Sprout development

In the first stage after planting of the seed tubers, sprouts will begin to develop from the eyes on the seed tubers, growing upwards towards the soil surface, and roots develop at the base of the sprouts that will be emerging. The number of sprouts that a tuber will produce is largely dependent on the genotype and the husbandry that it went through (Jefferies and Lawson, 1991). If tubers are planted into dry soil, they may not emerge and the growth of roots will be inhibited. Irrigation should be applied at planting time and not at emergence, since the latter could result in a shortened vegetative period, less stems being formed per plant, delay in tuber initiation and shortening of the tuber bulking period (Gunel and Karadogan, 1998). Furthermore, young tubers have been observed to show apical dominance and produce single sprouts from one eye whilst apical dominance is lost as the tubers age, resulting in an increase in the number of sprouting eyes. Conditions that are considered ideal for sprouting are darkness, temperatures between 15 to 20^{o}C and a relative humidity of 90% (Jefferies and Lawson, 1991).

1.4.2 Vegetative stage

Vegetative growth commences when the sprouts emerge after planting and leaves and branched stems develop from the nodes along the sprouts that will have emerged above the ground. Roots and stolons will also develop on nodes below the ground, and photosynthesis will begin. The vegetative stage generally refers to the period from early sprouting until tuber initiation (Ojala *et al*., 1990). Stress during this stage is usually referred to as early season stress and causes multiple stems, smaller plants and delayed tuber set. Nitrogen requirement is relatively low during this stage and excessive uptake will promote the partitioning of biomass into the leaves and stems, thereby prolonging this stage and delaying tuber initiation.

1.4.3 Tuber initiation

Tuber initiation has been defined as the time at which a tuberous swelling reaches twice the diameter of the sub standing stolon on 80% of the main stems, or in the case of stolons when sessile tuberous swellings are 2 mm in diameter in 90% of tubers (Jefferies and Lawson, 1991). Development of tubers at the stolon tips without them necessarily enlarging, marks the beginning of tuber initiation. It is marked by the swelling of the stolon tips when their elongation stops. Stolons will grow to different lengths before tubers are initiated and their length depends on the genotype and the environment. Stolons that are nearer to the soil surface have been observed to be longer and initiating tubers later when compared to the stolons formed closer to the mother tuber and deeper in the soil. Several steps controlled by hormonal balances and influenced by weather factors control tuberisation (Struik *et al*., 1989). This process occurs over a period of about two weeks until the final number of tubers is determined.

Tuber initiation may be delayed, impeded or inhibited by high temperatures. A relationship has been shown between growth of haulms and stems, where tuber initiation has been encouraged when haulm growth has been inhibited. The tuber numbers per plant will be limited by dry soil conditions during this period. If there is a long period of water stress before tuber initiation, the tuber set per stem will be reduced (MacKerron and Jefferies, 1986). In most cultivars, the end of this stage coincides with early flowering. The photosynthetic rate has been observed to increase after tuber initiation and this has been associated with the exponential tuber growth (Kolbe and Stephan-Beckmann, 1997).

1.4.4 Tuber bulking

The duration of the period when a closed canopy is maintained usually determines tuber bulking stage and the tuber size and mass will increase at a constant rate (Van Loon, 1981). During this period the crop is considered to be achieving maximum light interception. A leaf area index (LAI) of between 2 – 3 m^2 is reached in this period and also a density beyond which further improvements in ground cover are little and the effects on light interception become marginal (Allen and Scott, 1980). The accumulation of water, nutrients and carbohydrates causes tuber cells to expand. Although the vines and roots continue to grow, the increase in total plant dry matter is mainly due to the tubers bulking. The tuber dry matter yield has been found to initially increase exponentially after tuber initiation, with a long period of nearly linear growth observed thereafter (Kolbe and Stephan-Beckmann, 1997). This is followed by a decreasing rate and an end in growth as the plants senesce. Senescence will be hastened by any water stress during this period and if it occurs during the first part of this period, it may be indicated by leaves beginning to wilt, yellow, and drop off, starting at the bottom of the plant. Improved water availability after such has been observed to stimulate the top growth with new growth occurring. For maximum yields to be achieved, soil water content must not be allowed to fall under 50% of available crop water during this period. Stress during this stage usually results in reduced yield, specific gravity and lower tuber quality (Gunel and Karadogan, 1998).

When tubers are formed, soil temperature has been found to have an effect on the tuber numbers, rate and duration of tuber growth, distribution of assimilates to tubers and the occurrence of tuber malformations and disorders (Struik *et al*., 1989). A range of tuber sizes is present at any given time on any plant in any crop, and this range widens as the plant matures. (Jefferies and Lawson, 1991). Towards the end of this growth stage when the growth rate of tubers has been observed to decrease slowly, the photosynthesis rate also decreases (Kolbe and Stephan-Beckmann, 1997). Very high respiration rates have been shown in young tubers after tuber initiation and in the early stages of tuber bulking, gradually decreasing as the plant senesces.

1.4.5 Tuber maturity and Senescence

Tuber maturity will begin with the senescence of the crop canopy and its onset and progress is variable and appears to depend on the genotype and environment (Jefferies and Lawson, 1991). The onset of senescence is usually marked by signs of yellowing of the lower leaves, which progresses until 50% of the leaves remaining on the plant are yellow. Yellowing of the stems will follow, then their complete death when they are brown and fall to the ground. The older leaves begin to become pale, yellow and then necrotic as it spreads to the young ones and then eventually the canopy will be lost. The rate of growth of the tubers is lower than during the bulking stage. Translocation of the products of photosynthesis from the foliage and roots into the tubers largely represents the increases in tuber dry matter (Kolbe and Stephan-Beckmann, 1997). The maximum tuber yield is thought to be reached when most green leaves have died and the leaf area index has reached a value of +/- 0.75.

The rate of plant senescence will depend on the water availability or stress level during this period as well as the amount of nitrogen applied earlier in the season. Limited water and or nutrient supply will induce senescence. Usually little water is required for tuber bulking by potato plants during the maturation stage and the periderm of the tubers will thicken to form a skin as the crop senesces (Jefferies and Lawson, 1991). Maturation is associated with maximum achievement of dry matter content by the tubers, low reducing sugars and good skin set over the tuber. Stress in this stage and in the tuber bulking stage is also referred to as late season stress. It affects the tuber shape, and also the translucent or sugar end of tubers, causing sugar development in tubers and discolouration in storage and processing.

Harvesting of tubers occurs after this stage and soil water management is also important for harvest preparation. Some researchers have recommended that the available soil water be reduced from 65% to 50% of field capacity to allow for the maturity, russetting and skin setting of the tubers for a period of about 2 to 3 weeks. Soil water levels should be restored back to 65% of field capacity a few days before harvest to allow the tubers to rehydrate and ensure bruise prevention during harvest operation and handling. Tubers with low moisture content are susceptible to blackspot bruising whilst those with high moisture content are susceptible to shatter and pressure bruise. If tubers are going to be stored for a long period of time, this may cause storage problems with disease development.

In many potato crop systems, it is common to destroy the haulms prematurely by use of mechanical equipment or by applying chemical desiccants. In such instances the pattern of how the crop senesces will depend on the method that has been used.

1.5 Crop yield gaps

Crop yield gap is defined as being the difference between potential or attainable and average farmers' yields achieved. The yield potential of a crop can be described as the yield achieved when that crop is grown under favourable conditions without any limitations from water, nutrients, pests and disease (Evans and Fischer, 1999). Oerke *et al*. (1994) found that potential production is rarely achieved in field crops, with only a fraction of the calculated potential production ranging from 5 – 60% for country average yields being generally obtained. Lobell *et al*. (2009) observed a wide range of yield gaps around the world, with a range of average yields from 20 – 80% of yield potential. For potato farmers in the Sandveld region of South Africa, and other well-managed systems, actual yields are typically about 50 - 70% of the potential yields (Franke *et al*., 2011). The average farm yields are lower than the potential because perfect management of the crop and soil factors influencing plant growth and development is required, but is very difficult to achieve.

The yield gap with actual yield for a given environment can be quantified if the potential yield can be simulated. This concept has been used to understand the causes of yield gaps and if the actual yields can be raised by better management practices (Lobell *et al*., 2009). Crop models are used to estimate yield potential as they assume perfect management of the crop and the absence of most yield reducing factors. However validity relies on validation under field conditions. If the uncertainties that farmers face in assessing soil and climatic conditions can be reduced by use of modern day technologies, it should be possible to raise average yields closer to the potential yields.

1.6 The LINTUL model

The LINTUL model was the first to deviate from the De Wit School photosynthesis based models (Bouman *et al*., 1996). The model is based on the original LINTUL version by Spitters (1987) and the subsequent version by Spitters and Schapendonk (1990). The model can be considered as a functional model as it uses daily solar radiation as the amount of energy available for photosynthesis. This energy intercepted by the crop is approximated using information that is fed-back from the plant leaf area index to calculate approximate biomass production per unit of radiation intercepted (Basso *et al*., 2013). The LINTUL model therefore uses a linear relationship between the production of biomass and amount of solar radiation that the crop's canopy intercepts (Monteith and Moss, 1977; Allen and Scott, 1980).

The LINTUL model can be used to simulate the light interception and utilisation, temperature and day length reactions of potato crops grown under different climatic conditions. The physical yield of any crop is mostly determined by the dry matter production and its distribution, and the dry matter content of the harvestable organs as shown in Fig.1.5. Photosynthesis primarily drives the dry matter (DM) production and it depends to a great extent on the photosynthetically active radiation (PAR).

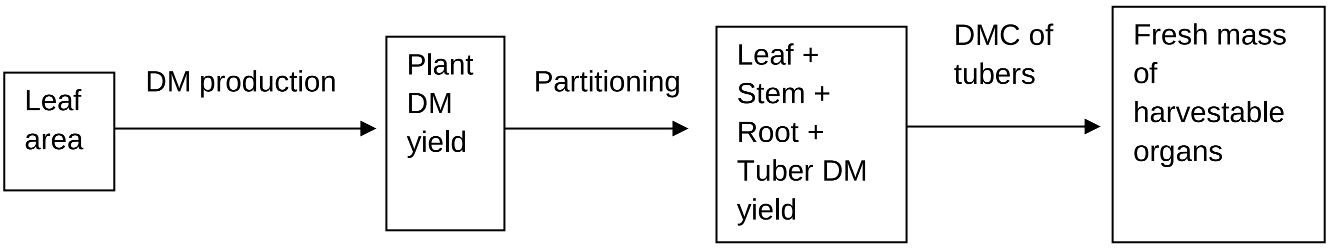

FIG.1.5: Important components of growth and yield of crops (Adapted from Marcelis *et al*., 1998)

In the LINTUL approach, dry matter production is calculated based on the daily radiation interception calculation using leaf area index and Lambert – Beer's law. The laws of Lambert and Beer relate the radiant power in a beam of electromagnetic radiation, usually ordinary light, to the length of the path of the beam in an absorbing medium and to the concentration of the absorbing species, respectively (Swinehart, 1962). The basic principle assumption from this law is that absorption of radiation increases with an increase in leaf area, but that mutual shading will decrease interception (Marcelis *et al*., 1998). This leads to exponential extinction of radiation as shown in equation 1.1:

$$I = I_o \times e^{(-k \times L)} \qquad \text{(Equation 1.1)}$$

In which k stands for the extinction coefficient, and I and I_o for the radiation level at canopy depth L (expressed in overlying Leaf area index - LAI) and at depth 0 above the canopy, respectively. Thus, the total dry matter produced in the LINTUL models is basically calculated by using the Monteith approach whereby the rate of crop growth is calculated from the radiation that the canopy intercepts and the RUE (Allen and Scott, 1980). The mass of the total dry matter is calculated by summing up the mass of the green leaf dry matter, the stem dry matter and the tuber dry matter.

The following simple routine shown in equation 1.2 applies in LINTUL:

$$Y = \frac{\text{R x RUE x HI}}{\text{DMC}} \qquad \text{(Equation 1.2)}$$

where Y = yield, R = amount of resource available (light/radiation in this instance), RUE = the efficiency of use of this resource, HI = harvest index and DMC = dry matter content of tubers (Haverkort, 2007).

The model with a module for calculating crop growth based on the RUE concept was developed by MacKerron and Waister (1985) and also Spitters and Schapendonk (1990). The result is that the gross dry matter production by the foliage is used to calculate the marketable yield by using the dry matter partitioning functions or harvest index. The original version of the LINTUL model multiplied the harvest index by the total above ground biomass, simulated from RUE to calculate the yield of storage organs (Spitters, 1987). Fig.1.6 illustrates how crop growth is calculated based on the light interception, RUE and harvest index in the LINTUL model.

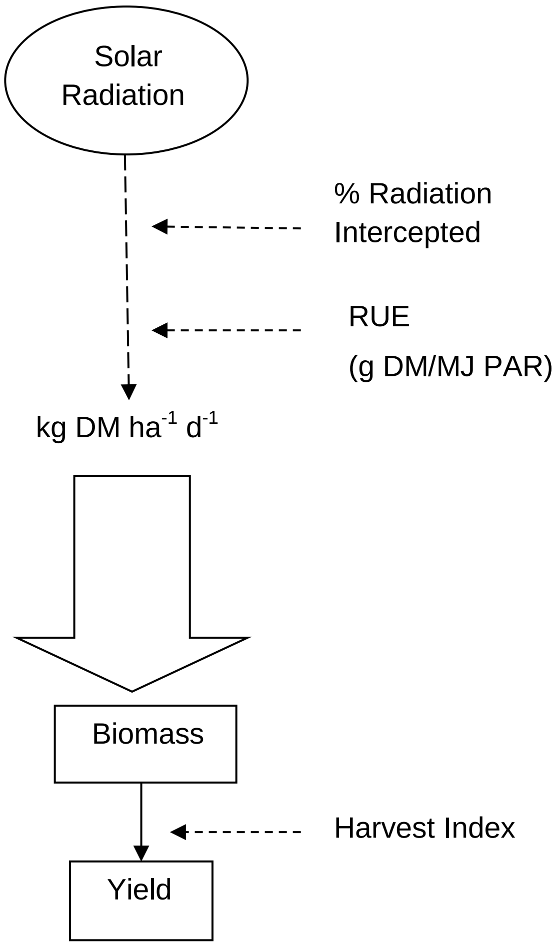

FIG.1.6: Diagram illustrating calculation of crop growth in the LINTUL model (Adapted from Wolf, 2002)

The total biomass formed in LINTUL is distributed into the roots, stems, leaves and storage organs (Spitters, 1989; Van Oijen, 1992). The simplified LINTUL version simulates growth of the storage organs directly from the PAR by introducing RUE for the organs. It assumes that storage organs are filled exclusively based on the current photosynthesis (Spitters, 1989).

The model simulates the potential dry matter production in different environments through the relative effect of temperature on rates of emergence, RUE, tuber initiation and tuber growth (Kooman and Haverkort, 1995). The effect of daylength on development rate until tuber initiation is represented quantitatively and the potential tuber dry matter production is calculated exploratively under some regimes of temperature and day length. The model is partly based on dry matter accumulation with allocation governed by a dominant tuber sink (Spitters 1989 and Kooman 1995).

Kooman (1995) analysed the temperature and day length effect on growth and development of 8 potato cultivars in different environments and found that dry matter production was directly influenced by temperature through its influence on daily growth rate. The duration of the growth cycle and the crop's yielding ability were limited by the indirect influence of temperature and day length on development. The growth cycle is divided into four phases and total crop dry matter production is determined by its length. Each phase starts with a characteristic development stage; Phase 0 is from planting to emergence, Phase 1 is from emergence to tuber initiation when only foliar growth occurs, Phase 2 is from tuber initiation till the end of leaf growth when there is competition between tubers and foliage for assimilates and Phase 3 is from the end of leaf growth until end of crop growth. Climate input data required by the model includes daily minimum and maximum temperatures, incoming solar radiation and rainfall, reference evapotranspiration, and CO_2 concentration. Management input data include the depth and date of planting (Haverkort *et al.*, 2013).

The LINTUL model parameter for accumulated degree days from crop emergence to 100% cover is fixed at 650, and this determines the time to crop emergence, leaf area development and harvest. Daily biomass growth is calculated using the crop's LAI, RUE of 1.25 g dry matter MJ^{-1} of intercepted radiation. The harvest index in the model is set at 75%. The density at which the crop is planted affects the yield potential at that location because rates of maximum dry matter accumulation occur when the plant density allows the leaf canopy to rapidly develop and intercept all the incoming solar radiation from very early in the growing season.

A relationship was established between the growth rate of tubers and temperature and there have been reports of high temperatures decreasing tuber growth rate and resulting in more assimilates being allocated to the foliage from the tubers (Kooman and Haverkort, 1995). The optimum temperatures that have been observed for tuber growth rates are a minimum between 0 – 4.4 ^{o}C, an optimum between 15 – 22 ^{o}C and a maximum from 25 – 35 ^{o}C. Very high temperatures have also been observed to increase respiration at the expense of photosynthesis as RUE is reduced, resulting in lower biomass accumulation (Haverkort *et al*., 2013). The time between the various crop developmental stages is reduced by higher temperatures whilst shorter photoperiods cause early tuber initiation and dry matter to be allocated more to the tubers and less to foliage, resulting in early maturation of crops (Haverkort, 2007). Lower temperatures below the optimum will slow down the assimilation processes. Generally, higher temperatures have been found to favour vegetative growth whilst lower temperatures favour tuber growth (Benoit *et al*., 1983)

CHAPTER 2: METHODOLOGY

2.1 The study areas

The field data for model calibration and validation was collected from different areas over two growing seasons. For model calibration, the field data was collected from Lichtenburg in the North West Province and for model validation it was collected from Dendron, Vivo, Soekmekaar and Marble Hall in Limpopo Province, as shown in Fig 2.1.

