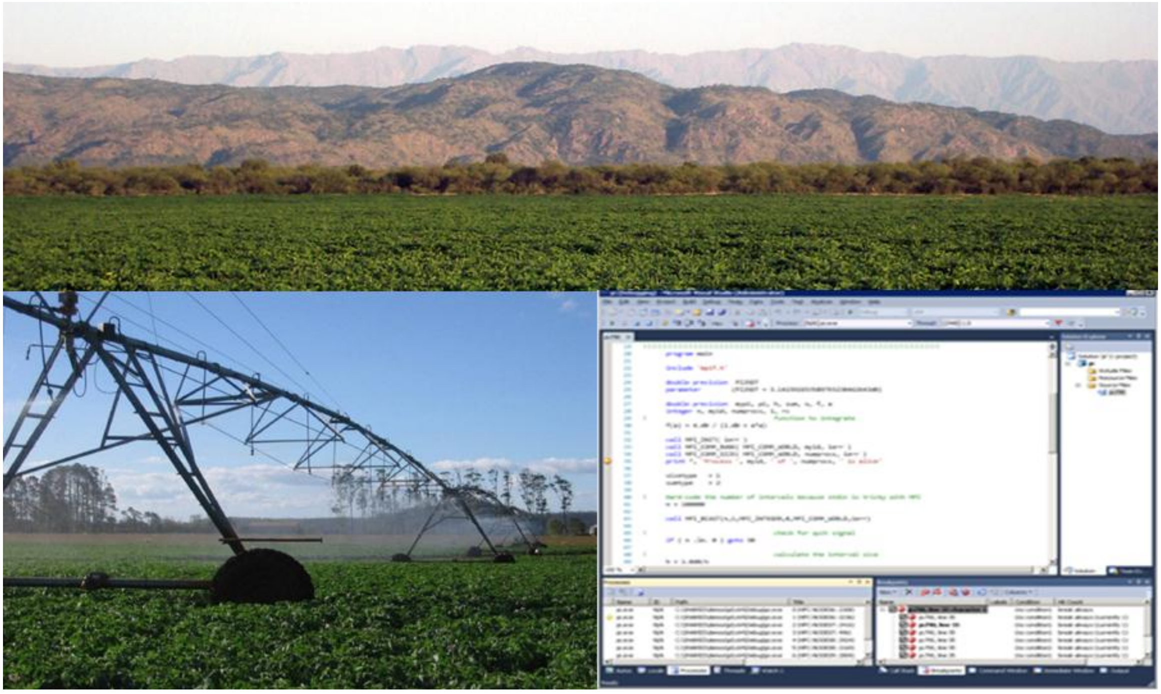
MSc Thesis

POTATO PRODUCTION AND WATER USE IN VILLA DOLORES, ARGENTINA

A MODELLING APPROACH



Sjaak Aben

MSc Thesis Plant Production Systems

June 2012

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SUMMARY

This research is based on questions from Farm Frites on productivity and water use efficiency in potato production. As a producer of potato products Farm Frites is concerned with raising productivity of their suppliers. Farm Frites is active in Argentina and interested in the Villa Dolores potato production area. Villa Dolores has a semi-arid climate, making a double crop season possible for potato if irrigation is applied.

Productivity (kg yield /ha) was assessed using production levels. Production levels are defined as the yields that are attained when certain factors are limiting. Potential production gives the highest yield in which the crop growth rate is only defined by temperature, radiation, CO_2, day length and crop characteristics. Water and nutrient limited production gives the yield limited by water, nutrients and physiological age of seed tubers. In the actual production level yield is reduced by weeds, pests, diseases and pollutants. The efficiency of water use is expressed as the dry matter production per litre of irrigation water applied.

For determining the production levels and irrigation use efficiency (IUE) in Villa Dolores the crop growth model LINPACsa was used. This is LINPAC (LINtul model for Annual and Perennial Crops) adapted for potato. For potato optimal nitrogen application for potential yield is difficult to determine in practice. It is assumed that potential levels were not attained in field experiments used for calibration of LINPACsa and therefore the highest production level in this report is called non- water limited rather than potential. It is assumed that yields attainable in practice will amount to 85% of the potential production level, the irrigation needed for these yields is also assumed to amount to 85% of what is needed for the potential production level.

The model was calibrated and validated for cultivars Eersteling, Bintje, Innovator, Shepody and Russet Burbank. Fresh tuber yield was simulated for the non-water limited production level of Innovator. Also, fresh tuber yields and IUE were determined for all cultivars and for Innovator at various planting and harvest dates using simulations at 85% irrigation level. Simulations were done for two soil types, two weather types and two cropping seasons based on nine weather years from the last decade.

For the Lovinkhoeve experiment with Bintje, which covers more than 3 decades, an upward trend in observed yields was found. Using the model, this trend was likely to be caused by management improvements. In an extra analysis nitrogen appeared to have been limiting for the light use efficiency at the end of the growing season in one of the field experiments. In general, data on field experiments was often lacking or uncertain, besides there was a large variance in observations for some field experiments. Despite the uncertainty on data for calibration, LINPACsa proved valuable in comparison with similar models. The model could simulate maturity of all cultivars relatively well except for Shepody. Allocation parameters for Russet Burbank proved not to be robust enough for simulation in Villa Dolores to get a realistic result. The non-water limited yields for Innovator were similar to the potential yields found in literature for the late season. The relative yield gaps (62% of highest production level) for the non- water limited yields were similar to those found for Western Europe.

Innovator attained the highest fresh tuber yields and irrigation use efficiencies. For the late season earlier planting dates led to higher fresh tuber yields but lower irrigation use efficiencies. For the medium early season no effect of planting day was found. On the soil type with the highest plant available water content the highest irrigation use efficiencies were attained. An overview of the combinations of cultivar, soil type and planting and harvest day that led to the highest fresh tuber yields and highest irrigation use efficiency was made for growers, the processing industry and policy makers to help improve the sustainability and profitability of the potato production chain in Villa Dolores.

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1 INTRODUCTION

1.1 Introduction

This research is based on questions from Farm Frites on productivity and water use efficiency in potato production in Argentina. Farm Frites is a producer of frozen and chilled potato products, mainly potato chips. It has factories in many different countries; the Netherlands, Belgium, Poland, Egypt and Argentina. These factories are supplied by farmers and factory owned farms.

One of the interests of Farm Frites is to increase yields by their growers and their own farms by increasing productivity. Productivity is defined in this report as the mass of the yieldable product per hectare. Increasing productivity of existing arable land relieves the pressure on land as a result of the increasing food demand of the growing world population. Also, higher yields are associated with bigger potatoes, this is beneficial in the potato chip industry as less product is lost in pealing and longer, more valuable chips can be made. Furthermore higher yields will lower the cost per kg of potatoes, which will allow lower priced end products, making the product more competitive on the market. The latter mechanism is however corrected in practice by decreasing acreages of potatoes grown as a reaction to lower market prices for potatoes.

In Argentina in the years 2005-2007 annually about 2 million tonnes of ware potatoes were produced on 80,000 ha for fresh consumption and processing, the latter mainly as frozen product. The average productivity was thus 25 tonnes per hectare but differs greatly between potato producing regions. The increasing demand for potatoes by the processing industry, especially for French fries, is expected to lead to an increase in production (Pirovano, 2008).

Farm Frites is interested in the potential of the Villa Dolores potato production area. Villa Dolores is an important production region for ware potatoes in Argentina with a production of approximately 240,000 tonnes in the season 2006-2007 (Caldiz & Struik, 1999; Pirovano, 2008). The region is located in the Cordoba province and has a semi-arid climate, a double crop season for potato is possible. Potatoes are grown in spring and autumn, sometimes on the same field, part of the yield of the spring crop is used as seed for the autumn crop (Fahem & Haverkort, 1988; Caldiz & Struik, 1999).

Improving the productivity of a region starts with exploring potential crop production. Potential production is realized in theory when growth conditions are optimal and crop production will only be defined by yield defining factors (YDF) (Fig. 1.1). In practice this potential is (almost) never reached. Yield defining factors are mainly environmental factors that cannot be influenced by management (in field crops). Incoming radiation, temperature, CO_2 concentration, day length and cultivar characteristics are the YDF in case of potato. In case of water and nutrient limited production, the crop production is also constrained by yield limiting factors (YLF). These factors can be optimized by management. Nutrients, water and physiological age of tubers are YLF. The actual production level is equal to the water and nutrient limited production level minus the losses by pests and diseases, weeds and pollutants. These four factors are called the yield reducing factors (YRF).

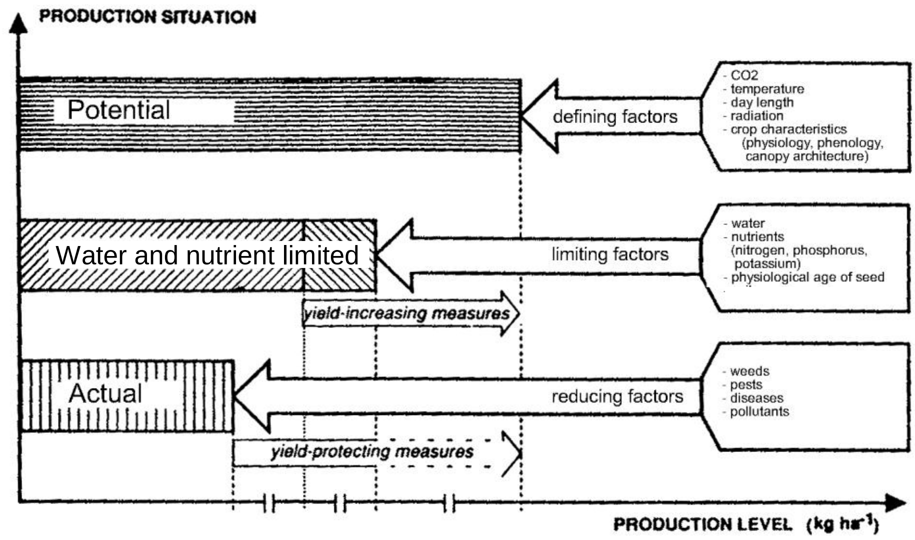


Fig. 1 Potential, water and nutrient limited and actual production levels that are connected by defining, limiting and reducing factors (Penning de Vries & Rabbinge,1995). Day length and physiological age of seed tubers were added according to Caldiz et al. (2002) by Huber (2010).

At the potential production level by definition the potential yield is attained because every day the potential crop growth rate is realised. This means that the crop is not limited in its growth by water or nutrients during any day of the growing season (De Wit, 1968; Penning de Vries & De Wit, 1982; Penning de Vries & Rabbinge, 1995). This concept of potential production works well for determinate crops like winter wheat. This crop forms a predefined number of leaves, after the last leaf the harvestable organs (ears) appear. The leaves have a limited lifespan and die after a certain temperature sum is reached (Porter, 1984; Maas, 1993). Potential crop growth results in this case in potential yield.

Contrary, the potato crop does not have a predefined number of leaves before tubers are initiated. Because senescence and subsequent ripening of the tubers is influenced by the amount of N applied, the growing season can be extended by application of more N. This is possible because new leaves are formed when the old ones have reached the end of their lifespan. In an experiment with nitrogen application MacKerron & Davies (1986) found that the moment that LAI drops below 3 (almost maximal light interception) can be delayed with 39 days by increasing N applications. Even at higher fertilizer applications (160kg N ha^{-1}) an increase in N fertilizer with 50% led to one week delay in the moment LAI drops below 3. Similar results have been found by Gunasena & Harris (1968), Dyson & Watson (1971) and Clutterbuck & Simpson (1978). The extended period of high light interception will lead to improved biomass growth. Therefore a high nitrogen application will lead to potential production.

On the other hand, increasing nitrogen application also leads to delayed initiation of tubers. Therefore tuber filling starts later, less biomass is used for tubers having an adverse effect on yield. High nitrogen applications can thus lead to lower yields (Gregory, 1965; Allen & Scott, 1980; Westermann & Kleinkopf, 1985; Veerman, 2003). Therefore the definition of potential yield in potato can be deceiving. To initiate tubers timely and therefore attain the highest yield possible there have to be some days in the growing season in which the crop is limited in its growth by nitrogen. However, when crop growth is limited by nutrients during part of the growing season, the production is not at a potential level.

For determining potential production levels and potential yields, crop growth models are used. These models are calibrated with yields from field experiments that are assumed to be close to potential production. However, the optimum amount of N needed for the highest yield in potato is hard to determine and may not have been applied in most field experiments. Because of the difficulty with the definition of potential production for potato and uncertainty about field experiments used, in this report the highest production level will be called non-water limited instead of potential.

The yields at the non-water limited level in the report are defined as the highest attainable given the nitrogen levels applied in the field experiments used for calibration of the model. The nutrient and water-limited production level will be calculated with a rain fed model version.