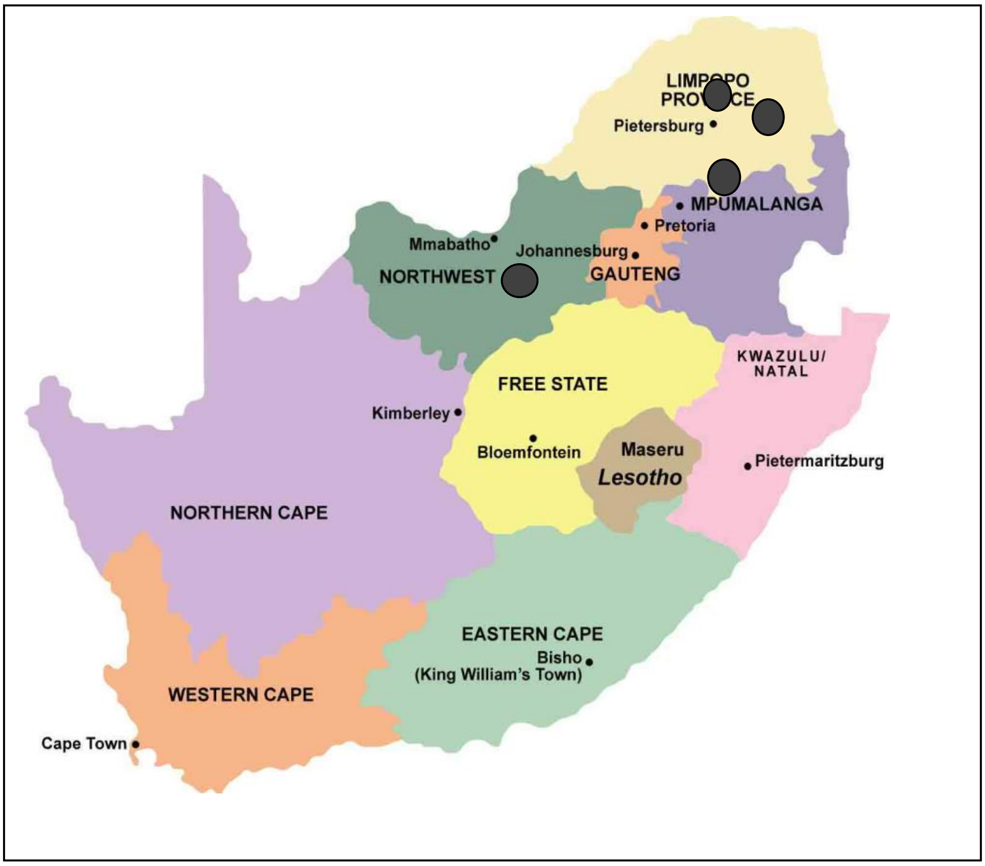

FIG 2.1: Map showing the study areas in South Africa.

2.1.1 Calibration data study area

The production areas that were sampled for model calibration were farms in the Grootpan and Brakpan areas in the Lichtenburg district, North West Province, South Africa, and are shown on the map in Fig.2.2. The area is approximately 280 km north west of Pretoria. Planting is normally from October to December, with harvesting taking place from March to May.

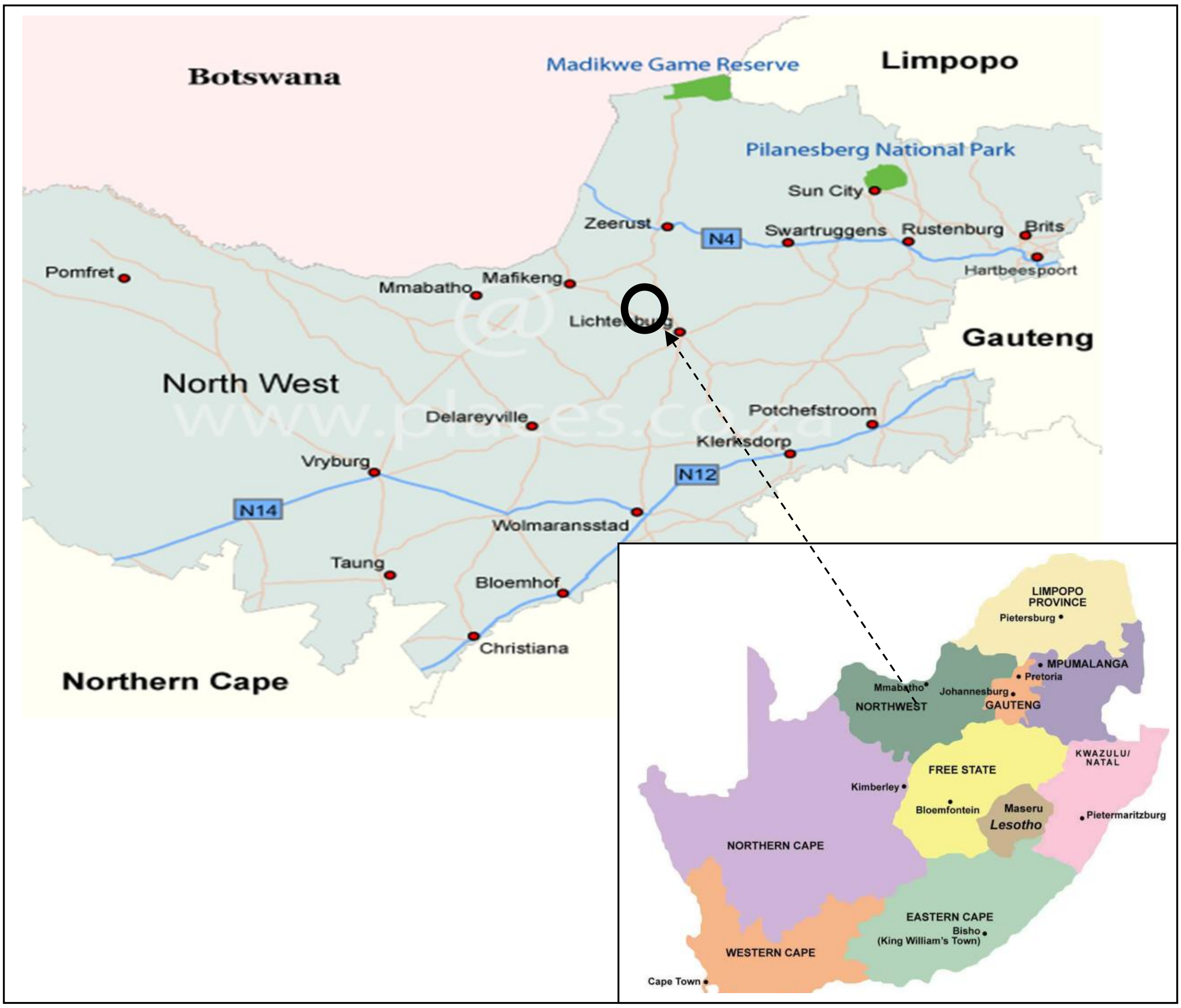

FIG. 2.2: Main production area in Lichtenburg, North West Province, South Africa.

2.1.2 Validation data study area

The production areas that were sampled for model validation are Marble Hall, Soekmekaar, Dendron and Vivo in Limpopo Province, South Africa and are shown on the map in Fig 2.3.

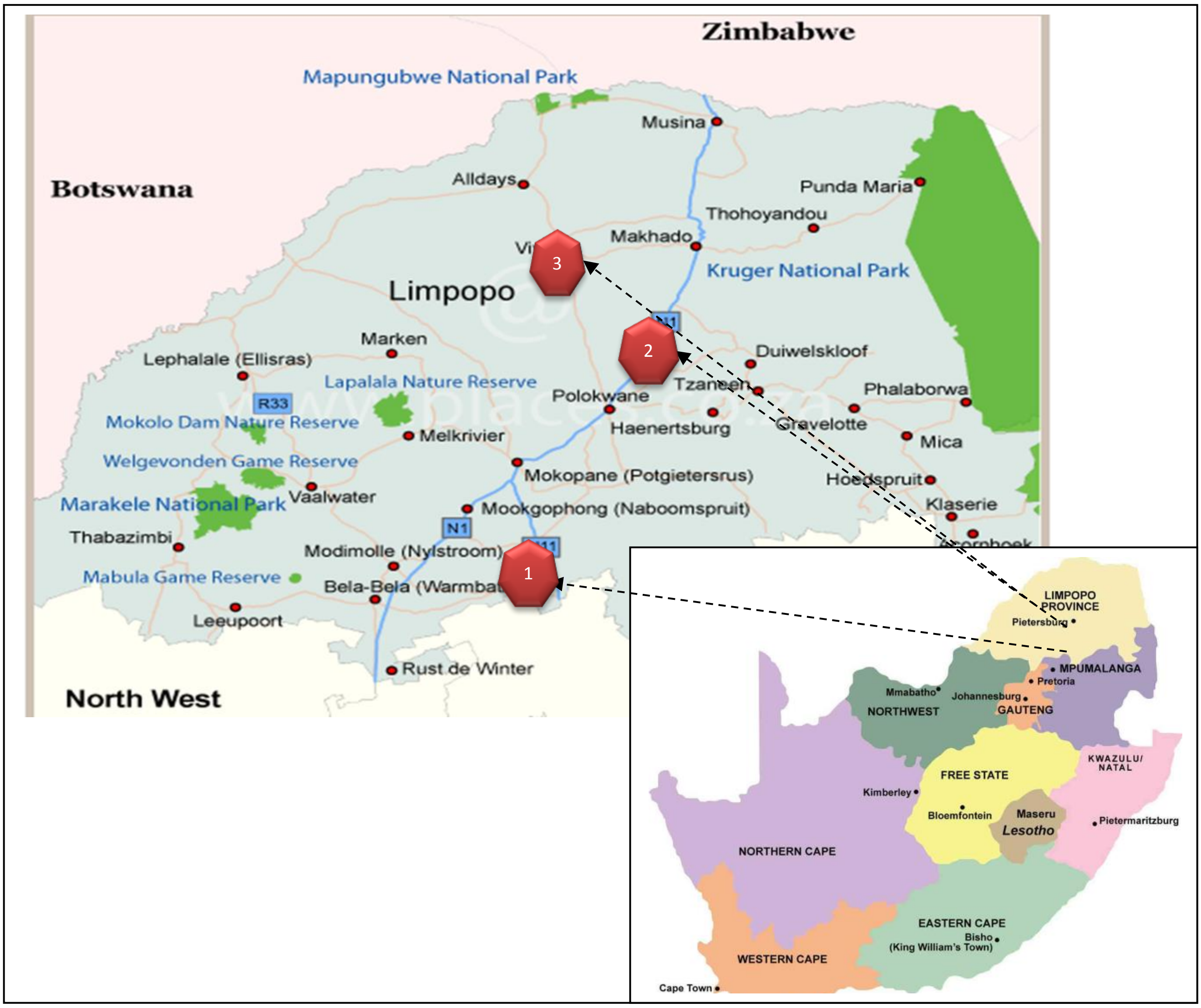

FIG 2.3: Production areas in Limpopo province, South Africa where data for model validation was collected (1=Marble Hall, 2=Soekmekaar and 3=Dendron/Vivo).

McCain Foods SA, through its contract growers and own farms, is annually growing 1,000 ha of processing potatoes in these areas in two seasons, late summer and early winter. Marble Hall is approximately 150 km north east of Pretoria whilst Dendron, Vivo and Soekmekaar are approximately 350 km north of Pretoria. Planting is normally from February to March, with harvesting taking place from May to June for the late summer crop and planting in May to June for August to October harvesting for the winter crop.

2.2 Potato varieties

Two main potato processing varieties for McCain Foods SA are grown in the production areas, namely Markies and Innovator, with a third one Pentland Dell only being grown at Lichtenburg.

Pentland Dell is a variety which was bred by the James Hutton Institute in the United Kingdom and has medium to long growth maturity (www.varieties.potato.org.uk). It has moderately high dry matter content. The plants are of medium height with small leaves that give them moderate foliage cover. The tubers are long and oval with white flesh and shallow eyes. Growing period for this variety depends on the season and is normally between 90 to 110 days from emergence to natural foliage die-back. Tubers are predominantly uniform medium and large sizes when growing conditions are optimal. If water and heat stress are experienced during the growing season, the tubers are less uniform and secondary growth and malformation may occur. The variety is moderately susceptible to late blight and fusarium dry rot, and very susceptible to early blight, common scab, blackleg and soft rot. It is highly resistant to the potato virus X, moderately resistant to potato leaf roll virus and fairly susceptible to potato virus Y (Denner *et al.*, 2012).

Markies is a variety that was bred by Agrico in the Netherlands. It is a late maturing variety with long oval shaped tubers that have a smooth yellow skin with shallow eyes and light yellow coloured flesh (www.fpd.co.za). It has very good resistance to leaf roll and late blight of foliage and tubers, and is moderately resistant to common scab. It also has high tolerance to drought stress (www.varieties.potato.org.uk).

Innovator is a variety originating from the Netherlands and was bred by BV HZPC. Its tuber DMC is high and suitable for processing. It has early to intermediate maturity with a growing period of 90 to 100 days after emergence under optimum conditions. The plants are medium large and semi-erect with moderately closed leaf canopy. The large to very large tubers are long to oblong and oval with cream coloured flesh, shallow eyes and a russetted tan coloured skin (www.HZPC.com). Dry matter content of the tubers is medium to high (McCain, 2014). The variety has good resistance to late blight, moderate resistance to leaf roll, potato virus X and Y powdery scab and common scab.

2.3 Data collection

2.3.1 Weather data

There are two weather stations in the Lichtenburg district which are monitored by the Agricultural Research Council (ARC) of South Africa and they were used for collecting the model input data. The locations of these stations are shown in Fig.2.4. The long term historical weather data and actual seasonal weather data were collected from these stations. Actual rain plus irrigation data was collected using rain gauges that were installed on each field. Weather stations also monitored by the ARC and Potatoes South Africa (PSA) in the other areas were also used to collect weather data for model validation. The locations of these stations are shown in Table 2.1.

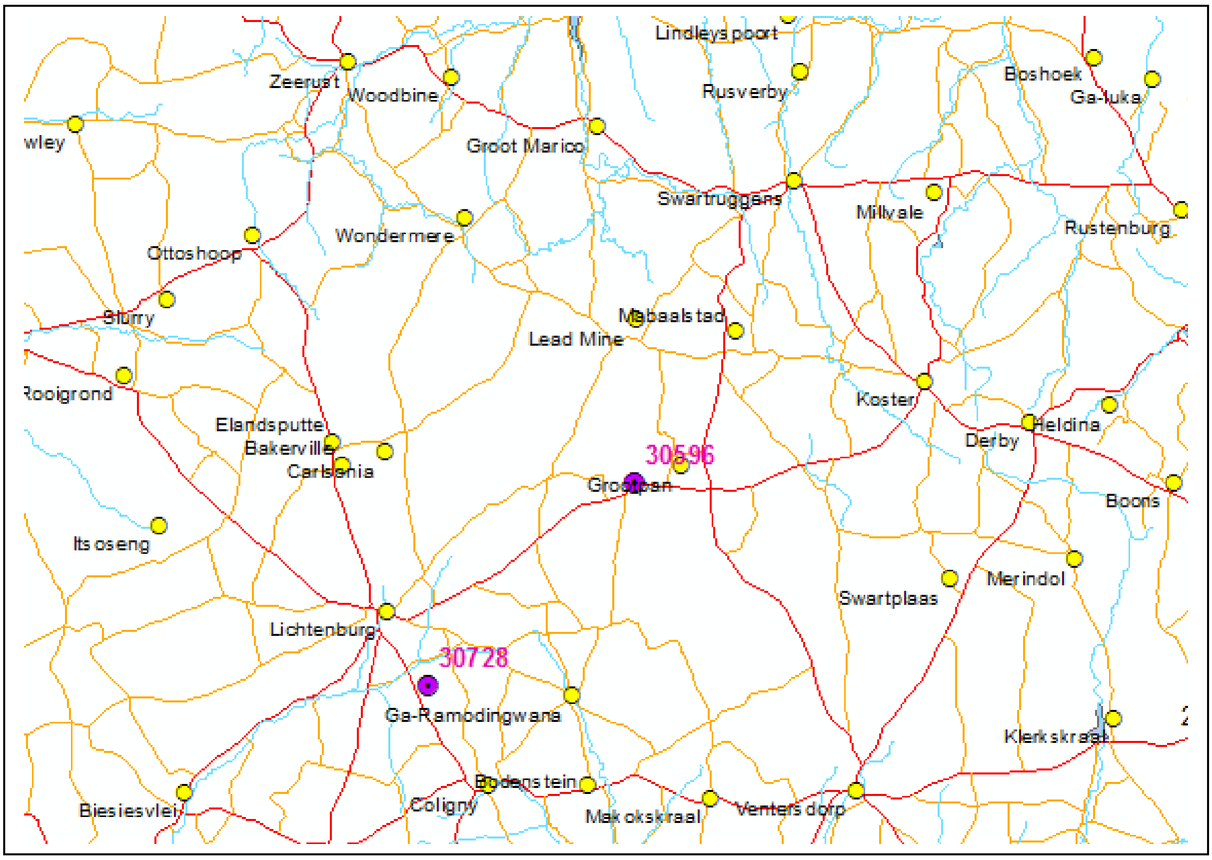

FIG.2.4. Lichtenburg district weather station locations (30728 =Brakpan, 30596 =Grootpan)

Table 2.1: Weather stations location details.