To assess productivity of different production areas, a yield gap approach can be used. A yield gap is the difference between the yields at two predefined yield levels, generally the gap between the actual yield and the potential yield. In this research the yield gap is defined as the gap between the actual yield and the non-water limited yield. In order to make a fair comparison between production areas the yield gap is made relative to the non-water limited yield.

Water limitation in most crops in Villa Dolores is amended by irrigation. Considering environmental sustainability of the potato chip sector, scarce resources like water should be used as efficiently as possible. Therefore determining irrigation needs and water use efficiencies can help in management decisions on water conservation versus yield optimisation. Another important factor in the potato chip industry is the year-round supply. This means storage facilities and harvest dates are important. Because harvest dates are dependent on the moment of planting, plant- harvest date combinations should be considered. Knowing the implications of different plant- harvest date combinations on yield and irrigation demands can help management decisions.

In this research the general assumption is made that 85% of non-water limited production can be achieved in practice because of nutrient constraints, harvest losses and (spraying) paths (less cropping area per ha). Furthermore, it is assumed that for this realistic production level 15% less irrigation is needed compared to the non-water limited production level because roughly 15% less biomass is produced. Simulations with 85% of the irrigation needed for non-water limited production will be referred to in this research as the 85% irrigation level. The yield and amount of irrigation needed at the 85% irrigation level can then be used to determine the use efficiency of irrigation.

Caldiz (2000) already determined potential yields for ware potato in various regions of Argentina including Villa Dolores. However, no cultivar specific effects were accounted for. Furthermore, irrigation efficiency was not included in this research.

For determining the non-water limited, rain fed and 85% irrigation production levels a simple and effective tool is needed. As relatively large areas are needed to supply a French fry factory Farm Frites prefers using a model that can handle large amounts of spatial data. In order to analyse the yield gap for a Farm Frites owned farm in Poland, Huber (2010) used the LINTUL1p and LINTUL2p models to determine the potential and water limited production. For this report the LINPAC model (JG Conijn, PRI, Wageningen, the Netherlands, unpubl. res.) will be adapted to include potato cultivars. LINPAC is a model for a wide range of crops and has a GIS interface for processing spatially explicit soil and weather data and producing spatially explicit output. In LINTUL1p and LINTUL2p no GIS interface is included.

The aims for this research are: (1) developing a model version of LINPAC for potato (2) to assess productivity and yield gap (3) and water use efficiency of the potato sector in Villa Dolores. To this end, LINPAC is adapted for various potato cultivars. The cultivars Shepody, Innovator and Bintje are used, two important cultivars for production of French fries and a cultivar widely used in field experiments. The model is used to determine non-water limited yields and yields at 85% irrigation for Villa Dolores. Also yields at 85% irrigation for different combinations of planting and harvest dates are determined by simulation. To assess productivity of the area, the relative yield gap is compared to other potato producing regions. Water use is assessed using dry matter yields and irrigation applied.

1.2 Report outline

In this report three main activities are described: i) the adaptation of LINPAC into LINPACsa ii) the calibration and validation of LINPACsa and iii) the exploration of the potential of Villa Dolores for potato production. In section 2.1 the Villa Dolores area is described. In section 2.2 the current model is described and in 2.3 the adaptations are explained. In section 2.4 -2.6 the processes of calibration and validation are described. In sections 2.7 and 2.8 the simulation process is described. In section 3.1 the calibration and validation outcomes are presented. In sections 3.2 and 3.3 the simulation outputs are presented. Calibration and validation is evaluated in 4.1 and 4.2. The potential of Villa Dolores for potato production is discussed in 4.3 and 4.4. Conclusions follow in chapter 5.

2 MATERIALS AND METHODS

2.1 Agro ecological description of Villa Dolores

2.1.1 General description of the area

The area of interest is located in Córdoba province in the centre of Argentina, named after the largest city in the area, Villa Dolores (31°56' 00" S, 65° 12' 00" W). It covers approximately 380,000 ha in the department of San Javier and part of San Alberto, both located in the north west of the province Cordoba on the border with the San Luis province (Fig. 2.1). The larger area is called Traslasierra which literally means behind the mountain ridge. It is a valley west of the mountain ridge Sierras Grandes which separates it from the province capital. The east of the area is part of this mountain ridge with high altitudes, sloping to the low land in the (north) west of the area (Fig. 2.2) (Dijkshoorn et al., 2008; INTA, 2011).

Fig. 2.1 Overview of the area of interest for this research.

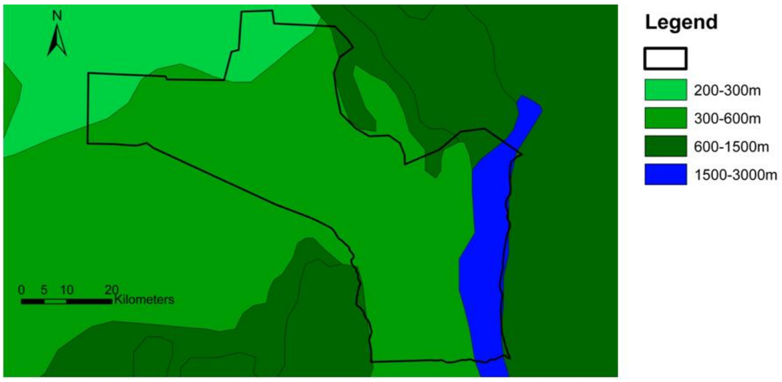


Fig. 2.2 Map of the elevation of the area.

2.1.2 Climate

There are two climate types in the area according to the Köppen-Geiger classification. The mountain side has a humid sub tropic climate (Cwa) exhibiting hot, humid summers and cool, dry winters. The lowland has a semi-arid climate (Bsk) characterised by a shortage of precipitation, moderately hot summers and cool winters (Peel et al., 2007).

Average temperatures and precipitation are based on measurements at Villa Dolores Airport in the years 2001-2006 (Fig. 2.4). The average yearly precipitation in this period was 620 mm (Fig.2.3). The yearly water deficit due to average evapotranspiration is approximately 400mm in the east to 480mm in the west of the area

(Ghida Daza & Sánchez, 2009). First dates of frost are around mid-May and late frosts are recorded historically around 15 September, no data was found on the chances and occurrence of frost during the cold periods.

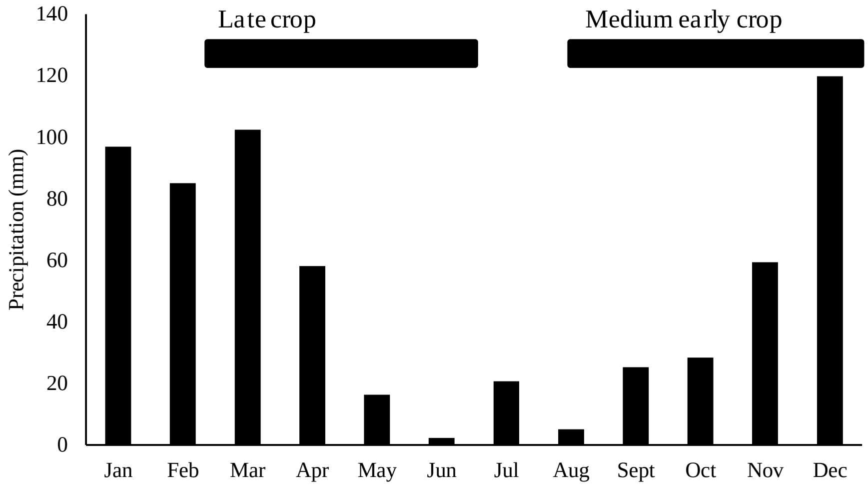


Fig. 2.3 Average monthly precipitation in Villa Dolores based on the years 2001-2006, measured at Villa Dolores airport (INTA, 2011). The black bars indicate the cropping seasons for potato.

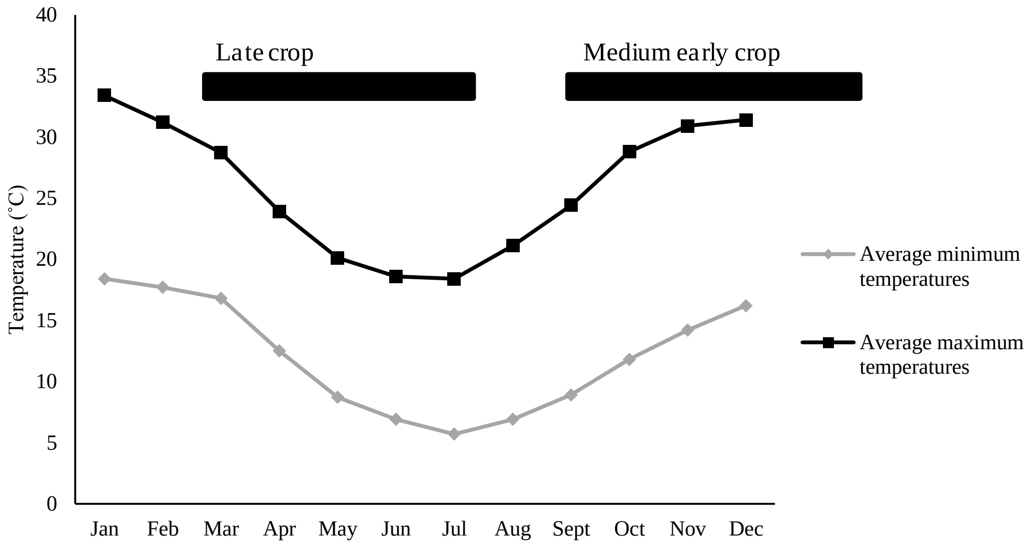


Fig. 2.4 Average monthly minimum and maximum temperatures in Villa Dolores based on the years 2001-2006, measured at Villa Dolores airport (INTA, 2011). The black bars indicate the cropping seasons for potato.

Only weather data averaged per month over multiple years was found, the spread in temperatures and rainfall could therefore not be determined. However, because of the elevation gradient in the area also the climate differs greatly, a temperature difference of at least 4˚C exists between the semi-arid lowland in the east and the more temperate mountain range in the west. There is a large difference in annual precipitation between the east and the west of the area (Fig. 2.6).

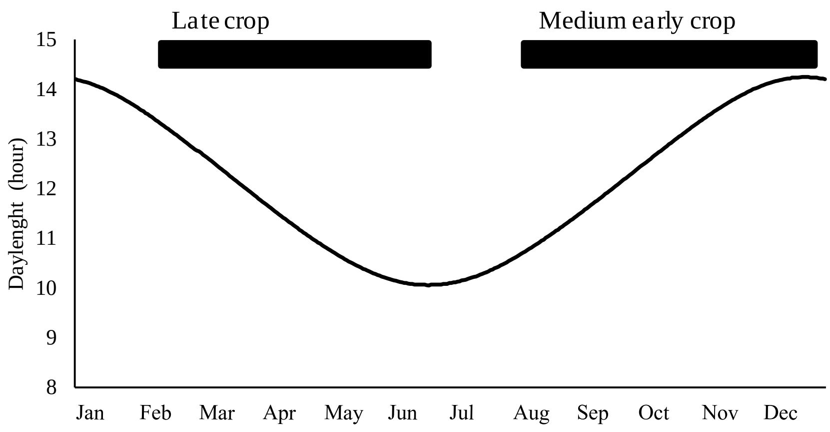


Fig. 2.5 Day length in Villa Dolores throughout the year for 2011 given in hours, day length is here defined as the time between sunrise and sunset (USNO, 2011). The black bars indicate the cropping seasons for potato.

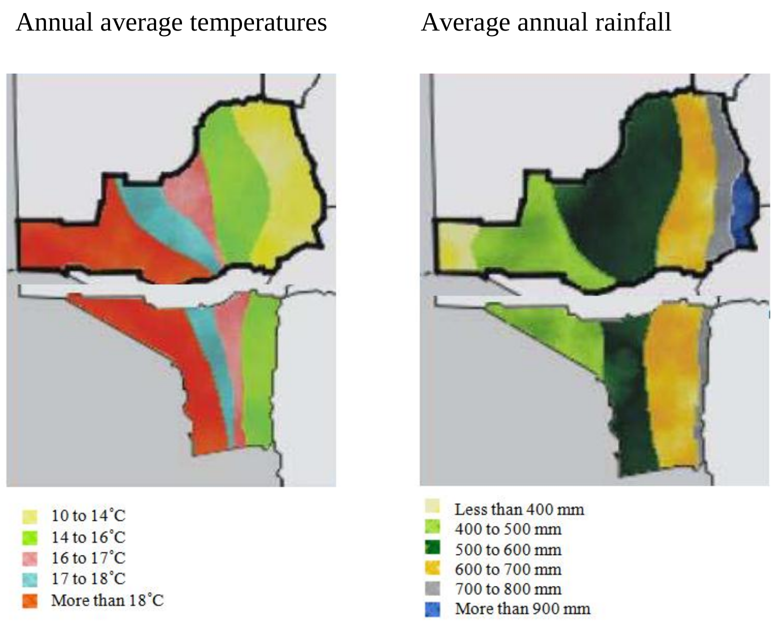


Fig. 2.6 Gradient in temperature and precipitation in the departments San Javier (below) and San Alberto (MAGyA, 2011).