Name	Latitude (°S)	Longitude (°E)	Altitude (m)
Lichtenburg (Brakpan)	26.2265	26.23689	1489
Koster (Grootpan)	25.99017	26.50456	1534
Marble Hall	25.02642	29.36634	846
Vivo (Urk)	23.15006	29.859	849
Soekmekaar (Uitdraai)	23.708011	29.478128	817
Dendron (Sandput)	23.273885	29.135773	1120

The weather variables required as input data for the model are average daily maximum and minimum temperatures, average daily solar radiation, total evapotranspiration and rainfall.

The recorded daily values were averaged and totaled monthly, with the average and total figures used as input into the model. Two sets of weather data are required for use in the model, the long term average data for the area and the actual seasonal weather data.

The collected long term weather data for use in calibration and validation of the model varied in period of years covered. For Grootpan it was 9.6 years, Lichtenburg 6.8 years, Marble Hall 10.8 years, Dendron/Vivo 8.5 years and Polokwane/Soekmekaar 13 years.

2.3.2 Leaf and tuber sample data

In Lichtenburg, four fields were selected for destructive growth sampling, two in each area (Grootpan and Brakpan). The fields were divided into three sections using general observations based on expected variability in crop growth as shown in Fig 2.5. In each section of the field, plots that were 10 m x 10 m (100 m^2) were marked i.e. 3 x 100 m^2 plots per each field. In total on all four fields there was 12 x 100 m^2 main plots. Data for destructive sampling was collected from sub-plots in these main plots. The sub-plots were 3 m x 0.9 m (2.7 m^2). Information on inputs used, land and soil preparation activities, all crop management practices and activities carried out on the fields were also observed and recorded.

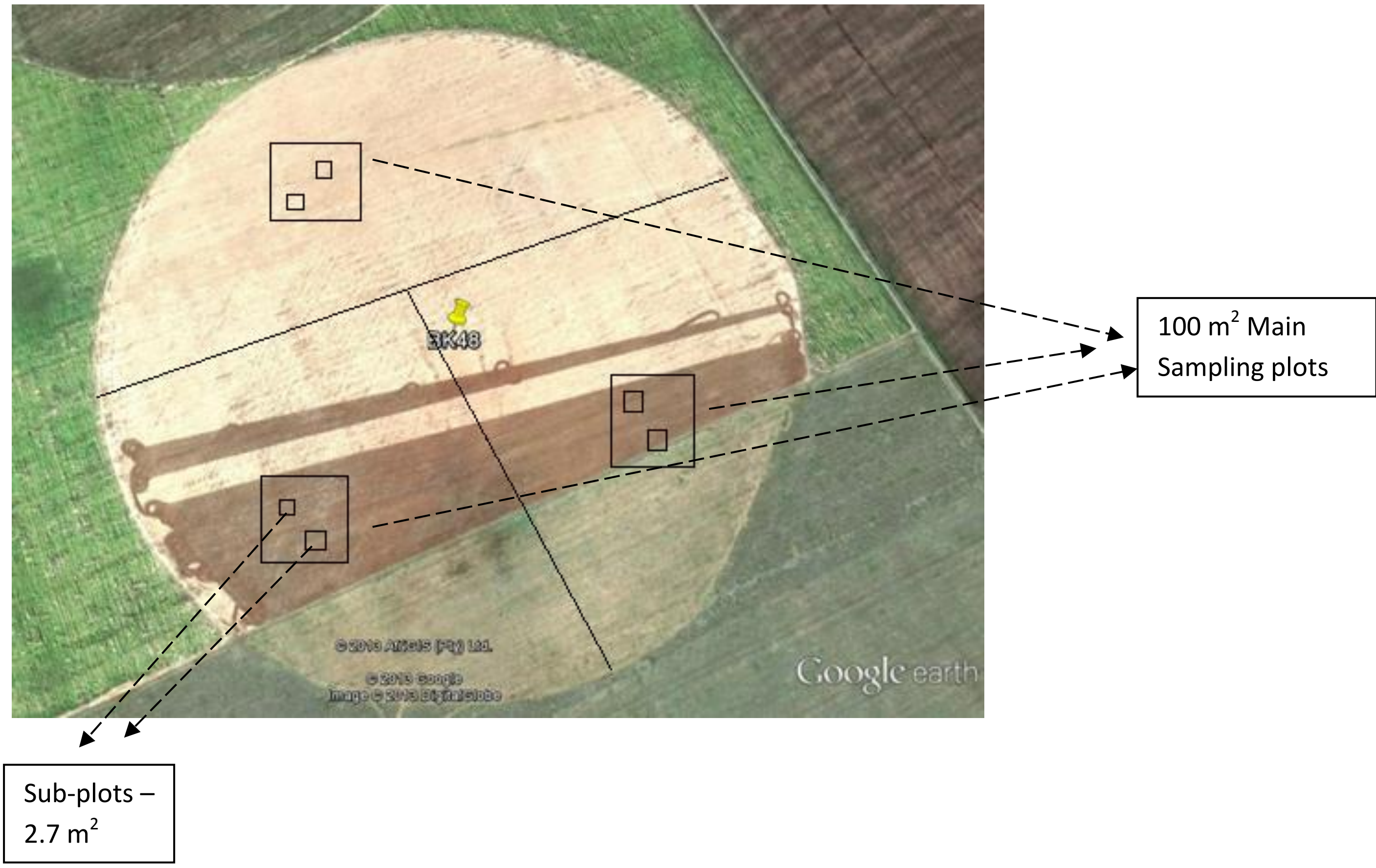

FIG 2.5: Example of a field showing different sections with the sampling main plots and sub-plots.

Data on emergence, plant canopy development and destructive sampling was also collected from these plots.

2.3.3 Sampling procedure

Destructive sampling was conducted from different sub-plots measuring 3 m x 0.9 m and positioned within the main plots at each sampling event. Complete stem, leaf and tuber samples were collected from the sub-plots as from 14 days after emergence (DAE) and at 14 day intervals thereafter until the leaves and stems senesced. There were 2 sub-plots (2.7 m^2 each) for each main plot (100 m^2) at each sampling event. Total plant fresh biomass was determined by weighing the stems, leaves and tubers. The number of plants and stems in each sub-plot sampled were counted and recorded. Sub-samples of fresh leaves, stems, and tubers (about 300g) were taken from each sample for dry matter content determination in the laboratory. The sub-samples were cut into small pieces, weighed, placed in a paper bag and dried in an oven at 70 ^{o}C for at least 48 hours (or until constant mass) to determine dry matter (DM) content of stems, leaves and tubers for total sample dry matter yield calculations.

The tuber samples were also counted, weighed for total fresh mass, then sorted according to the following sizes; 0 - 35, 36 - 50, 51 - 60, 61 - 70 and +70 mm diameter and re-weighed to get the mass of each size class.

2.3.4 Assessing dry matter, fresh matter yield and harvest index

The mass of the total dry (W_{Tot}) matter was calculated using equation 2.1

$$W_{Tot} = W_l + W_{st} + W_{Tub} \quad \text{(Equation 2.1)}$$

where W_l is mass of green leaf dry matter, W_{st} is mass of stem dry matter and W_{Tub} is mass of tuber dry matter. The Harvest index (HI) was calculated using Equation 2.2

$$HI\ (\%) = \frac{W_{Tub}}{W_{Tot}} \times 100 \quad \text{(Equation 2.2)}$$

where W_{Tub} is mass of tuber dry matter and W_{Tot} is mass of total dry matter. Stem and leaf dry matter content (DMC_{l+st}) was calculated according to Equation 2.3

$$DMC_{l+st} = \frac{S_{DM(l+st)}}{S_{FM(l+st)}} \text{ x } 100 \quad \text{(Equation 2.3)}$$

where DMC_{l+st} is the dry matter content of leaves and stems, $S_{DM(l+st)}$ is the sample dry mass and $S_{FM(l+st)}$ is the sample fresh mass. Mass of leaf and stem dry matter yields were calculated using Equation 2.4

$$W_{l+st} = \frac{DMC_{l+st}}{100} \times S_{FM(l+st)} \qquad \text{(Equation 2.4)}$$

where W_{l+st} is the mass of leaf and stem dry matter, DMC_{l+st} is the dry matter content of leaves and stems and $S_{FM(l+st)}$ is the leaf and stem fresh sample mass. The tuber dry matter content (DMC_{Tub}) was calculated using Equation 2.5

$$DMC_{Tub} = \frac{S_{DM(Tub)}}{S_{FM(Tub)}} \text{ x } 100 \qquad \text{(Equation 2.5)}$$

where $S_{DM(Tub)}$ is the tuber sample dry mass and $S_{FM(Tub)}$ is the tuber sample fresh mass. The tuber dry matter yield (W_{Tub}) was calculated according to Equation 2.6

$$W_{Tub} = \frac{DMC_{Tub}}{100} \times S_{FM(Tub)} \qquad \text{(Equation 2.6)}$$

where DMC_{Tub} is the dry matter content (%) of tubers and $S_{FM(Tub)}$ is the mass of the tuber fresh sample. Tuber dry matter yield in kg ha^{-1} (YDM_{Tub}) was calculated using Equation 2.7

$$YDM_{Tub} = \frac{H_A}{A_s} \times W_{Tub} \qquad \text{(Equation 2.7)}$$

where H_A is the area per hectare (10 000 m^2), A_s is the sample area in m^2 and W_{Tub} is the mass of the sample tuber dry matter yield. Fresh tuber yield in kg ha^{-1} (Y_{HA}) was then calculated using Equation 2.8

$$Y_{HA} = \frac{100}{DMC_{Tub}} \times YDM_{Tub} \qquad \text{(Equation 2.8)}$$

where DMC_{Tub} is the dry matter content (%) of tubers and YDM_{Tub} is the tuber dry matter yield per hectare.

The total dry matter yield in grams per plant (YDM_{Tot}) was calculated using Equation 2.9

$$YDM_{Tot} = \frac{W_{Tot}}{N_{plt}} \qquad \text{(Equation 2.9)}$$

where is W_{Tot} is the mass of the total dry matter and N_{plt} is the number of plants in the sample area.

The total fresh matter yield in grams per plant (YFM_{Tot}) was calculated using Equation 2.10

$$YFM_{Tot} = \frac{S_{FM\ (l+st+Tub)}}{N_{plt}} \qquad \text{(Equation 2.10)}$$

where $S_{FM\ (l+st+Tub)}$ is the mass of the total fresh sample including leaves, stems and tubers and N_{plt} is the number of plants in the sample area.

2.3.5 Assessing tuber size distribution

In calculating the tuber size distribution, the forecasted average tuber mass and tuber count at crop end were calculated during the growing season at each sampling event. The forecasted average tuber mass and count was then compared to the actual observed at crop end using regression analysis.

McCain Foods SA takes 10 kg potato tuber samples from a delivered load for quality assessment, hence a 10 kg sample was preferred in this study. The average tuber count per 10 kg sample (N_{ta}) was calculated according to Equation 2.11

$$N_{ta} = \frac{N_{tub}}{S_{FM(Tub)}} \times 10 \qquad \text{(Equation 2.11)}$$

where $S_{FM(Tub)}$ is the tuber sample fresh mass in kilograms and N_{tub} is the number of tubers in the sample. The forecasted tuber count per 10 kg at crop end (N_{ce}) was calculated according to Equation 2.12

$$N_{ce} = N_{ta} \times \frac{Y_{HA}}{Y_F} \qquad \text{(Equation 2.12)}$$

where N_{ta} is the average tuber count per 10 kg at sampling, Y_{HA} is the tuber yield in kg ha^{-1} of the area sampled and Y_F is the forecasted yield at crop end (kg ha^{-1}). The average tuber mass per 10 kg and the forecasted tuber mass per 10 kg at crop end were also calculated at each sampling event using Equations 2.13 and 2.14

$$M_{ta} = \frac{10}{N_{ta}} \qquad \text{(Equation 2.13)}$$

where M_{ta} is the average tuber mass per 10 kg at sampling and N_{ta} is the average tuber count per 10 kg at sampling.

$$M_{ce} = \frac{10}{N_{ce}} \qquad \text{(Equation 2.14)}$$

where M_{ce} is the forecasted tuber mass (in grams per tuber) at crop end and N_{ce} is the forecasted tuber count per 10 kg at crop end.

2.4 LINTUL model simulations

The LINTUL-POTATO crop growth model simulates potential and water limited attainable crop yield. Weather and management input data collected was used in the model to produce simulations for the entire growing season for development of ground cover, total dry matter accumulation and tuber fresh matter yield from planting to harvest. Management input data includes date of planting and planting depth. Crop yield potential has been observed to considerably vary owing to different planting dates and maturity ratings (Lobell *et al*., 2009; Franke *et al*., 2011). The soil texture is also part of the input data into the model. Soil texture affects crop growth indirectly by influencing the soil available water for plant growth. The different texture classes have different parameter values for field capacity, wilting point and available soil water (Andales *et al.,* 2011).

The sequence of events in LINTUL-Potato has crop development starting at planting, where the planting depth and effective temperature determine the time it will take the crop to emerge. Leaf area expansion in the early crop growth stages is determined by temperature. The leaves are divided into classes that are based on the day the leaves are formed. The different leaf daily classes will senesce when the leaf area that is above the leaf layer causes strong shading (Kooman & Haverkort, 1995). The growth rate of tubers also affects the duration of leaf growth, with fast tuber growth reducing the duration. When the leaves in the latest class senesce, then crop growth will cease. The dry matter produced daily is calculated from the amount of photosynthetically intercepted radiation intercepted by the crops' canopy and also from the leaf area index and its conversion efficiency for dry matter production.

Temperature and daylength will determine the crops' development rate from after emergence till tuber initiation. After tuber initiation, allocation of assimilates to the tubers is top priority, with tuber growth mainly being a result of the product of the relative growth rate and the tuber mass. Thereafter, as the tubers become larger, they become an increasing sink. Initially, they are not large enough for all the assimilates needed to maintain simultaneously exponential tuber and leaf growth. However, all assimilates produced will go to the tubers in the later stages of crop growth (Kooman & Haverkort, 1995).

Data from the destructive measurements was used for model calibration and independent data collected from other production areas in a different cropping season were used to validate the model. For model calibration, summer potato crops grown in the main season were used, whilst for model validation, winter potato crops grown in the low season were used.

2.4.1 Model calibration

In calibrating the model, input data collected from field observations, destructive plant sampling and weather stations was used. For the variety Pentland Dell there were two fields used to calibrate the model, namely Brakpan (BK) and Piet Botha (PB). Another two fields with different varieties, Innovator and Markies, were also used to calibrate the model. The fields were Steyn Marynick (SM) for the Innovator and Han Liebenberg (HL) for the Markies. For BK and SM, the long term and actual season's weather data as recorded at the Lichtenburg weather station was used. These two fields were approximately 15 km apart. The long term weather data for the period July 2006 to January 2013 was used as shown in Table 2.2

Table 2.2: Average Long term weather data for Lichtenburg (Source: Agricultural Research Council SA)

Variable	Jan	Feb	Mar	April	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Rain (mm)	97.8	63.5	66.3	50.9	13.8	18.3	1.9	6.1	13.8	40.0	49.4	87.6
Radiation (MJ m^{-2})	20.6	21.0	17.8	14.9	15.5	14.7	15.9	20.0	24.7	23.3	22.3	22.4
Max Temp (°C)	27.9	27.9	27.1	23.5	21.3	18.2	18.3	21.3	26.0	27.5	28.0	28.5
Min Temp (°C)	16.0	15.1	13.8	10.7	6.3	2.5	2.0	4.3	8.3	12.1	13.6	15.3
ETo (mm)	124.1	106.7	103.1	72.4	75.5	78.1	87.4	116.2	155.0	160.9	193.3	147.6

For field PB and HL which were approximately 10 km apart, the long term and actual season's weather data as recorded at the Koster weather station was used. The long term weather data for the period June 2003 to January 2013 was used as shown in Table 2.3.

Table 2.3: Long term weather data for Grootpan (Source: Agricultural Research Council SA)

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain (mm)	101.4	90.0	86.4	44.0	14.5	10.3	0.9	6.9	13.4	36.6	61.8	83.4
Radiation (MJ m^{-2})	20.2	19.9	17.4	14.9	13.8	12.6	13.2	16.1	19.9	20.6	21.5	22.3
Max Temp (°C)	26.9	26.8	25.4	22.8	21.3	18.7	18.4	21.3	25.7	27.2	27.8	27.7
Min Temp (°C)	15.9	14.8	12.9	9.1	4.3	0.8	0.1	3.4	7.6	11.8	13.5	14.9
ETo (mm)	143.2	107.8	79.6	85.0	80.2	64.9	72.7	91.7	126.7	142.6	179.1	134.1

Other input data used for BK was a planting depth of 15 cm, rooting depth of 50 cm, soil texture of 18% clay, a tuber dry matter content of 22% for the variety Pentland Dell and 100% of the planted area was under irrigation. For PB, the planting depth and rooting depth used were also 15 cm and 50 cm respectively and the soil texture was 24% clay. Tuber dry matter content was the same as for BK since the variety was the same and the whole area was also under irrigation.

The other two fields had different varieties. For field SM the cultivar was Innovator, and a planting depth of 15 cm and rooting depth of 50 cm was used. Soil texture was 22% clay and the tuber dry matter content used was 19.5%. Area under irrigation was 100%. Markies was the variety planted on HL and planting and rooting depth were 15 cm and 50 cm respectively. Soil texture on this field was 27% clay and tuber dry matter content used was 19%. Area under irrigation was also 100%.