2.1.3 Soil

In the study area Haplic Kastanozems are most abundant, furthermore in the mountainous east of the area Lithic Leptosols occur and in the north Calcaric Regosols can be found (Dijkshoorn et al. 2008) (Fig. 2.7). Haplic Kastanozems are rich in organic matter, the parent material is usually loess. The soils are usually quite fertile but irrigation is needed for good yields, which brings the risk of salinization. Also these soils can be prone to wind and water erosion especially when left fallow.

Lithic Leptosols are rocky soils, with less than 10cm of soil, and usually less than 20% fine soil in the soil layer. Pure cropland on these soils leads to high risks of erosion, alternative land use forms are forest and grazing land.

Calcaric Regosols are poorly developed mineral soils containing a calcaric layer near the surface, sometimes linked to erosion in mountainous and arid regions. The parent material is very fine and unconsolidated with a low water holding capacity. Irrigation is needed for crop growth, however this is often not economically viable (FAO-Unesco, 1988; IUSS Working Group WRB, 2006).

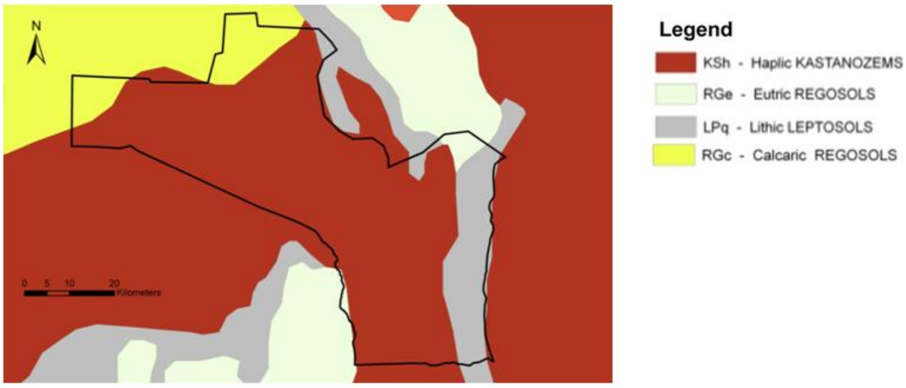


Fig. 2.7 Map of the soil types in Villa Dolores (Dijkshoorn et al., 2008).

Overall from the soil types it appears that the greatest edaphic constraint is the low water holding capacity. Also the Lithic Leptosols are very shallow and the Calcaric Regosols have a high irrigation need. The risk of erosion, either water or wind driven is great on all soils. When irrigation is used this brings the risk of salinization. For potato cultivation especially the Haplic Kastanozems and Calcaric Regosols are of interest. In Appendix 7 a further differentiation in soil types is made and soil properties are quantified.

2.1.4 Current agricultural practice

In the region there is a division between irrigated agriculture in the low land and small holder farming in the high lands (INTA, 2011). In the high lands mainly fruits, aromatic and medicinal herbs are grown and livestock is held. These cultivations are fed by springs from the mountains. In the low land mainly wheat, maize, potato, sunflower and soybean is cultivated with potato being the second crop in cultivated area with 6481 ha. The total area used as arable land in Villa Dolores is unknown, but the area cultivated with the main crops mentioned above sums up to approximately 20,000 ha (MAGyA, 2011).

Potatoes in Villa Dolores are planted in two seasons (Figs 2.3-2.6). The late crop is planted at the end of summer (10th of February- 5th of March) and harvested in winter (30th of June- 30th of September). The medium early crop is sown in spring (15th of July – 10th of August) and harvested in summer (November/December, before the 25th of December) (INTA, 2011; Caldiz, 2000; M Huarte, INTA, Argentina, pers. comm; M Pasman, Farmer in Villa Dolores, Argentina, pers. comm). A crop rotation of two potato crops per 4 years is practiced on a commercial, pivot irrigated farm in Villa Dolores (Table 2.1), (M Pasman, Farmer in Villa Dolores, Argentina, pers. comm).

Table 2.1 Crop rotation for two cropping seasons per year on a commercial, pivot irrigated farm in Villa Dolores

	Late crop	**Medium early crop**
First year	Maize	Potato
Second year	Wheat	Soybean
Third year	Maize (Seed)	Unknown
Fourth year	Potato	Maize

The late potato crop is planted during a long day period (Fig. 2.5) with high temperatures (Fig. 2.4), these conditions can delay tuber initiation depending on cultivar. During the growing season irradiance and temperature decrease which reduces growth. The first frost which (depending on the location within the area) will come in around the 15th of May and the high temperatures around planting strongly reduce the length of the growing season (Driver & Hawkes, 1943; Bodlaender, 1963; Gregory, 1965; Caldiz, 2000, Pasman 2011).

The medium early crop is planted at short days promoting early maturity. High temperatures at harvest can cause quality loss and problems with storability. Also the high temperature prevents a longer growing season, normally farmers try to harvest before the 25th of December (Driver & Hawkes, 1943; Bodlaender, 1963; Gregory, 1965; Caldiz, 2000; M Huarte, INTA, Argentina, pers. comm; M Pasman, Farmer in Villa Dolores, Argentina, pers. comm).

Potatoes are planted at 25cm depth measured from the top of the ridge with a between- row spacing of 88 cm (M Pasman, Farmer in Villa Dolores, Argentina, pers. comm). The largest part of the water used for irrigation in the area originates from an artificial lake created by a dam in the Rio de los Sauces river. This water is used mainly for furrow irrigation on approximately 12.000 ha of arable land. Another 10.000 ha is irrigated by pivots, which mainly use water pumped up from subterranean sources (INTA, 2011). The area under irrigation includes main and smaller cultivations in the area. The medium early potato crop is the more demanding in irrigation than the late potato crop due to a longer growing season and high temperatures, high irradiance and low humidity at the end of the season. Average application for this season is 450-650mm while the irrigation application for the late crop is 250-350mm (M Pasman, Farmer in Villa Dolores, Argentina, pers. comm).

Table 2.2 Average fresh tuber yields attained in Villa Dolores according to several sources. For all source the period on which these averages are based are unknown.

Source	**Cultivar**	**Season**	**Yields (tonnes/ha)**
M Pasman	Undefined, ware potato	Late	24-32
Caldiz (2000)	Undefined, ware potato	Late	18
INTA (2011)	Undefined, ware potato	Late	25
M Pasman	Undefined, ware potato	Medium early	32-42
Caldiz (2000)	Undefined, ware potato	Medium early	25
INTA (2011)	Undefined, ware potato	Medium early	30

Yields in the medium early season (August-December) are higher than yields in the late season (February-June) (Table 2.2). Highest reported average yields came from a commercial, pivot irrigated farm, for this report the figures from this farm are assumed to be a reflection of best performing farm in the region (M Pasman, Farmer in Villa Dolores, Argentina, pers. comm).

Potato is mainly produced for domestic use in industry or fresh consumption, 10% is exported. In the area cultivars grown for processing are Innovator, Asterix, Quennebec, Atlantic and Daisy. Cultivar Spunta is used for fresh consumption. Potatoes are sold through intermediaries, on the central market of Buenos Aires or through contracts with processing industries (INTA, 2011; M Pasman, Farmer in Villa Dolores, Argentina, pers. comm).

2.2 Structure of the LINPAC model

The model used in this report is based on the LINPAC model (JG Conijn, PRI, Wageningen, the Netherlands, unpubl. res.). LINPAC is a crop growth simulation model with a time step of 1 day. LINPAC (LINtul model for Annual and Perennial Crops) consist of several modules written in Fortran 95. For this research the COMPAQ Visual Fortran 6.6 compiler was used. The core module simulates crop growth and the soil water balance and is therefore called *CropSoil*. The description below especially concerns *CropSoil* and only in some occasions the role of the *CropSeas* and *WFPROD* and *UTILS* modules will be mentioned. The *CropSeas* and *WFPROD* modules determine the length of the cropping seasons and generate daily weather data from monthly data. The *UTILS* module contains some of the subroutines mentioned in the description below.

The description is divided in five main sections that are commonly found in Light INTerception and UtiLisation (LINTUL) models: Temperature sums, LAI, Biomass, Yield and Soil-water. Names of variables, parameters and subroutines in the model are given in *italics*. Examples of parameter values given are for tropical maize which was already included by Conijn (PRI, Wageningen, the Netherlands, unpubl. res.). A parameter listing for LINPAC is given in Appendix 3.

2.2.1 Temperature sums

- Base temperature

A fixed base temperature can be given (*Tmbase*) to calculate the effective temperature that contributes to the temperature sum. Another option is to calculate the base temperature based on the average minimum and maximum temperature sums in the growing season.

- Calculation temperature sum

The total temperature sum (*Tmsum*) is calculated from the moment the crop is planted. The base temperature is subtracted from the daily average temperature to get the effective temperature (*Tmeff*). Temperatures above a maximum temperature do not contribute more than this maximum temperature to the effective temperature. The cumulative effective temperature is the temperature sum. A second temperature sum (*Tsm*) starts accumulating after emergence and governs most phenological processes.

- The temperature sums at which phenological stages begin or end:
  - *Tsmem* (emergence) 60 ˚Cd
  - *Tsm0* (max LAI reached under potential conditions) 750 ˚Cd
  - *Tsm1* start translocation to yield. End juvenile leaf area growth 750 ˚Cd
  - *Tsm 2* start developmental leaf area decline (end constant phase) 900 ˚Cd
  - *Tsm 3* end crop 1500 ˚Cd
  - *Tsmrd* end root growth phase (0.75 *Tsm0*) 562.5 ˚Cd

However, temperature sums 0-3 are recalculated in the *CropSeas* module. If the accumulated temperature sum after emergence is higher than the predefined crop life temperature sum (*Tsm3*), all temperature sums will be increased. If the temperature sum over the growing season is lower, all temperature sums will be decreased. This approach is used to mimic cultivars that are adapted to local climates.

2.2.2 Leaf area index (LAI)

- Initial leaf area growth

The initial leaf area (*Laiem* in m^2m^{-2}) is calculated with an expolinear growth function based on Goudriaan & Monteith (1990) (Eq.1.1) (for parameter listing see Appendix 3). This is chosen to get the initial exponential growth that is typical for leaf area and the linear phase that follows in one expression. The coefficients *cm*, *rm* and *tb* determine the initial density and growth rate of the crop. The zero will be replaced in the calculation of leaf area by the accumulated temperature sum after initialisation.

Equation 1.1 $$Laiem = \frac{cm}{rm} * \ln(1 + e^{rm*(0-tb)})$$

- Leaf area growth after initialisation

There are three phases of leaf area growth in the model. After initialisation the first phase in the leaf area growth starts, the expolinear phase (Fig. 2.8). The zero in the expression for LAI at emergence is replaced by a temperature sum (Eq. 2.3). By adding the effective temperature (*Tmeff*) and the temperature sum used in the last *Lai* calculation this temperature sum is calculated. The inverse expolinear function calculates the temperature sum used in the last *Lai* calculation (Eq. 2.2). This phase lasts until the maximal LAI (*Laimx*) is reached or until *Tsm1* is reached. *Tsm0* is the moment when *Lai* reaches maximum if the leaf area growth is optimal. It is used to determine the coefficients *cm* and *tb*. Optimal leaf area growth is not necessarily reached because it can be limited by stress factors mentioned in the sections below.