The input data was used to run simulations throughout the growing season at 2 week intervals from 14 DAE. Every time a leaf and tuber sample was taken, a growth simulation was run with the model and the predicted and forecasted yields recorded. The growth simulation used real-time actual season weather data up to the day of sampling and then long term weather data till the expected harvest date. The predicted yields based on the data used as input into the model at the various sampling intervals were compared with the observed yields based on the samples obtained from the fields. Based on comparisons between the model predicted yield and the actual observed yield per sampling event from the sampling conducted throughout the growing season, actual : attainable yield ratios were determined for use in calculating the actual yield from the model predicted yield. This represents the percentage of the attainable yield as determined by the model that was actually achieved under field conditions. The adapted ratios were those from the sampling event when Harvest Index (HI) was close to 75%. Since in the LINTUL model we used a HI of 75%, the ratio achieved at the sampling point closest to this HI value would be more accurate.

The attainable yield simulated by the model at each sampling event and the actual yield observed from the samples were used to calculate the ratio for comparison using Equation 2.15

$$V_R = \frac{Y_{HA}}{Y_{LN}} \qquad \text{(Equation 2.15)}$$

where V_R is the varietal ratio of actual : attainable yield, Y_{HA} is the observed yield per hectare and Y_{LN} is the LINTUL predicted attainable yield per hectare.

2.4.2 Model validation

Model validation and evaluation can be thought of as a documentation of model accuracy for specific predictions in specified environments, with appropriate consideration given to possible errors in input variables or evaluation data (Jones *et al*., 2003). The essential parts of any minimum data set for evaluation are a complete record of the information required to run the model and the field information on the aspects for which the model is being validated. The data sets should have not been previously used for calibration and should represent the complete array of environments and crop sequences for which the model will be applied. In this study, the same procedure used to calibrate the model was used in validation, except that independent crop, field and weather data from different production areas was used.

The production areas used for the validation were Marble Hall, Soekmekaar, Dendron and Vivo. The main variety used for validation was Innovator, which was grown on 10 different fields. Markies, which was grown on 2 different fields was also used as shown in Table 2.4. Samples were taken from the various fields at different stages in the growing season. Some fields were sampled early in the season and then again late in the season at harvest or closer to harvest. Row spacing was different for the different fields and ranged from 0.75 m to 0.90 m.

The sample length used was 3 m along the row/ridge. Sample area was calculated using Equation 2.16

$$A_S = R_L \times R_S \quad \text{(Equation 2.16)}$$

where A_S is the size of the sample area (m^{-2}), R_L is the length (m) of the row sampled and R_S is the spacing between the rows sampled in metres. The yield per hectare was calculated by multiplying the mass of the harvested sample with the proportion of the sample area to a hectare following the procedure below:

- Calculate the sample area by multiplying the length of sample area with the row spacing as in Equation 2.16.
- Calculate the average mass of all the samples collected from the same field.
- The average yield per hectare was then calculated using Equation 2.17.

$$Y_{HA} = \frac{10000}{A_S} \times S_{FM(Tub)} \quad \text{(Equation 2.17)}$$

where Y_{HA} is the yield per hectare (kg ha^{-1}), A_S is the sample area and $S_{FM(Tub)}$ is the mass of the sample.

Table 2.4: Validation field details

Field No	Production area	Field Name	Latitude (°S)	Longitude (°E)	Variety planted	Planting date	Long term weather	Short term weather	Planting depth (cm)	Soil % Clay	Tuber DMC %
1	Marble Hall	Lupedi	24°56.721	29°21.069	Innovator	6-Jun-14	Marble Hall	Marble Hall	18	15	19.5
2	Marble Hall	Henk P3	24°59.315	29°09.852	Innovator	7-Jul-14	Marble Hall	Marble Hall	15	18	19.5
3	Marble Hall	Rodash L1	24°57.387	29°14.306	Innovator	19 Jun 14	Marble Hall	Marble Hall	15	18	19.5
4	Vivo	Fick	23°06.109	29°29.188	Innovator	18-Jun-14	Dendron	Urk	15	18	20.0
5	Vivo	Philny	22°51.592	29⁰09.460	Innovator	21-May-14	Dendron	Urk	18	25	19.5
6	Vivo	Elmar	23°04.913	29°07.297	Innovator	20-Jun-14	Dendron	Urk	15	20	19.5
7	Dendron	Pretorius	22°31.091	28°43.923	Innovator	24-Feb-14	Dendron	Sandput	15	15	19.5
8	Soekmekaar	Bagga	23°28.599	29°56.468	Innovator	20-May-14	Polokwane	Uitdraai	15	18	19.5
9	Soekmakaar	Mohali	23°26.503	29°53.081	Innovator	9-Jun-14	Polokwane	Uitdraai	15	15	19.5
10	Soekmakaar	Dora	23°27.672	29°57.869	Innovator	27-May-14	Polokwane	Uitdraai	15	15	19.5
11	Dendron	Lekgraal	23°21.287	29°33.593	Markies	10-Jul-14	Dendron	Sandput	18	15	19.0
12	Dendron	Soetdorings	23°18.331	29°32.327	Markies	16-Jul-14	Dendron	Sandput	18	15	19.0

Model yield predictions were calculated for the different sampling dates by inputting the required field and weather data into the LINTUL model (Section 2.4.1). The predicted yield was then multiplied by the varietal ratio to obtain the actual yield using Equation 2.18

$$Y_F = Y_{LN} \times V_R \qquad \text{(Equation 2.18)}$$

where Y_F is the forecasted yield (tha^{-1}), Y_{LN} is the LINTUL calculated yield and V_R is the varietal ratio of actual: attainable yield. The calculated forecast yield was then compared to the actual observed yield using a regression analysis.

The long term weather data that was used as input into the model for validation, was collected from weather stations in the various areas. For Marble Hall, long term weather data used was from the period April 2002 to January 2013 and is shown in Table 2.5.

Table 2.5: Long term weather data for Marble Hall (Source: Agricultural Research Council SA)

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain (mm)	93.7	74.8	65.9	29.6	5.7	4.2	1.6	3.6	13.2	44.8	80.4	112.4
Radiation ($MJ\ m^{-2}$)	24.5	24.7	21.7	17.9	16.4	14.6	15.7	18.8	23.1	24.3	24.7	25.0
Max Temp (°C)	31.5	32.2	30.5	27.7	25.8	23.1	23.1	26.0	30.7	31.1	31.0	30.8
Min Temp (°C)	19.0	18.3	16.8	13.3	7.7	4.1	3.2	6.5	10.7	15.1	17.0	18.2
ETo (mm)	155.5	147.7	140.5	92.0	92.1	75.4	83.4	107.8	141.0	144.6	147.3	161.6

Seasonal weather data was collected from the same station. For Soekmekaar, long term weather data from 13 years for Polokwane was used as shown in Table 2.6. The actual seasonal data was collected from the weather station at Uitdraai.

Table 2.6: Long term weather data for Polokwane (Source: Africa Weather Services)

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain (mm)	72.6	57.9	48.2	36.2	9.0	4.9	1.6	1.7	3.6	41.5	93.8	89.1
Radiation (MJ m^{-2})	23.3	24.9	21.1	18.1	17.7	16.4	17.0	19.7	23.1	24.0	23.4	23.2
Max Temp (°C)	27.8	28.1	26.9	24.7	23.1	20.6	20.3	23.2	26.1	26.8	26.8	27.2
Min Temp (°C)	17.4	16.9	15.5	12.6	8.3	5.6	4.6	7.3	10.7	13.5	15.3	16.6
ETo (mm)	159.7	152.2	139.2	100.5	95.5	81.6	92.8	119.6	153.1	172.8	155.1	158.5

The same long term weather data was used for Dendron and Vivo. However, the actual seasonal weather data used was different and obtained from the weather station at Sandput for Dendron and Urk for Vivo.

Table 2.7: Long term weather data for Dendron (and Vivo) for 8.5 years (Source: Potatoes South Africa)

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain (mm)	74.2	18.6	47.1	29.3	9.5	3.5	2.5	1.5	6.1	45.4	77.9	69.8
Radiation (MJ m^{-2})	23.3	24.9	21.1	18.1	17.7	16.4	17.0	19.7	23.1	24.0	23.4	23.2
Max Temp (°C)	30.4	31.0	29.9	27.0	26.0	23.4	22.8	25.2	28.9	29.6	29.7	29.6
Min Temp (°C)	17.7	17.3	15.6	12.4	9.6	6.2	5.8	7.9	11.7	14.4	15.9	16.7
ETo (mm)	159.7	152.2	139.2	100.5	95.5	81.6	92.8	119.6	153.1	172.8	155.1	158.5

2.5 Data analysis

In validation of the model, a comparison was done by plotting model results against the actual yield results. Model accuracy was tested using the Pearson's correlation coefficient (r) , the Spearman's rank-order correlation coefficient (r_s), the regression coefficient of determination (R^2), mean absolute error (MAE), root mean square error (RMSE) and Dimensionless index (D-index) values. The MAE and RMSE both express average model-prediction error. Willmott and Matsuura (2005) however found MAE to be a more natural measure of average error and recommended its use in dimensioned evaluations and inter-comparisons of average model-performance error. They also demonstrated that RMSE was not a true or reliable measure of average error and should therefore not be used to compare average performance of two or more models. This is because RMSE is based on the sum of squared errors and is a function of the average error (MAE), the distribution of error magnitudes (squared errors) and $n^{1/2}$. It therefore does not describe the average error alone. The D-index of agreement has an upper value of 1.0 for a perfect model and a lower value of -1.0. A t-test (SPSS) was also used to test for any significant differences between the model forecasted and observed yields, the forecasted and observed tuber numbers, and the average tuber mass per 10kg.

CHAPTER 3: RESULTS

3.1 Model Calibration

When calibrating models, usually a selected number of uncertain parameters are adapted, within their domain, to obtain a better quantitative agreement between model results and reality. For the LINTUL model, the parameters which include the growth rate of sprouts, the harvest index and the degree days from emergence to 100% crop cover are shown in Table 3.1.

Table 3.1: LINTUL model parameters

Parameter	**Value**
Harvest index (%)	75
Sprout growth rate (mm/degree day)	0.7
Degree days emergence - 100% crop cover	650
RUE (all radiation) (g/MJ light intercepted)	1.25
Min temp photosynthesis (T.Average)	3
Min temp optimal photosynthesis (T.Average)	15
Max temp optimal photosynthesis (T.Average)	20
Max temp photosynthesis (T.Average)	28

In this study, the LINTUL model was calibrated using data collected at Lichtenburg, North West Province for three different varieties, namely Pentland Dell, Innovator and Markies which were grown on different farms. The parameter value of 75% for harvest index was also obtained in the calibration. Weather data from two weather stations in the Lichtenburg area was used as input data into the LINTUL models used in the calibration. The model predicted yields were compared to the actual observed yields at sampling in the season (December 2013 to May 2014). Leaf and tuber samples were collected at about two weekly intervals from after the emergence of sprouts until harvest. The data collected from the fields were these varieties where grown, was used to calculate the actual: attainable ratios per variety using equation 2.16 (Section 2.4.1). The actual: attainable yield ratios calculated and adapted for the different varieties were 0.78 (78%) for Pentland Dell, 0.61 (61%) for Innovator and 0.70 (70%) for Markies. Since there were two fields for Pentland Dell, one being a low potential and the other a high potential crop, the average was calculated and used as the ratio for an average Pentland Dell crop. The data collected from the samples was also used for growth analysis.

3.1.1 Growth analysis results

Total dry matter (DM) and fresh matter (FM) yields for the different varieties grown were measured and the results are shown in Fig 3.1 and Fig 3.2. The development of FM and DM yields for potatoes as the crop grows, followed a nearly linear growth pattern which levelled off or slightly dropped at crop end depending on the variety. The growth analysis data collected over the season for the different varieties agreed with the findings of Kolbe and Stephan-Beckman (1997). They found that after tuber initiation, the tuber dry matter initially increases exponentially, after which a long period of nearly linear growth can be seen, followed by a decreasing rate and finally an end to growth as the shoot senesces.

Crop growth on all the fields in the study was generally good. The variety Pentland Dell was grown on two fields, namely BK and PB. On BK, the FM and DM yield development followed a nearly linear growth as shown in Fig.3.1. The crop was however, affected by early blight (*Alternaria solani*) and had to be harvested pre-maturely three weeks before the planned harvest date. In this study, the crop planted on this field was considered to be of low potential. The other Pentland Dell crop grown on field PB was therefore considered to be of high potential and it grew for five weeks longer than the crop on BK. FM and DM yield development was also observed to follow a nearly linear growth as shown in Fig.3.1. The variety Innovator, was grown on the field SM and FM and DM yield were also observed to follow a nearly linear growth as shown in Fig.3.2. There was however, a dry spell towards the end of the season as a result of a pivot breakdown, which caused a sharp decline in yield development. The third variety in the study, Markies, was grown on field HL and its FM and DM yield development was observed to follow a nearly linear growth as shown in Fig 3.2. Crop growth was good on this field, but was slightly affected mid-season by early frost damage.

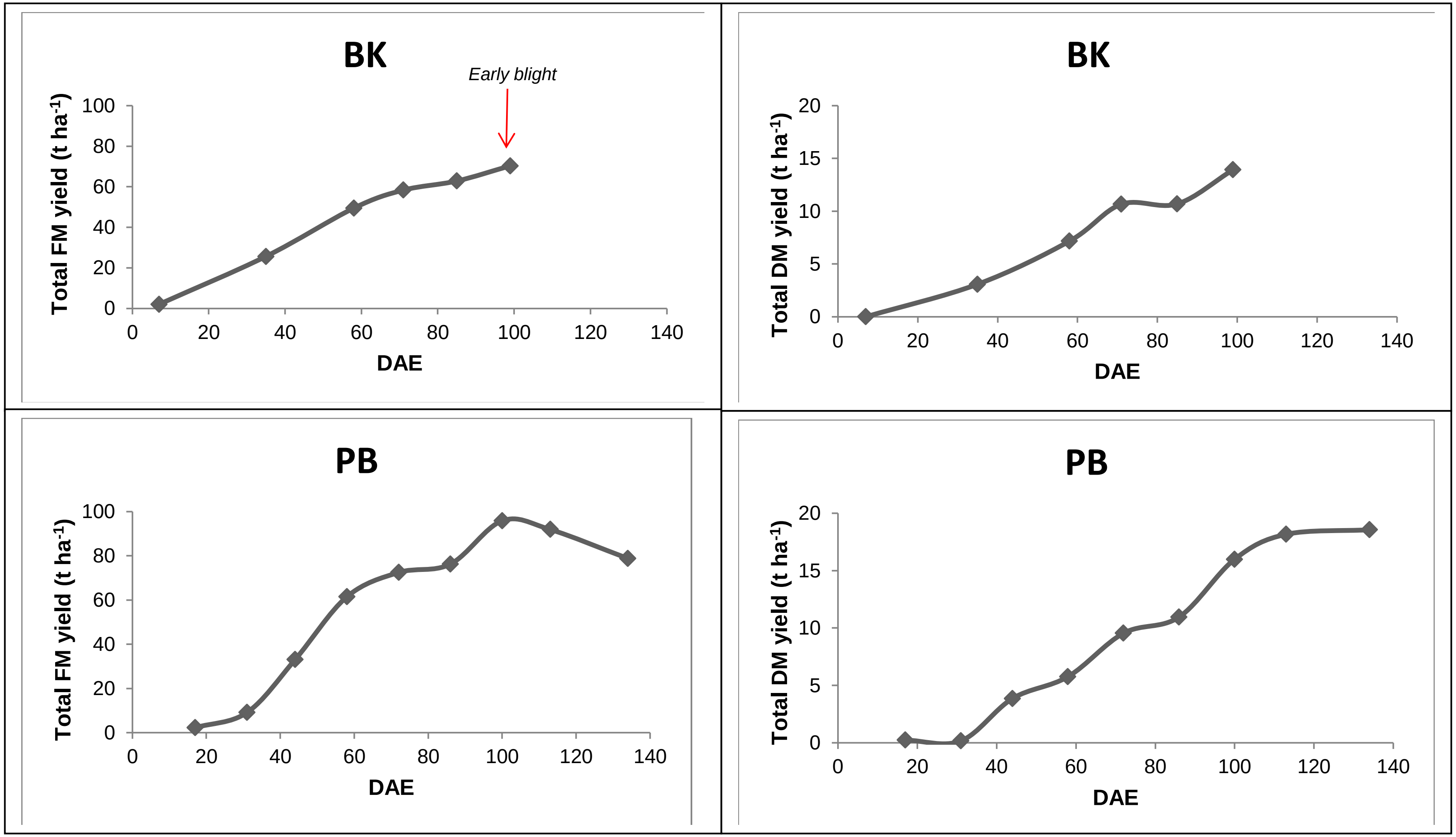

FIG.3.1: Total FM and DM yields recorded for Pentland Dell variety planted on the different fields BK and PB (Model calibration data).

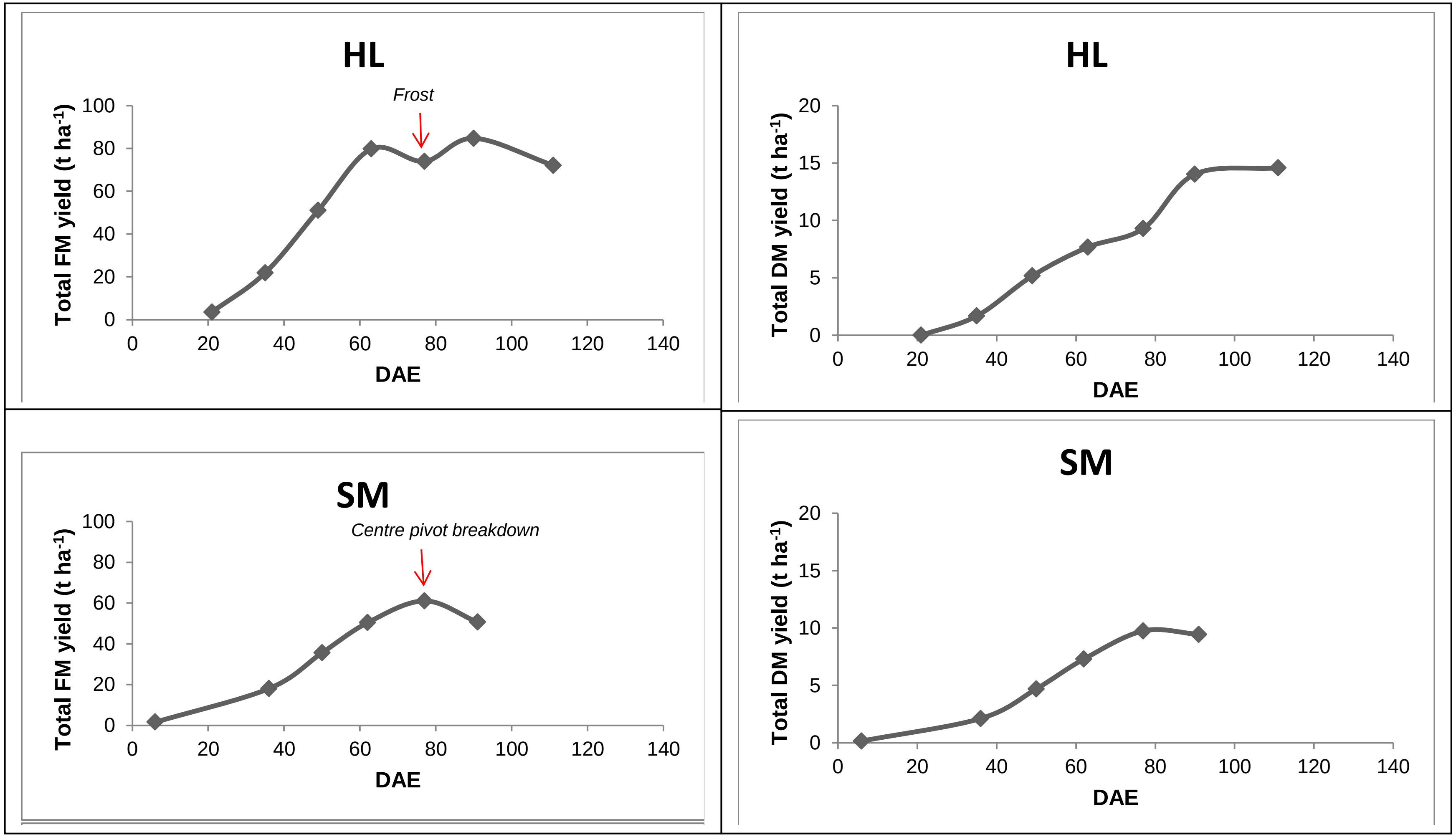

FIG.3.2: Total FM and DM yields recorded for Markies (HL) and Innovator (SM) planted on the different fields HL and SM (Model calibration data).

Data for tuber fresh matter (TFM) and tuber dry matter TDM yields was also measured and the results are shown in Fig 3.3 and Fig 3.4. Early in the season before tuber initiation, the TFM fresh yield was 0 as no tubers had formed as yet. After initiation, tubers were initially small and their TFM and TDM yield were low. As the leaves and branches expand more assimilates from photosynthesis were translocated and deposited in the tubers, and they expanded in size (Kolbe and Stephan-Beckmann, 1997). As the tubers expanded in size, their TFM and TDM yields also gradually increased. For the variety Pentland Dell grown on field BK, the TFM and TDM yields increased exponentially until the crop was harvested as shown in Fig 3.3. For field PB, the TFM and TDM yields also followed a nearly linear growth pattern as shown in Fig 3.3. Towards crop end or final harvest, the TFM and TDM yields increased at a decreasing rate as the crop matured and the leaves and stems senesced.

For the fields HL (Markies) and SM (Innovator), the TFM and TDM yields followed nearly linear growth patterns as shown in Fig 3.4. Towards crop end, the values levelled off as the leaves senesced and the crop matured. The growth analysis data collected over the season agreed with the findings of Kolbe and Stephan-Beckmann (1997). They found that after tuber initiation, the TDM yield initially increased exponentially, after which a long period of nearly linear growth was observed, followed by a decreasing rate and finally an end tp growth as the shoots senesced.

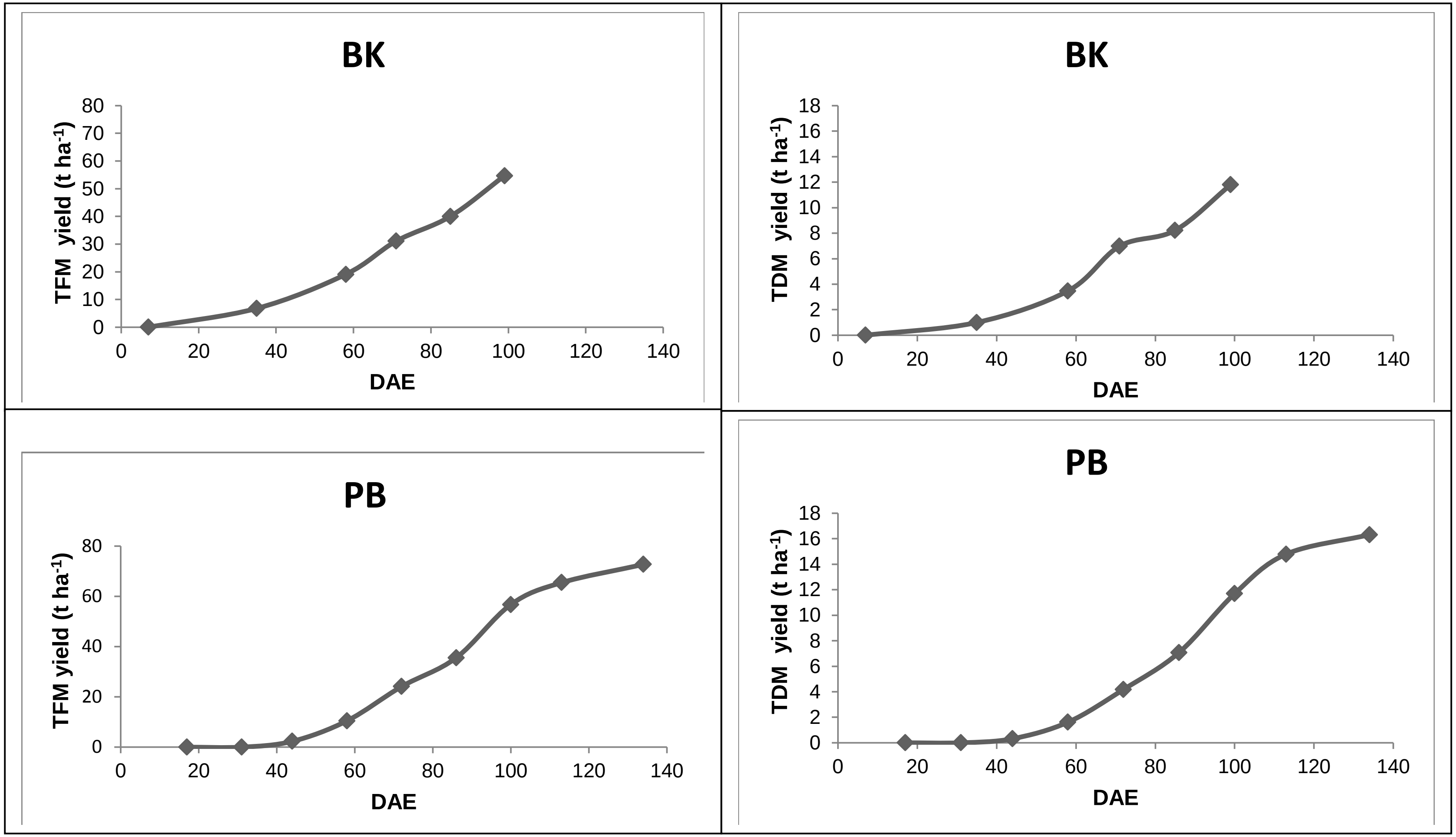

FIG.3.3: TFM and TDM yields recorded for Pentland Dell variety planted on the different fields BK and PB (Model calibration data).

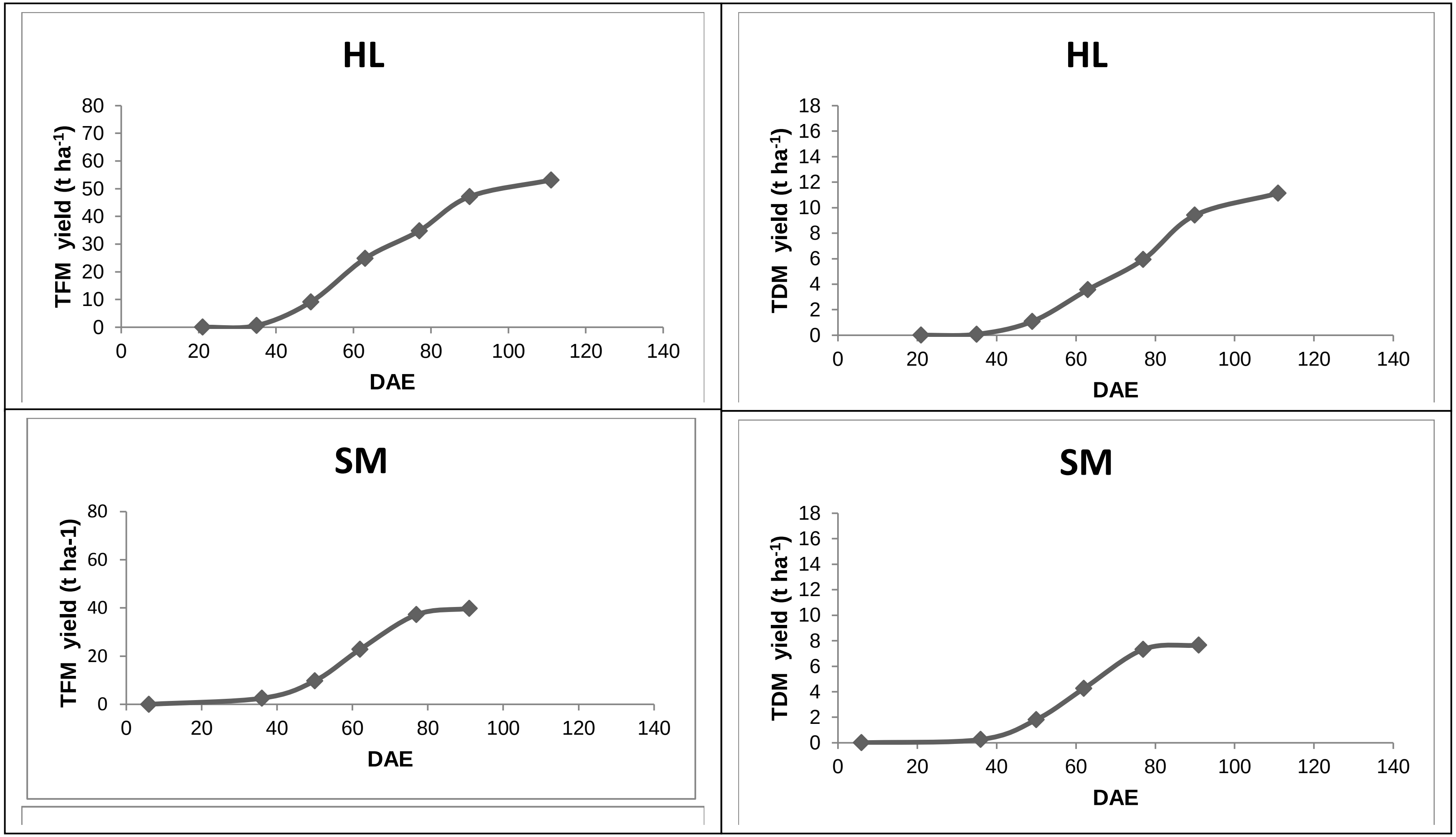

FIG.3.4: TFM and TDM yields recorded for Markies variety (HL) and Innovator variety (SM) planted on different fields (Model calibration data).

3.1.2 Final tuber yields

Pentland Dell

This variety was grown on two farms, BK and PB and the results shown in Table 3.1 and 3.2 were compared collectively. Tables 3.2 and 3.3 show the actual observed and model simulated tuber yields as recorded at different sampling dates (2 weekly intervals) in the growing season as well as the final forecasted yields.

The model predicted yields were higher than the observed yields because the model simulates the attainable yield under conditions where only water is the limiting factor and other yield limiting factors are absent. This difference in yield also known as the yield gap was higher in the early stages of crop growth. This could be a result of the model using a HI of 75%, which under field conditions has been observed to vary throughout the crop growth stages. Earlier in the season from emergence stage to the tuber initiation stage, HI is 0 as there is no tuber yield yet. Economic yield for potatoes is obtained from the tubers, so only until that stage when tubers are formed and begin to bulk will the economic yield start to be realized. HI of potatoes increases progressively from tuber initiation onwards, gradually rising as the tubers bulk and mature (Hay, 1995). As the crop progresses to maturity, the plants begin senescing and will eventually die off, resulting in loss of above-ground dry matter and only leaving the tubers for harvest. In this study, the HI considered was only up to the stage when it was close to 75%. Beyond this stage, HI was not recorded as shown in Table 3.2.

Table 3.2: Calibration data set for forecasted attainable yield and observed potato tuber yield of Pentland Dell (Field BK) considered low potential in 2013 season.

Date	DAE	HI %	Model simulated Attainable fresh tuber yield at sampling (t ha^{-1})	Actual Observed fresh tuber yield at sampling (t ha^{-1})	Actual: Attainable ratio at sampling	Model Forecasted Attainable fresh tuber yield at final harvest (t ha^{-1})	Expected actual fresh tuber yield at harvest based on ratio (t ha^{-1})
2-Jan-14	35	33	14.3	6.8	0.48	80.6	38.7
16-Jan-14	58	49	29.9	19.1	0.64	84.4	54.0
29-Jan-14	71	65	44.1	31.1	0.71	80.2	56.9
12-Feb-14	85	77	60.4	40.0	0.66	79.5	52.5
26-Feb-14	99		71.9	54.7	0.76	81.5	61.9
11-Mar-14 (Final harvest)	112		82.3	51.9	0.63	82.3	51.8

NOTE: Expected actual fresh tuber yield at harvest is calculated from the model forecasted attainable fresh tuber yield and the actual: attainable ratio at sampling

It was observed that a HI of 77% which was close to the 75% considered of interest in this study, was achieved at 85 DAE as shown in Table 3.1 and the expected fresh tuber yield at harvest of 52.5 t ha^{-1} compared well to the actual observed yield at final harvest of 51.9 t ha^{-1}. At that stage the actual: attainable ratio was 0.66 (66%). The crop grown on this field was considered a low potential crop since it was infected by early blight (*Alternaria solani*) and the crop had to be harvested pre-maturely at 112 DAE in comparison to the other Pentland Dell crop that was harvested at 134 DAE. The fresh tuber yield expected at final harvest as forecasted at the various sampling dates varied from 38.7 t ha^{-1} as at 35 DAE to 51.8 t ha^{-1} as at the final harvest date at 112 DAE. The actual yield forecast also remained quite consistent from as early as 35 DAE to the harvest date. As shown in Table 3.2, from 58 DAE the yield forecasted was quite accurate as it compared well to the actual observed at final harvest.

The other Pentland Dell crop (PB) was grown on another farm approximately 60 km away. This crop was considered a high potential crop as growth was vigorous and it grew three weeks longer than the BK Pentland Dell crop (Table 3.2). A HI of 73% (close to 75% of interest) was achieved at 100 DAE and the actual: attainable ratio was 0.90 (90%) which indicates it was a high yield potential Pentland Dell crop as shown in Table 3.3. Usually when HI is lower than 75%, the tubers will not have attained the assumed usable economic yield and harvest will be premature. Beyond 75 % HI, leaf senescence was considered to be greater than 80% and the foliage DM could not therefore be collected (Haverkort, 2014; Personal communication). The fresh tuber yield forecasted at final harvest at the various sampling dates varied little from 65.7 t ha^{-1} as at 44 DAE to 73.0 t ha^{-1} at harvest which compared well to the actual observed of 72.7 t ha^{-1} at final harvest.

Table 3.3: Calibration data set for forecasted attainable yield and observed potato tuber yield of potato variety Pentland Dell (Field PB) considered high potential in 2013 season.

Date	DAE	HI %	Model simulated attainable fresh tuber yield at sampling (t ha^{-1})	Actual Observed Fresh tuber yield at sampling (t ha^{-1})	Actual: Attainable ratio at sampling	Model Forecasted attainable fresh tuber yield at final harvest date (t ha^{-1})	Expected actual fresh tuber yield at harvest based on ratio (t ha^{-1})
29-Jan-14	44	9	3.0	2.3	0.76	86.5	65.7
12-Feb-14	58	28	12.7	10.4	0.82	83.4	68.4
26-Feb-14	72	45	27.8	24.1	0.87	86.5	75.3
12-Mar-14	86	65	47.7	35.5	0.74	83.9	62.1
26-Mar-14	100	73	62.7	56.7	0.90	86.3	77.7
8-Apr-14	113		73.2	65.4	0.89	87.5	77.9
29-Apr-14 (Final harvest)	134		84.9	72.7	0.86	84.9	73.0

NOTE: Expected actual fresh tuber yield at harvest is calculated from the model forecasted attainable fresh tuber yield and the actual: attainable ratio at sampling

The combined observed yield results from the two fields (BK and PB) were regressed against model simulated yields for each sampling date and the results are shown in Fig.3.5 and Table 3.4.