Equation 2.2 $$Tsumold = tb + ln(e^{LAI*\frac{rm}{cm}} - 1)/rm$$

Equation 2.3 $$Lai = \frac{cm}{rm} * \ln(1 + e^{rm*((Tsumold+Tmeff)-tb)})$$

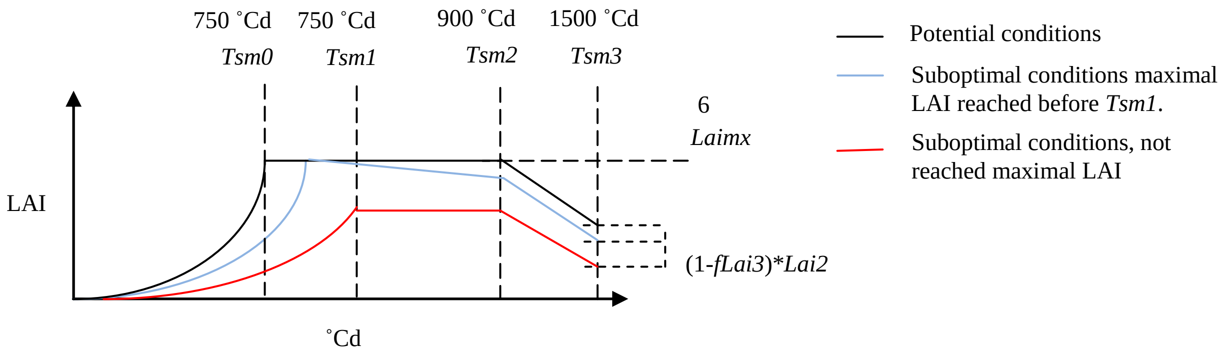


Fig. 2.8 Schematic representation of three possible LAI growth and decline scenarios in the LINPAC model. The black and blue lines reach maximum LAI in the expolinear phase. The black line is the potential scenario and reaches maximum LAI at *Tsum0*, the lowest temperature sum in which *Lai* 6 can be reached. The blue line stands for suboptimal conditions (mild water deficit or *xLueToxred*= toxic soil conditions), but still reaches *Lai* 6 before *Tsm1*. The red line does not reach *Lai* 6 before *Tsm1* and thereafter goes into the constant phase. In the constant phase also decline of *Lai* is possible because of leaf death due to serious water deficit (transpiration ratio under 0.7) as is shown in the blue scenario. From *Tsm2* onwards *Lai* declines until a certain fraction of *Lai* at *Tsm2* (1-*fLai3*), which takes exactly until *Tsm3* unless there is a serious water deficit.

- Leaf area growth in the constant phase

In the constant phase *cLai* (the growth rate of *Lai*) is zero. This phase begins with the LAI reaching maximum or with reaching *Tsm1* and ends at *Tsm2*. Only leaf death due to water shortage (*Dlai*) can change *Lai* during this phase.

- Leaf area decline in the last phase

When *Tsm2* is reached leaf area decline sets in as a result of leaves reaching the end of their physiological life span. Leaf area decline is linearly dependent on effective temperature. This makes the leaf area decline almost linearly to a fraction (*1-fLai*) of the LAI that was reached at *Tsm2*. This minimum is reached at *Tsm3*.

- Soil toxic effects

If there are any soil toxic conditions parameter *xLueToxRed* directly gives the retarding effect on leaf area growth.

- Water stress

Reduced transpiration, expressed as the ratio between actual and potential transpiration (*TrRat*), is translated into a reduction factor. If the ratio is below 0.7 it is translated linearly in a leaf death rate. This leaf death rate is bound by a maximum (*dLmax*).

2.2.3 Biomass

- Emergence

There is a fixed temperature sum for emergence (*Tsmem*), if this is reached, crop growth processes start and the temperature sum that governs the phenological processes starts accumulating.

- Light interception

Lai is used to determine intercepted PAR (photosynthetic active radiation, defined in the model as 50% of the radiation from the weather file) through an extinction equation with extinction coefficient k (*Kpar* = 0.6). Also reflection (-5% of PAR) is taken into account. The fraction of PAR that is intercepted is called *Fint*.

- LUE

Light use efficiency (*Lue* in g DM MJ^{-1}) is defined in the model with a fixed value, e.g. 4 for maize.

- LUE reductions

Light use efficiency can be reduced due to soil toxic conditions by a reduction factor *xLueToxRed* and sub or supra optimal temperatures (Fig. 2.9). Both reducing factors are linear.

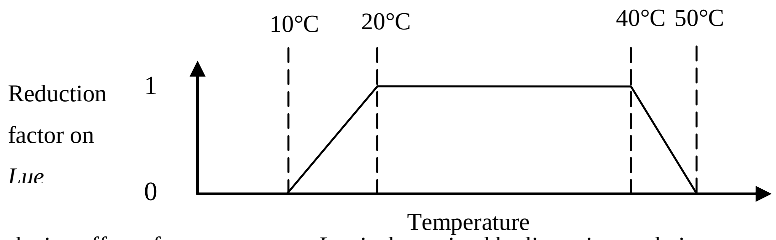


Fig. 2.9 The reducing effect of temperature on *Lue* is determined by linear interpolation.

- Biomass calculation

Biomass (*Biom*) is calculated by multiplying *Lue* with the photosynthetic active radiation and the fraction of this radiation that is intercepted by the crop (*Fint*).

- Water stress

Reduced transpiration, expressed as the ratio between actual and potential transpiration (*Trrat*) is multiplied with the biomass growth rate *cBiom* if *Trrat* is below 0.7 causing a linear reduction.

- Sinkcap

If water shortage occurs during flowering, *cBiom* can be reduced by the *Sinkcap* parameter. Because during the flowering season water stress leads to less kernels and a lower sink strength in case of tropical maize. The flowering period in degree day is indicated by an interval around *Tsm1* of *Tsm1-Flper* until *Tsm1+Flper*. *Sinkcap* is the ratio of cumulative actual transpiration over cumulative potential transpiration during the flowering period. The parameter is multiplied with *cBiom* causing a linear reduction in biomass growth rate. *Sinkcap* is only used for reduction of *cBiom* if it is lower than the daily *TrRat* otherwise the latter will be used as the reduction factor.

2.2.4 Yield

- Dry matter distribution

Yield is calculated as a daily rate. This is done for seeds or for whole plant biomass yield. Part of the yield is based on the total daily biomass production in the generative phase (starts at *Tsm1*). Another part is formed by translocatable biomass (*Biom1*) formed in the vegetative period (based on a fixed fraction *Trloc*). The second part is reallocated during the rest of the crop life (until *Tsm3*) as a function of daily temperature. A fraction (*Seedaf*) of the resulting generative biomass is allocated to the seeds.

- Yield loss due to stress

Because plant biomass is reduced by water stress and stress during flowering, yield will also be reduced. Therefore yield is reduced with the same fraction as plant biomass.

2.2.5 Soil water

- Initial root length

Root growth starts with an initial value of 0.05 m (*Rtdem*) for annuals and with the total rootable depth for perennials.

- Root growth

Roots grow as a linear function of the accumulated temperature sum until *Rdepth* is reached at *Tsmrd* (0.75**Tsm1*).

- Soil depth and rootable depth

Soil depth (depth of soil layer) and maximal rootable depth of the crop are given per soil type. When the soil (S*depth*) is shallower than maximal rootable depth (*Rdepth*), soil depth is the limiting factor for root growth and *Rdepth* will assume the value of soil depth. If the maximal rootable depth is smaller than the soil depth, soil depth assumes the value of *Rdepth*. This is done because soil water processes below the maximal rootable zone are not considered in this model.