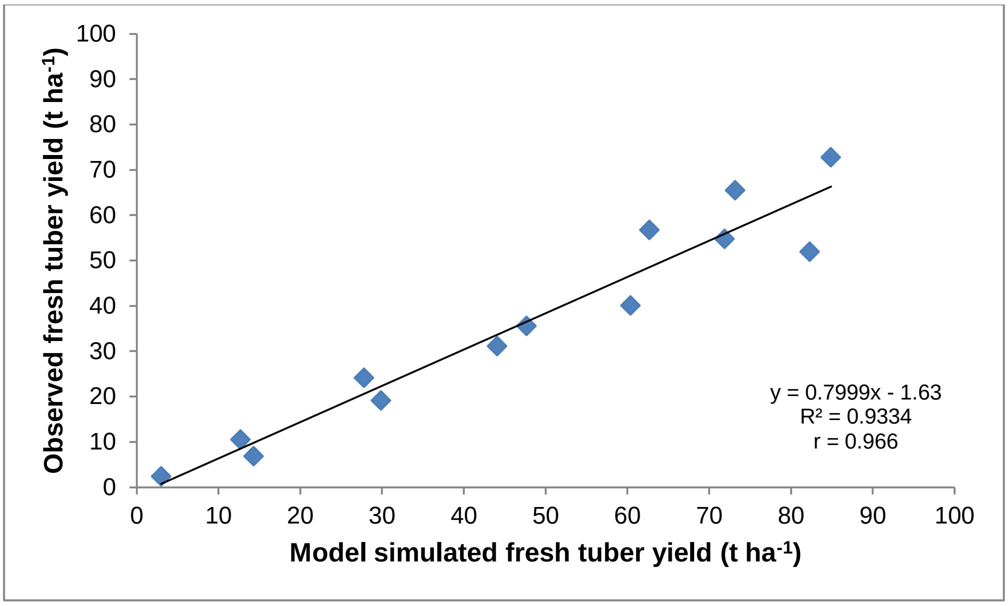

FIG.3.5: Pentland Dell fresh tuber yield correlation from 35 to 134 DAE

There was a strong correlation between the model predicted yield and the observed yield with an r value of 0.97 (R^2 = 0.93). Data from the thirteen sampling events was used in the analysis. RMSE was high at 13.57 t ha^{-1}. The MAE was also high at 11.09 t ha^{-1} as shown in Table 3.4. The observed and the model simulated attainable yields at sampling were different resulting in the high error values. The expected fresh tuber yields at final harvest as calculated from the model forecasted attainable fresh tuber yields and the actual: attainable ratio, however compared well to the observed yield at harvest from as early in the season as 44 DAE.

Table.3.4: Summary of fresh tuber yield regression and correlation results (actual vs simulated attainable yield) for Pentland Dell calibration data set in 2013 season.

	Model Simulated fresh tuber yield	Observed fresh tuber yield
N	13	13
MSE	184.132	
RMSE (t ha^{-1})	13.570	
MAE (t ha^{-1})	11.094	
r	0.966	
R^2	0.933	
D-index	0.921	

Innovator

This variety was grown on field SM and the yield results are shown in Table 3.5. Innovator is a short grower and early maturing variety and hence the HI of 75% was achieved earlier when compared to the other varieties. The variety was harvested 105 DAE in comparison to Pentland Dell, which was harvested at 112 DAE for the premature crop, and 134 DAE for the mature crop.

Table 3.5: Calibration data set for forecasted and observed potato tuber yield of potato variety Innovator (Field SM) in 2013 season.

Date	DAE	HI %	Model simulated attainable fresh tuber yield at sampling (t ha^{-1})	Actual observed Fresh tuber yield at sampling (t ha^{-1})	Actual: Attainable ratio at sampling	Model Forecasted attainable fresh tuber yield at final harvest (t ha^{-1})	Expected actual fresh tuber yield at harvest based on ratio (t ha^{-1})
2-Jan-14	36	7	2.5	2.5	1.00	81.6	81.6
16-Jan-14	50	34	18.5	9.7	0.52	85.9	44.7
29-Jan-14	62	52	34.4	22.7	0.66	83.0	54.8
12-Feb-14	77	74	60.6	37.2	0.61	82.1	50.1
26-Feb-14	91		73.6	39.8	0.54	84.4	45.6
11-Mar-14 (Final harvest)	105		85.3	38.6	0.45	85.3	38.4

NOTE: Expected actual fresh tuber yield at harvest is calculated from the model forecasted attainable fresh tuber yield and the actual: attainable ratio at sampling

For this variety, 74% HI (close to target of 75%) in this study was achieved at 77 DAE and the actual: attainable ratio was 0.61 (61%) as shown in Table 3.5. The forecasted fresh tuber yield at final harvest as determined at the various sampling events varied from 81.6 t ha^{-1} to 38.4 t ha^{-1} as shown in Table 3.5. The expected actual yield at 74% HI was 50.1 t ha^{-1} and it did not compare well to the actual observed yield of 38.6 t ha^{-1} at final harvest. The reason for this could be a result of sprinkler problems experienced on this field early in the season. The sprinklers initially applied variable amounts of water across the field resulting in uneven emergence of sprouts as they emerged at different time periods, with some areas emerging as late as two weeks when compared to the rest of the field.

The observed fresh tuber yield from five sampling events was regressed against model simulated yields and the results are shown in Fig 3.6 and Table 3.6.

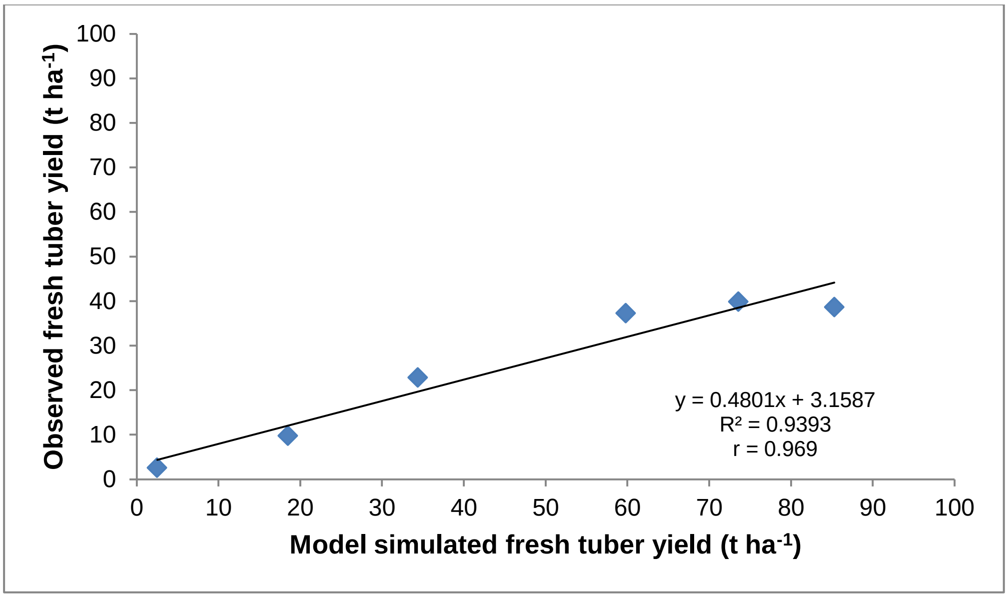

FIG.3.6: Innovator fresh tuber yield correlation from 36 to 91 DAE

The correlation between the model simulated and observed yields was high with an r value of 0.97 (R^2 = 0.94) as shown in Fig.3.6. The RMSE and MAE were high at 25.98 t ha^{-1} and

20.60 t ha^{-1} respectively as shown in Table 3.6. The observed and simulated yields were different throughout the growing season from 36 to 105 DAE.

Table.3.6: Summary of fresh tuber yield regression and correlation results (actual vs simulated attainable yield) for variety Innovator calibration data set in 2013 season.

	Model Simulated fresh tuber yield	Observed fresh tuber yield
N	6	6
MSE	674.849	
RMSE (t ha^{-1})	25.978	
MAE (t ha^{-1})	20.597	
r	0.969	
R^2	0.939	
D-index	0.652	

Markies

This variety was grown on field HL and the actual and forecasted fresh tuber yield results are shown in Table 3.7. The crop was affected by some frost damage around 111 DAE, which caused early foliage death.

Table 3.7: Calibration data set for forecasted and observed fresh tuber yield of potato variety Markies (Field HL) in 2013 season.

Date	DAE	HI %	Model Simulated attainable fresh tuber yield at sampling (t ha^{-1})	Actual observed fresh tuber yield at sampling (t ha^{-1})	Actual: Attainable ratio at sampling	Model Forecasted attainable fresh tuber yield at final harvest (t ha^{-1})	Expected actual fresh tuber yield at harvest based on ratio (t ha^{-1})
12-Feb-14	35	4	1.0	0.6	0.60	86.2	51.7
26-Feb-14	49	21	9.3	9.1	0.98	89.6	87.8
12-Mar-14	63	47	26.8	24.8	0.93	86.7	80.6
26-Mar-14	77	63	44.5	34.8	0.78	89.2	69.6
8-Apr-14	90	67	56.0	47.2	0.84	90.8	76.3
29-Apr-14	111	76	75.8	53.1	0.70	87.3	61.1
19-May-14 (Final harvest)	131		89.5	56.3	0.63	89.5	56.4

A HI of 76% (close to target of 75% in this study) was achieved at 111 DAE and the actual : attainable ratio was 0.70 (70%) as shown in Table 3.7. This variety was harvested at 131 DAE. At HI of 76%, the forecasted fresh tuber yield was 61.1 t ha^{-1} which compared well to actual observed at final harvest of 56.3 t ha^{-1}. The forecasted fresh tuber yield for this variety was accurate from about 111 DAE (approximately 3 weeks before harvest) as shown in Table 3.7. Model simulated and observed fresh tuber yield data for this potato variety from the six sampling events during the growing season was regressed and the results are shown in Fig 3.7.

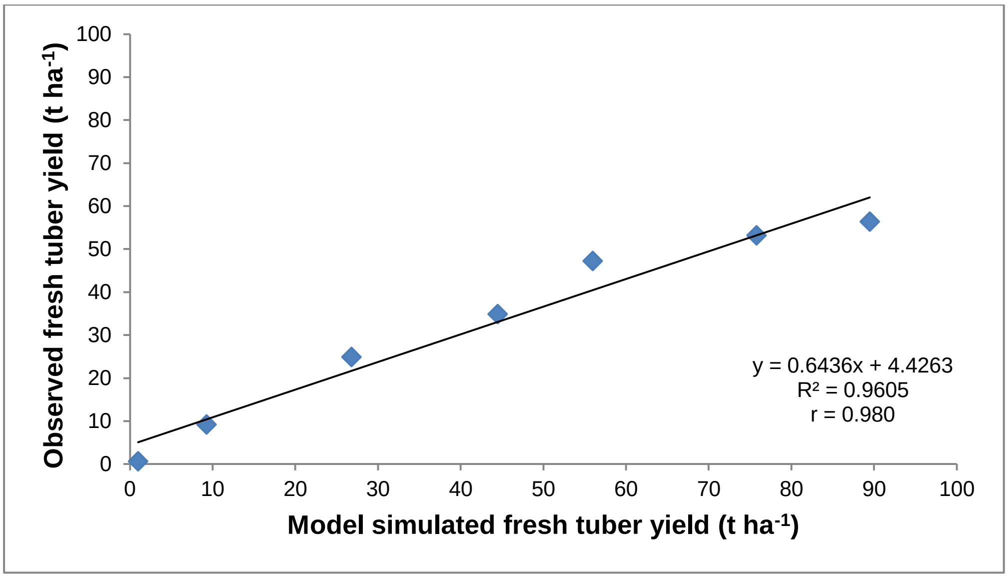

FIG.3.7: Markies fresh tuber yield correlation from 35 to 131 DAE

The correlation between model simulated and observed yields was high with a r value of 0.98 (R^2 = 0.96) as shown in Fig 3.7. The RMSE and MAE were high at 16.00 t ha^{-1} and 10.99 t ha^{-1} respectively as shown in Table 3.8. This is due to the high variance between the model simulated attainable yields and the actual observed yields from 77 DAE to 131 DAE (the final harvest date).

Table.3.8: Summary of fresh tuber yield regression and correlation results (actual vs simulated attainable yield) for Markies calibration in 2013 season.

	Model Simulated fresh tuber yield	Observed fresh tuber yield
N	7	7
Mean	43.271	32.278
Standard dev.	33.093	21.734
Std error of mean	12.508	8.215
MSE	256.055	
RMSE (t ha^{-1})	16.002	
MAE (t ha^{-1})	10.994	
r	0.980	
R^2	0.960	
D-index	0.900	

3.2 Model validation

Validation involves comparisons of predictions by the model with the results from independent experiments. Models can also be evaluated by comparing model outputs with real data and a determination of suitability for an intended purpose, which in this case is yield forecasting (Van Ittersum et al., 2003). The calibrated model was validated using independent data collected from crops grown on various farms in four different production areas namely Marble Hall, Dendron, Vivo and Soekmekaar. The main variety grown in the validation season was mostly Innovator, which was grown on 10 fields. There were also two fields with Markies and the data could not be statistically analysed as there were not enough datasets. The data that was validated was therefore for Innovator only. The variety Pentland Dell was not planted in the validation season.

In validating the model, the fresh tuber yield expected at final harvest was forecasted at 65 DAP using the LINTUL model. The potato processing industry needs to at least know what yields to expect from as early as 6 to 8 weeks before harvest. The chosen 65 DAP which were used in the forecasting, correspond well to this time period for the early (Innovator) and late (Pentland Dell) maturing varieties used in this study. The model forecasted attainable yield was multiplied by the varietal ratio as determined in the model calibration (section 3.1) to obtain the expected actual yield. The forecasted actual yield was then compared with the actual observed yield using a regression analysis, a Pearson correlation test (assuming the forecasted and actual yields were normally distributed) and a Spearman rank correlation test to measure the strength of association between the forecasted and actual observed yields.

For the variety Innovator, the ratio used was 0.61 and the results are shown in Table 3.9. The actual: attainable fresh tuber yield ratios at harvest were also calculated for each of the fields. The ratios varied from 0.50 to 0.68 as shown in Table 3.9 with an average of 0.60.

Table.3.9: Summary of fresh tuber yield results at harvest for Innovator validation in the 2014 season.

Field Name	Model Forecasted Attainable yield at harvest (t ha^{-1})	Model Forecasted fresh tuber yield at harvest (t ha^{-1})	Actual Observed fresh tuber yield at harvest (t ha^{-1})	Actual: Attainable ratio at harvest	Days to harvest
Bagga	75.0	45.8	39.3	0.52	128
Dora	56.9	34.7	28.3	0.50	112
Mohali	76.5	46.7	44.3	0.58	127
Philny	77.8	47.5	43.7	0.56	125
Elmar	67.6	41.2	44.5	0.66	109
Rodash L1	81.0	49.4	55.4	0.68	137
Lupedi	68.0	41.5	40.6	0.60	122
Pretorius	66.0	40.3	41.0	0.62	105
Henk P3	66.0	40.3	41.1	0.62	112
Fick	69.2	42.2	44.9	0.65	111
Average				0.60	

NOTE: Model forecasted fresh tuber yield = model forecasted attainable yield x varietal ratio of 0.61

The model forecasted fresh tuber yield at harvest was calculated with the LINTUL model using actual weather data from planting and till 65 DAP, and long term weather data for the remainder of the crop season was used up to harvest. The model forecasted fresh tuber yield was calculated as 61% of the model calculated attainable yield. The actual observed fresh tuber yield was the yield of the tubers that were harvested at crop end. The actual:

attainable ratio was the ratio of the actual observed fresh tuber yield at harvest to the model forecasted attainable yield at harvest.

3.2.1 Forecasted vs observed yields

The forecasted fresh tuber yields at final harvest or crop end calculated using the LINTUL model were regressed against the actual observed fresh tuber yields at final harvest and the results are shown in Fig 3.8 and Table 3.10.

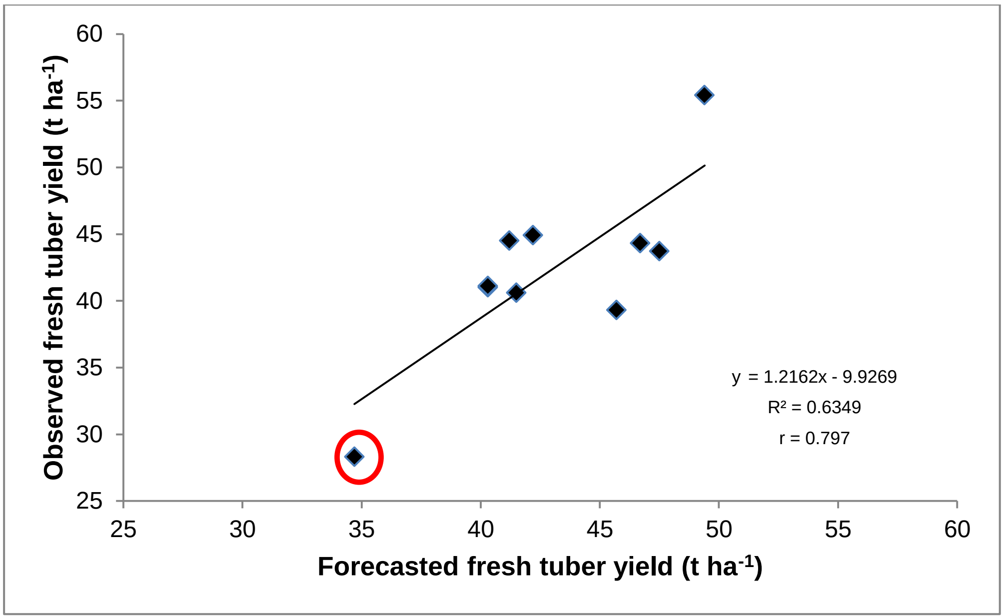

FIG.3.8: Correlation between LINTUL model forecasted and observed fresh tuber yield for Innovator in the 2014 season (Validation data set).

The forecasted fresh tuber yields compared well to the observed fresh tuber yields at final harvest with R^2 = 0.63 as shown in Fig 3.8. Results of the Pearson correlation test showed a strong correlation between the forecasted and observed yields with an r value of 0.80. Since the data was not normally distributed and a monotonic relationship was observed to exist between the forecasted and observed final yields, a Spearman's rank order correlation was also used to analyse the data. Results showed a strong positive association between the forecasted and observed final yields with r_s = 0.56 (Appendix 4). On some farms, the model overestimated the final yield, whilst on others it underestimated yields and it was very accurate on three farms. Frost was experienced on all the validation fields at least once in the growing season. This resulted in some crop damage which could have influenced crop growth and also final tuber yields. Some fields also experienced water problems as a result of pump and centre pivot breakdowns, which caused temporal water stress. On the field Dora (encircled in Fig.3.8), the water problem was more prolonged and had a detrimental effect on crop growth and development. If this field had been excluded, the r value would have been 0.61 (R^2 = 0.37). Different seed sizes were also used on the different farms, with cut-seed also being used. The physiological age of seed tubers has also been observed to have an influence on growth and development of the potato crop (Struik, 2007). Older seed was faster to emergence and also resulted in earlier senescence in comparison to younger seed. It is known that the physiological age has an effect on the vigour of the growing stems as well as their physiological behavior, which includes the time of tuber onset, tuber number and size distribution, onset of senescence, number of sympodial branches, and flowering behaviour.

The RMSE was low at 3.98 t ha^{-1}. MAE was also low at 3.34 t ha^{1}, as shown in Table 3.10 indicating that there was low error in the comparison. Another reason for deviation between observed and forecasted fresh tuber yields can be the observed differences in practices used by farmers on their crops. Row spacing ranged from 0.75 m to 0.90 m between the planting ridges. Consequently the plant densities were different across the farms. The crop that was planted closer managed to close their canopy early whilst those that were planted further apart did often not manage to close their canopy. Plants are thought to maximize light interception and utilization when they have a closed canopy, especially if water is not limiting

(Jefferies and Lawson, 1991). For those fields where the crops did not have a closed canopy, it can be assumed that there was not maximum use of the available incoming solar radiation. This could have also accounted for the yield over estimation by the model on some of the fields in the study.

Table.3.10: Summary of fresh tuber yield regression and correlation results for Innovator validation in 2014 season

	Forecasted fresh tuber yield	Observed fresh tuber yield
N	10	10
MSE	15.824	
RMSE (t ha^{-1})	3.978	
MAE (t ha^{-1})	3.340	
r	0.797	
r_s	0.559	
R^2	0.635	
D-index	0.849	

3.3 Forecasted vs observed tuber sizes

In forecasting the tuber sizes, 10 kg tuber samples were collected at various sampling dates during the season. The data from these samples was used to calculate and forecast the average tuber count and average tuber mass at final harvest according to the procedures described in section 2.3.5. The forecasted average tuber count and tuber mass at final harvest was regressed against the actual observed tuber count and tuber mass. A correlation analysis was also done using both the Pearson's and Spearman's correlation tests. The results for the tuber distribution data are summarised in Tables 3.11 and 3.12. Data for the potato variety Innovator, was the only one used in forecasting the average tuber count and tuber mass 10 kg^{-1} sample. Data from fields used in the calibration (Lichtenburg – SM field) and validation was collectively used for the forecasting. The fields used were also sampled at different dates after planting and data from the last sampling event done before the final harvest was used as shown in Table 3.11. Not all the 10 fields used in the validation were used in forecasting the tuber sizes as some of the data used was collected independently and was incomplete for the tuber size distribution of the sample.

The potato processing industry wants to be able to forecast the expected tuber count and average tuber mass 10 kg^{-1} sample as early as possible before a potato crop is due for harvest. For the fields used in this study, accurate forecasts were produced from as early as 7 weeks before harvest as shown in Table 3.11.

Table.3.11: Summary of tuber count data collected at last sampling before final harvest and used to forecast tuber count for final harvest (Innovator variety).

Field	DAP at Sampling	Observed fresh tuber yield at sampling in t ha^{-1} (Y_{HA})	Forecasted fresh tuber yield at final harvest in t ha^{-1} (Y_F)	No of tubers 10 kg^{-1} at sampling (N_{ta})	No of tubers 10 kg^{-1} forecasted at final harvest (N_{ce})	No of tubers 10 kg^{-1} observed at final harvest (N_A)	Days to Harvest
SM	79	22.77	50.63	95.22	42.82	55.00	120
BAGGA	105	27.16	44.84	128.00	77.54	97.29	128
MOHALI	85	21.86	54.35	167.79	67.49	89.24	134
DORA	98	22.38	59.66	159.23	59.73	82.37	151
RODASH L1	109	32.37	46.54	111.18	77.32	75.53	130
LEKGRAAL	91	20.69	58.50	188.34	66.60	93.62	120

Note: Y_{HA} is the observed fresh tuber yield in t ha^{-1} at the sampling date, Y_F is the forecasted fresh tuber yield in t ha^{-1} at final harvest, N_{ta} is the tuber count No 10 kg^{-1} sample at the sampling date, N_{ce} is the forecasted tuber count No 10 kg^{-1} sample at final harvest (calculated using Equation 2.13) and N_A is the actual tuber count No 10 kg^{-1} sample at final harvest.

Table.3.12: Summary of average tuber mass data collected at last sampling during the season and forecasted for final harvest for Innovator variety.

Field	DAP at Sampling	g per tuber			Days to Harvest
		Average tuber mass at sampling (Mta)	Forecasted average tuber mass at crop end (Mce)	Actual average tuber mass at crop end (M_A)	
SM	79	105	234	182	120
BAGGA	105	78	129	103	128
MOHALI	85	60	148	112	134
DORA	98	63	167	121	151
RODASH L1	109	90	129	132	130
LEKGRAAL	91	53	150	107	120

Note: M_{ta} is the average tuber mass in grams per tuber at sampling date, M_{ce} is the forecasted average tuber mass in grams per tuber at crop end (calculated using Equation 2.15) and M_A is the actual average tuber mass in grams at crop end/harvest.

The results of the regression analysis on the tuber count data is shown in Fig.3.9

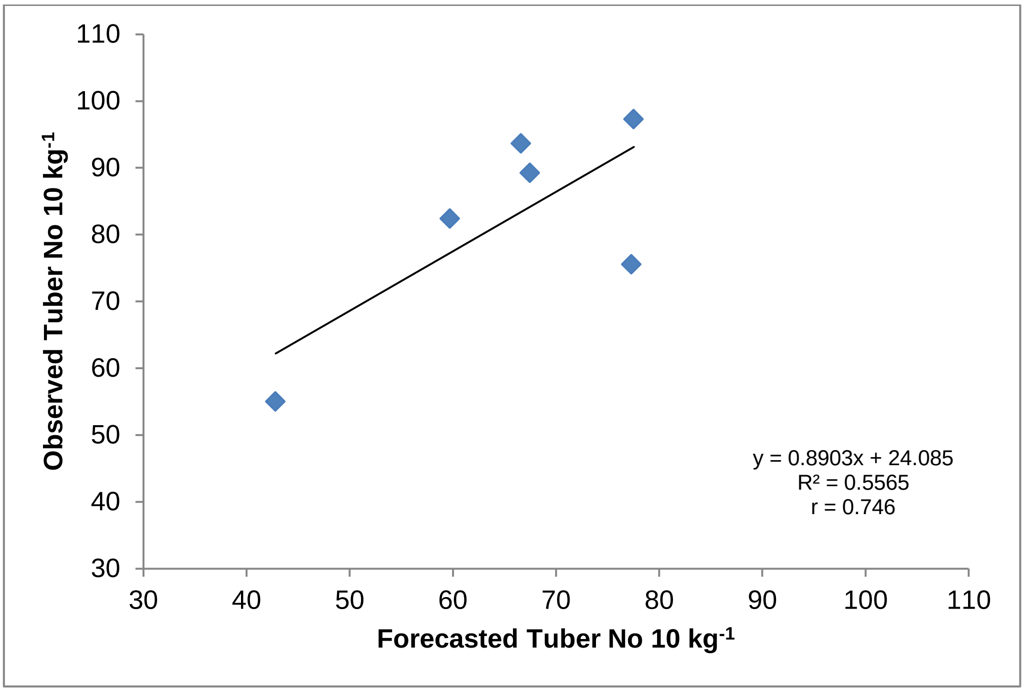

FIG.3.9: Correlation between the forecasted and observed tuber count numbers at final harvest for Innovator in 2014 season.

The forecasted and observed tuber count data compared well with R^2 = 0.56. They also correlated well with a r value of 0.75 as shown in Table 3.13. There was also a strong association between the forecasted and observed tuber count numbers at final harvest with r_s = 0.64 (Appendix 6). The RMSE was 19.40 tubers 10 kg^{-1} and the MAE was 17.52 tubers 10 kg^{-1} as shown in Table 3.13. The error between the forecasted and observed tuber counts was also high although this method of estimating tuber count per 10 kg was accurate. According to McCain Foods Limited, a good potato tuber sample should have a tuber count of less than 60 tubers 10 kg^{-1} sample. Thus, if a field is harvested at crop end and a random 10 kg sample is taken from the harvested tubers, the number of tubers in the 10 kg sample should not be more than 60. If more than 60 tubers, then the potato tubers will be considered to be of smaller sizes not ideal for processing. This will also influence grading of the sample.

This information is useful to the potato processing industry as an early forecast indicating that the tuber count will be much greater than 60, will be an early warning that small tubers may need to be sorted at harvest.

Table.3.13: Summary of regression and correlation results between forecasted and actual tuber No per 10 kg sample for Innovator in the 2014 season.

	Forecasted tuber No 10 kg^{-1} sample at harvest	**Observed tuber No 10kg^{-1} sample at harvest**
N	6	6
MSE	376.199	
RMSE (tuber No 10kg^{-1})	19.396	
MAE (tuber No 10kg^{-1})	17.522	
r	0.746	
r_s	0.638	
R^2	0.557	
D-index	0.413	

To reduce error in the comparison of the forecasted and actual tuber numbers 10 kg^{-1} shown in Table.3.13, a correction factor was used. Under field conditions, when farmers harvest their crop, tubers considered as smalls or less than 35 mm in diameter and unmarketable are graded out and discarded during the harvesting operation. McCain Foods Limited through data collected over 15 years at various factories worldwide, estimates these discarded potatoes to be on average 15% of the total observed yields. The correction factor which deducted the 15% from the varietal ratio therefore removed the smalls and rejects from the total forecasted sample mass. A summary of the forecasted tuber numbers and average tuber mass results 10 kg^{-1} sample after use of the correction factor is shown in Table 3.14.

Table 3.14: Summary of forecasted tuber count and average tuber mass data at final harvest after use of correction factor (Innovator variety).

Field	No of tubers per 10 kg forecasted at harvest with correction factor	No of tubers per 10 kg observed at harvest	Forecasted average tuber mass at harvest with correction factor (g $tuber^{-1}$)	Actual average tuber mass at harvest (g $tuber^{-1}$)
SM	56.79	55.00	176	182
BAGGA	102.82	97.29	97	103
MOHALI	89.49	89.24	112	112
DORA	79.21	82.37	126	121
RODASH	102.54	75.53	98	132
LEKGRAAL	88.32	93.62	113	107

Using the correction factor did not change the coefficient of determination, but reduced the error. The RMSE reduced from 19.4 to 11.6 tubers 10 kg^{-1} sample, whilst the MAE reduced from 17.5 to 7.2 tubers 10 kg^{-1} sample as shown in Table 3.15.

Table.3.15: Summary of regression and correlation results after using correction factor between forecasted and actual tuber No 10 kg^{-1} sample for Innovator in the 2014 season.

	Forecasted tuber No 10 kg^{-1} sample at harvest	Observed tuber No 10 kg^{-1} sample at harvest
N	6	6
MSE	133.577	
RMSE (tuber No 10 kg^{-1})	11.558	
MAE (tuber No 10 kg^{-1})	7.173	
r	0.746	
r_s	0.493	
R^2	0.556	
D-index	0.842	

The correlation between the forecasted and observed average tuber mass (size) was strong with a r value of 0.87 as shown in Fig.3.10. For an Innovator crop that is growing very well with good potential for achieving the attainable yield, an average tuber mass between 180 – 200 g $tuber^{-1}$ would be expected (McCain Foods SA, 2014). Most of the fields sampled in this study had a lower average tuber mass, showing that they were low potential fields and which is why the tuber No.10 kg^{-1} sample was also greater than 60. This could be an indication that production practices for the Innovator variety need to be looked at carefully and improved so as to achieve better yields that are closer to the attainable. If the Innovator crop grows better, the size of the tubers will also increase and thus more tubers of the acceptable size will be produced and also a higher final yield. Since there were strong outliers, a Spearman's rank correlation test was also used to test the strength of the association between the forecasted and observed average tuber mass at final harvest. Results showed a r_s value of 0.493 which indicates a strong positive association (Appendix 5)

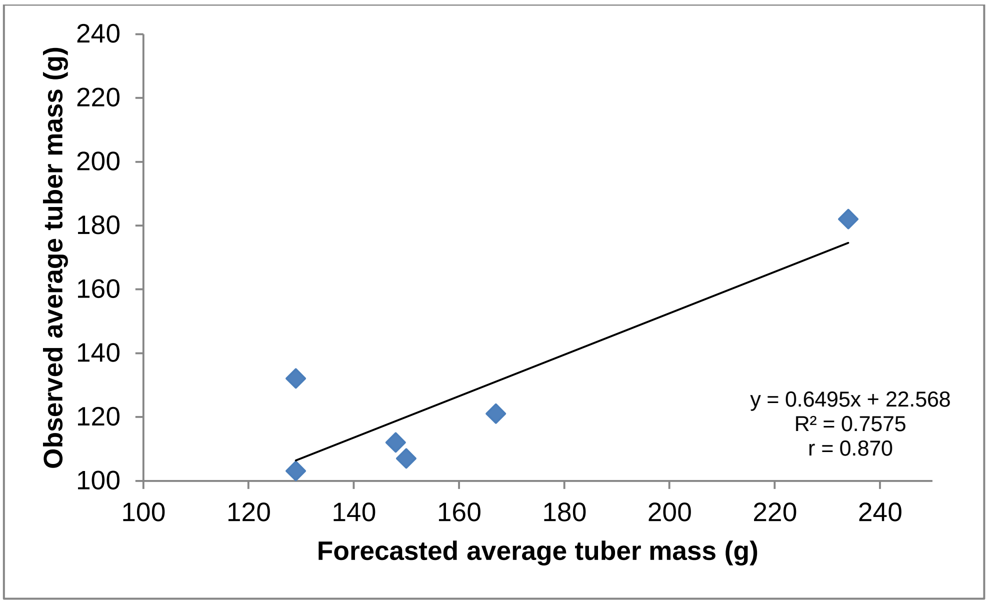

FIG.3.10: Correlation between the forecasted and observed average tuber mass (size) for Innovator in 2014 season

The RMSE was high at 37.97 g tuber^{-1} and MAE was also high at 34.33 g tuber^{-1} as shown in Table 3.16. Error was therefore high when estimating the average tuber mass expected at harvest, and a correction factor had to be used. In spite of that, the correlation was strong and the method can therefore be useful to forecast the average tuber mass expected at harvest.

Table.3.16: Summary of regression and correlation results between forecasted and actual average tuber mass (size) for Innovator in the 2014 season.

	Forecasted average tuber size	Observed average tuber size
N	6	6
MSE	1441.667	
RMSE (g tuber^{-1})	37.969	
MAE (g tuber^{-1})	34.333	
r	0.870	
r_s	0.493	
R^2	0.757	
D-index	0.621	

Using the correction factor for small sized tubers and grade outs which are unusable at the factory, improved the correlation and regression coefficients and reduced the error as shown in Table 3.17. The r value slightly improved from 0.870 to 0.874, r_s improved from 0.493 to 0.600 and R^2 improved from 0.758 to 0.763. The RMSE improved from 37.97 g tuber^{-1} to 14.66 g tuber^{-1} whilst the MAE also improved from 34.33 g tuber^{-1} to 9.50 g tuber^{-1} as shown in Table 3.17.

Table.3.17: Summary of regression and correlation results after using correction factor between forecasted and actual average tuber mass (size) for Innovator in the 2014 season.

	Forecasted average tuber size	Observed average tuber size
N	6	6
MSE	214.833	
RMSE (g tuber^{-1})	14.657	
MAE (g tuber^{-1})	9.500	
r	0.874	
r_s	0.600	
R^2	0.763	
D-index	0.923	

Using the correction factor therefore reduced error in the analysis by improving the values for comparison between the forecasted and actual tuber counts and average tuber mass.

A T-test was also used to assess whether there were significant differences between the forecasted and observed values for the final fresh tuber yield, tuber No 10 kg^{-1} and average tuber mass 10 kg^{-1} and the results are shown in Table 3.18.

Table.3.18: T-test results for forecasted and observed fresh tuber yield (t ha^{-1}), tuber No 10 kg^{-1} and average tuber mass (g tuber^{-1}) per 10 kg sample at final harvest.

Paired Samples Test									
Segment		Paired Differences					t	df	P-Value (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95 % Confidence Interval of the Difference				
					Lower	Upper			
Fresh tuber yield at harvest	Forecasted - Observed	0.64	4.138	1.309	-2.320	3.600	0.489	9	0.637 ns
Tuber count 10 kg^{-1} at harvest	Forecasted - Observed	-16.93	10.381	4.238	-27.828	-6.039	-3.995	5	0.010 s
Average tuber mass 10 kg^{-1} at harvest	Forecasted - Observed	33.33	19.916	8.131	12.432	54.234	4.100	5	0.009 s
Tuber count 10 kg^{-1} at harvest (corrected)	Forecasted - Observed	4.33	11.843	4.835	-8.096	16.762	0.896	5	0.411 ns
Average tuber mass 10 kg^{-1} (corrected)	Forecasted - Observed	-5.83	14.730	6.013	-21.291	9.625	-0.976	5	0.377 ns

A p-value of 0.637 is an indication that the final observed yield was not significantly different from the forecasted yield since the p-value of the paired samples t-test was greater than 0.05 at the 5 % significance level as shown in Table 3.17. For the observed tuber count number 10 kg^{-1} and the average tuber size 10 kg^{-1}, the differences with the forecasted values were significant before use of correction factor since the p-values were both less than 0.05. However, after using the correction factor, there were no significant differences between the forecasted and observed tuber count number 10 kg^{-1} and the average tuber size 10 kg^{-1} as the p-values were greater than 0.05 as shown in Table 3.17.

Calibration of the LINTUL model in this study was good for all the three potato varieties used as the model simulated yields correlated well to the actual observed yields. The results also showed that the expected actual fresh tuber yield at harvest can be forecasted accurately from as early as eight weeks before harvest. Farmers are usually contracted to produce and deliver an agreed tonnage of potatoes to the factory at a certain time period. Being able to forecast the expected yields using the LINTUL model will help monitor if farmers are still on track to produce and deliver the set targets. If not, then alternative plans can be made early so as to not have a raw material shortage at the factory.

Validation was also good as the model forecasted fresh tuber yields compared well to the collected independent data. Yield forecasts produced at 65 DAP which corresponded to approximately eight weeks before harvest of an average potato crop, were accurate. The tuber number and mass 10 kg^{-1} sample were also forecasted accurately from about seven weeks before harvest. Being able to forecast the expected tuber No 10 kg^{-1} early before harvest will assist McCain Foods in giving an indication of the size of the tubers. If tubers are forecasted to be small and greater than 60 per 10 kg sample, then management can plan on sorting the tubers at harvest to make them better suited for processing at the factory. If too small and unsuitable for sorting, then strategic decisions such as retaining the potato tubers for seed purposes as “farm saved seed” can be made. In such an instance, an early forecast will therefore assist with getting the tubers tested early before they are harvested for diseases and disorders that might also make them undesirable for seed purposes.

The different customers that McCain Foods produces French fries for, have specific size requirements. The information produced by the forecasts will therefore assist management in allocating specific tuber sizes to particular customer products. Also at the factory, potato tubers delivered by farmers are stored in bulk bins before they are processed in the factory. Information from forecasts can be used to plan the storage at the factory with tubers of similar sizes being stored together.

DISCUSSION AND CONCLUSIONS

The results from this study have shown that reasonably accurate prediction of potato growth and yield for the processing industry is possible from as early as eight weeks before harvest with the use of a simple crop growth simulation model such as LINTUL-POTATO. This can be achieved through the use of current and long term historical weather data, as well as other crop and management input data. The yield forecasts produced were generally accurate but the level of accuracy will depend on the quality of the calibration data used. The Null hypothesis for the study that a simple model can be used to accurately forecast yields of potato using long term historical and actual weather data can thus be accepted. LINTUL-POTATO can be used to produce accurate yield forecasts early in the growing season from the period after the tubers have been set. Different sets of forecasts can be produced. For example, a yield forecast can be done using historical long term weather data for a particular production area and another forecast can be done using the current season's weather data. The yield curves of the two forecasts can then be compared to give an indication of how the current season will compare to the average long term. This can easily show if the current season will be a good or below average one compared to the history of that particular production area. Management can therefore make decisions early in the season and such decisions could be to plant more hectares to meet the volume requirements in cases were the current season is indicated as going to be not so good. Management can also use modelling to explore new production areas by using weather data to run simulations and estimate timing and yields, which is in agreement with the findings of Haverkort (2007). The LINTUL model can thus be used to forecast yield performance in any region well in advance and allow decisions to be made about possible supply strategies.

Crop growth simulation models have been designed to simulate crop growth in response to environmental and management factors based on the underlying physiological mechanisms

(Saarikko, 2000). Their application requires experimental data for calibration and are more widely applicable allowing an application outside their calibration area. In the present study, experimental data that was collected for calibration in the Lichtenburg area was used to calibrate the model, making it more useful for other production areas around South Africa. The calibration data set was however small, and this may have limited the accuracy of the forecasts. For a yield forecasting system to be successful, the crop simulation model should have a good ability to quantify the influence of weather, soil and management conditions on the crop yield, which is what the LINTUL-POTATO model does. The system should also be able to properly integrate model simulation results over a range of spatial scales (Hansen and Jones, 2000). Models need to be general and not site specific (Hackett et al., 1979) since potato production in South Africa occurs at various locations, elevations and different climatic conditions. Interaction of the crop, soil, weather and management factors therefore has a strong influence on the accuracy of the yield forecasts using the model. The accumulation and partitioning of biomass and phenological development of a potato crop are influenced by many factors individually or in combination. The most important are the environmental variables temperature, photoperiod or day length and intercepted radiation. The simulation of potato growth across diverse environments and different cultivars must take these factors into account (Griffin *et al*., 1993).

Potential and attainable yields are rarely achieved under field conditions, mainly due to the presence of yield limiting and yield reducing factors. In this study, actual yields were observed to be between 61 to 90% of the attainable, which compares well to what was also observed by Franke *et al.* (2011) for potato farmers in the Sandveld region of South Africa. One of the questions that farmers and their advisers frequently ask themselves is what the maximum possible yield for a particular area is and crop modelling can be used to answer this question (Hackett *et al*., 1979). The influence of these factors will need to be reduced to a minimum if attainable yields are going to be achieved and the yield gap reduced. Weeds can be controlled using pre-emergence and post-emergence herbicides so that they do not compete with the crop for resources. Pests need to be controlled using various control mechanisms that are not only limited to application of pesticides. Diseases will also need to be prevented and controlled using different strategies. Decision support systems can be used to improve the effectiveness of various control methods. The main pests affecting potato production in the country are nematodes, potato tuber moth, leaf miner and American bollworm. The main diseases are early and late blight, as well as common, powdery and fissure scab, fusarium and the viral diseases PVY and PVX.

Attainable yields vary between varieties and how they interact with the environment. In this study, the variety Pentland Dell was found to have the highest potential to reach the attainable yield, whilst Innovator had the lowest potential. It can be assumed that the variety Pentland Dell interacts better with the local environmental conditions in South Africa under the current management regime to produce good yields. Different varieties will therefore require different management practices in their production in order for them to perform to their full potential.

The other factors influencing potato growth and ultimately yield forecasting are management factors. The plants in this study were planted at different crop densities. Plant spacing within the rows and between the rows was variable. Plants that develop and close their canopy faster have been found to make maximum utilization of the available solar radiation in biomass production. The crops that were grown in the validation season were subjected to very low winter temperatures. It was observed that most of these plants did not develop a full canopy. The recommendation is therefore that for a winter crop, the plants have to be planted at a higher population so as to produce a crop that has a complete canopy cover.

This will enable maximum use of the available solar radiation as well as other resources. The frost that some of the plants were subjected to caused leaf damage and slowed down crop development. This ultimately decreased the accuracy of the yield forecasts using the LINTUL model. It was also observed that after frost damage, the plants would re-initiate the formation of tubers and new stolons develop. This would also be expected to disrupt normal crop development and affect the rate of tuber growth.

The physiological and chronological age of the seed also affects crop development (Struik, 2007). Older seed was observed to sprout faster, grow rapidly and senesce earlier when compared to younger seed. The seed used by growers was of varying ages and the crops therefore developed differently. Different seed types were also used, namely cut seed, chats, seed sizes 1-3 ounces and 3-5 ounces. The number of main and lateral stems that developed were different and ultimately the tuber set and development also differed. The depth at which the seed is planted will also determine how quickly the sprouts will emerge and the crop develops. Seed that is planted deeper generally emerges late and crop development may be slower. This may however be necessary when planting into cold soils in the colder months of the year.

The tuber numbers that were set per plant varied considerably amongst plants of the same variety planted on the same field. At the same yield level, different size distributions were observed. However, the tuber count at harvest was estimated with an accuracy of R^2 = 0.76. The average tuber mass was also estimated with some accuracy in the present study. Therefore the hypotheses that the tuber count and size (mass) of potatoes can be accurately forecasted using a simple model was accepted. The tuber set is influenced amongst other factors by the number of main and lateral stems that will develop from the seed piece, the number of eyes that the seed piece will have and the soil temperature at tuber initiation

(Struik et al.,1989)**.** As the tubers increase in size, their bulking rate will be influenced by factors such as the soil temperature, the fertilization regime and moisture availability (Struik et al.,1989). The rate at which the tubers will grow is therefore variable and any stress factor during bulking stage will influence how the tubers will grow.

DMC of tubers is variable and also influenced by a range of factors. The rate and amount of nitrogen and potassium applied to the crop will affect it. A higher nitrogen amount tends to reduce DMC, whilst a higher potassium amount tends to increase the DMC (Ojala *et al*.,1990) . However a balance of the N : K is needed**.** The length of the growing season will also affect DMC (Haverkort, 2014 – Personal Communication). If season is long, then a higher DMC will be expected in comparison to a shorter season, which is also influenced by a cultivar effect. The amount of water applied to the crop will also affect DMC, especially closer to harvest (Ojala *et al.,*1990). The period between the last irrigation and harvest therefore has a huge influence on DMC. If irrigation was stopped earlier, then DMC would be expected to be higher (Gunel and Karadogan, 1998). The clay percentage in the soil is also thought to have an influence on the DMC, with a higher clay percentage giving an increased DMC (Haverkort, 2014 – Personal Communication). Forecasting of dry matter was not possible in this study as the number of samples required in order to do so is very large, and it is recommended that a further study be conducted using samples from potato crops grown under different conditions in different areas. The hypothesis that a simple model can be used to forecast tuber DMC is rejected.

Variability in weather conditions is one of the major sources in yield variation in agriculture and for decision support systems to be successful they largely depend on their ability to predict future weather conditions. Weather predictions are at best reasonably accurate for only a few days ahead and decision support systems have to rely on probability analyses using long term historical or generated weather data. Using actual and long term weather data as input into the LINTUL model produced accurate potato yield forecasts in this study. The accuracy of the forecasts produced largely depended on the proximity of the production area to the weather station used to collect the weather data. The further the weather station is, the less accurate the forecasts produced. The LINTUL model is a simple model which can be used to accurately forecast yield of potatoes using long term historical weather data and real time current weather data.

The LINTUL model is a good tool for planning purposes by potato processing companies. It can be used to produce accurate potato yield and tuber size forecasts from as early as eight weeks before harvest. This will assist the company in monitoring if the planned targets will still be achieved. If the forecasts indicate that the targets will no longer be achieved, the company can make alternative plans so as to avoid having raw material shortages at the factory. The company can also use the model to produce different sets of forecasts, comparing the current season with the long term average season. If the forecasts indicate that the season will produce lower yields than the average season, then the company can decide to increase the area to be planted or reduce the contracted tonnage per hectare.

McCain Foods would also like to explore the yielding potential of new potato production areas so as to spread the production seasons and ensure continuity of potato supply to the factory throughout the year. The LINTUL model is a tool that can potentially be used to assess the potential of such new areas and produce information that can assist with decision making. Different planting dates can also be tested with the LINTUL model to identify the optimal planting dates. Potato crops can therefore be planted on the dates when the model indicates the highest potential to achieve the attainable yields. The supply risk periods when the attainable yields are lower can also be identified through use of the LINTUL model. Strategic decisions such as planting more hectares in the optimal period and harvesting and storing tubers in the sub-optimal period can be made with the use of the model.

With use of the LINTUL model, the performance of farmers can also be measured. The model produces forecasts of attainable yields in different production areas. The actual yields that farmers in those particular areas are producing can be compared to the model produced yields to identify the yield gaps. Strategies that will help reduce the yield gaps can therefore be implemented and help improve potato yields. Models are therefore important tools that can be used to improve potato production for the processing industry. They are cost effective tools with the capacity to forecast yield in potatoes, based on simple crop and weather data.

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APPENDIX 1: Soil analysis results for determining clay percentage of calibration fields for use as input into LINTUL model

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INSTITUTE FOR SOIL, CLIMATE AND WATER

INSTITUUT VIR GROND, KLIMAAT EN WATER

Client : **Mr A Machakaire**
Klient :
Mc Cain Foods SA
P O Box 1023
Delmas
2210

Tel :
Fax / Faks :
Date / Datum : 28-05-2014

RESULTS FOR REPORT No:
RESULTATE VIR VERSLAG Nr GROND 201415 5162

T	LabNo	SENDER_NR	1 Total N %	2 Clay Hydrome %
M	1	UR 1 40%	0.035	
M	2	UR 1 60%	0.040	
M	3	UR 1 100%	0.038	
M	4	UR 2 40%	0.036	
M	5	UR 2 60%	0.038	
M	6	UR 2 100%	0.040	
M	7	URea 40%	0.036	
M	8	URea 60%	0.036	
M	9	URea 100%	0.038	
M	10	BK		18
M	11	HL		36
M	12	PB		24
M	13	SM		22

METHODS USED FOR ANALYSIS :

Serial	Method
1	Total N Digest
2	Clay Hydrometer

Serial	Method

Serial	Method

APPENDIX 2: T- test ANOVA results for comparing means of forecasted and observed final fresh tuber yield (ton ha^{-1}), tuber No 10 kg^{-1} and average tuber mass (g $tuber^{-1}$)

Paired Samples Statistics

Segment			Mean	N	Std. Deviation	Std. Error Mean
Final yield	Pair 1	Forecasted	42.95	10	4.369	1.381
		Observed	42.31	10	6.668	2.109
Tuber count	Pair 2	Forecasted	65.23	6	12.938	5.282
		Observed	82.17	6	15.438	6.303
Tuber mass	Pair 3	Forecasted	159.50	6	39.216	16.010
		Observed	126.17	6	29.267	11.948

Paired Samples Test

Segment			Paired Differences					t	df	P-Value (2-tailed)
			Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
						Lower	Upper			
Final yield	Pair 1	Forecasted - Observed	.64	4.138	1.309	-2.320	3.600	.489	9	.637
Tuber count	Pair 2	Forecasted - Observed	-16.93	10.381	4.238	-27.828	-6.039	-3.995	5	.010
Tuber mass	Pair 3	Forecasted - Observed	33.33	19.916	8.131	12.432	54.234	4.100	5	.009

APPENDIX 3: T-test ANOVA results for comparing means of forecasted and observed tuber No 10 kg^{-1} and average tuber mass (g tuber^{-1}) at final harvest after using the correction factor of 15 %

Paired Samples Statistics

Segment			Mean	N	Std. Deviation	Std. Error Mean
Tuber count	Pair 1	Forecasted	86.50	6	17.202	7.023
		Observed	82.17	6	15.381	6.279
Tuber mass	Pair 1	Forecasted	120.33	6	29.317	11.969
		Observed	126.17	6	29.267	11.948

Paired Samples Test

Segment			Paired Differences					t	df	P-Value (2-tailed)
			Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
						Lower	Upper			
Tuber count	Pair 1	Forecasted - Observed	4.33	11.843	4.835	-8.096	16.762	0.896	5	0.411
Tuber mass	Pair 1	Forecasted - Observed	-5.83	14.730	6.013	-21.291	9.625	-0.970	5	0.377

APPENDIX 4: Spearman's rank-order correlation analysis for forecasted and observed final tuber yields

			Forecasted	Observed
Spearman's rho	Forecasted	Correlation Coefficient	1.000	.559
		Sig. (2-tailed)		.093
		N	10	10
	Observed	Correlation Coefficient	.559	1.000
		Sig. (2-tailed)	.093	
		N	10	10

APPENDIX 5: Spearman's rank-order correlation analysis for forecasted and observed average tuber mass at final harvest

			Forecasted	Observed
Spearman's rho	Forecasted	Correlation Coefficient	1.000	.493
		Sig. (2-tailed)		.321
		N	6	6
	Observed	Correlation Coefficient	.493	1.000
		Sig. (2-tailed)	.321	
		N	6	6

			Forecasted (Corrected)	Observed (Corrected)
Spearman's rho	Forecasted (Corrected)	Correlation Coefficient	1.000	.600
		Sig. (2-tailed)		.208
		N	6	6
	Observed (Corrected)	Correlation Coefficient	.600	1.000
		Sig. (2-tailed)	.208	
		N	6	6

APPENDIX 6: Spearman's rank-order correlation analysis for forecasted and observed tuber No 10 kg^{-1} at final harvest

			Forecasted	Observed
Spearman's rho	Forecasted	Correlation Coefficient	1.000	.638
		Sig. (2-tailed)		.173
		N	6	6
	Observed	Correlation Coefficient	.638	1.000
		Sig. (2-tailed)	.173	
		N	6	6

			Forecasted (Corrected)	Observed (Corrected)
Spearman's rho	Forecasted (Corrected)	Correlation Coefficient	1.000	.493
		Sig. (2-tailed)		.321
		N	6	6
	Observed (Corrected)	Correlation Coefficient	.493	1.000
		Sig. (2-tailed)	.321	
		N	6	6