- Soil layers and drainage

Two homogeneous soil layers are simulated, the top one is rooted (layer 1) and the rest of the soil depth is taken up by the second layer. If layer 1 is at field capacity, the excess water from layer 1 is drained to layer 2. When layer 2 is at field capacity, water is drained from the system. The thickness of layer 1 (*Tkl1*) grows with rooting depth and is initiated as the top 0.2 m of the soil. Layer 2 (*Tkl2*) is shrinking at the rate of root exploration (*Tkl_dif*) (the growth rate of layer 1). Water explored by root growth (*Wtransf*) is determined by the rate of root exploration (*Tkl_dif*) and the soil water content of layer 2 (*Wsoil2*).

- Interception

Rain intercepted by the crop canopy is calculated in the *Intercep* subroutine based on LAI. The thin layer of intercepted rain decreases the potential transpiration in subroutine *ETpot*. Interception of irrigation is not taken into account here, therefore irrigation application is assumed to be net irrigation, when it comes to interception.

- Runoff

After interception of water applied, runoff is calculated. This is split up over runoff from irrigation and from rain. Runoff is calculated in function *Frunoff* as a function of texture class, slope class and net precipitation (precipitation minus interception) for rain (*RunofR*). Runoff from irrigation (*RunofI*) is determined based on net irrigation (no interception), texture class and slope class. By using a looped calculation an estimation of gross irrigation (including runoff, not including interception) is made.

- Infiltration

Infiltration into layer 1 is the result of the product of rain and irrigation minus interception (only for rain) and runoff.

- Potential evapotranspiration

Reference evapotranspiration is calculated with the Penman-Monteith equation (*Etmeth* = 2) in subroutine *ETpot* using temperature, wind speed, vapour pressure, total radiation, rain and irrigation intercepted, latitude and altitude. This reference evapotranspiration is split up in potential evaporation (*Epot*) and potential transpiration (*TrPot*).

- Actual transpiration

Actual transpiration (*TrAct*) always equals potential transpiration (*TrPot*) when the model is set to non-water limited production (*Ilev* = 1). When the model is set to rain fed, actual transpiration only equals potential transpiration if there is enough water available for transpiration (*Wsoilcr*). *Wsoilcr* is defined as the amount of water in soil layer 1 above wilting point in mm. It is determined using the plant available soil water between field capacity and wilting point, potential transpiration and a transpiration constant (*TrCrt*) (Equation 2.5) and therefore changes depending on potential transpiration. *TrCrt* is a measure of the drought tolerance of the crop, the higher the constant the less water needs to be available to keep actual transpiration equal to potential transpiration.

If the amount of available soil water (*Wsoiltr*) is below critical water amount (*Wsoilcr*), actual transpiration is calculated as a fraction (*Wsoiltr/Wsoilcr*) of potential transpiration. This fraction increases linearly from 0 at wilting point to 1 at critical water amount (Fig. 2.10). The effect of water logging is not taken into account.

Equation 2.4
$$Wsoilcr = \frac{Wsoilfc - Wsoilwp}{1 + \frac{TrCrt}{TrPot}}$$

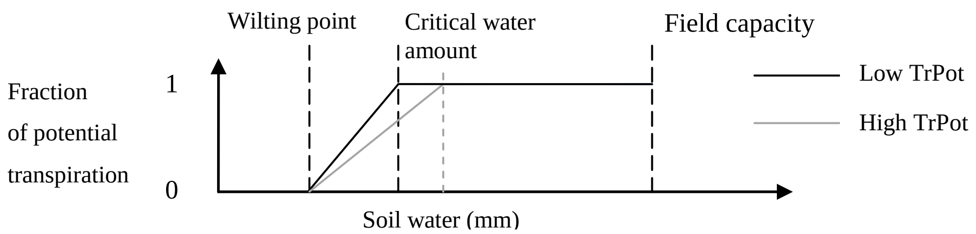


Fig. 2.10 Actual transpiration as a fraction of potential transpiration. Between wilting point and critical water amount actual transpiration is below potential transpiration. The critical water amount is higher when potential transpiration is higher (blue line).

- Actual evaporation

Evaporation equals potential evaporation when the amount of water in the top soil layer is above 85% of field capacity (*Wsoilfc = tkl1*xtotalwatcont*) (Fig. 2.11). Between air dry and 85% of field capacity in the top layer, the fraction of potential evaporation shows a quadratic increase from 0 to 1.

- Reduction due to water stress

When actual transpiration is below potential transpiration the crop processes do not work optimally. Therefore the transpiration ratio (*TrRat= TrAct/TrPot*) is used to express reduction of different processes due to water stress.

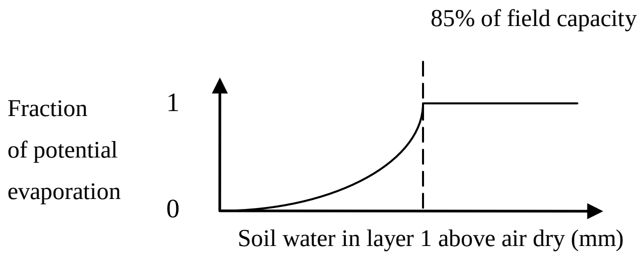


Fig. 2.11 Actual evaporation is determined in the model based on potential evaporation and soil water in the top layer of the soil. Between air dry and 85% of field capacity, actual evaporation is below potential evaporation.

- Initial soil water

Amounts of water in soil layer 1 and 2 are set at field capacity in subroutines *Cropseas* and *WFPROD* and. The soil water module starts calculations before planting day therefore the soil water conditions at crop emergence are updates based on observed weather conditions.

- Irrigation need potential production

Rain fed production is set by *Ilev* = 2, in this model setting transpiration depends on water available in the soil. Non-water limited production is set by *Ilev* = 1 where after transpiration is made equal to potential transpiration by applying the water deficit (*Wdeficit*) as irrigation. Net irrigation equals water deficit, for gross irrigation an estimation of runoff of irrigation water is added. Water deficit is determined as the positive difference between critical water amount (*Wsoilcr*) (below this amount transpiration will not equal potential transpiration) and actual water amount available for the plant (*Wsoiltr*).

2.3 Adapting LINPAC for potato

The LINPAC model was included in the TIPS_Z modelling environment (Jansen, 2002) in order to perform an automatic calibration of the model for potato parameters. Also part of the model structure was adapted to allow simulation for potato. To run LINPAC in the TIPS_Z modelling environment, the *WFPROD* and *Cropseas* modules were not included. Instead some of the procedures necessary for running LINPAC in TIPS_Z were included in the *Soilcrop* module. The version of LINPAC running in TIPS_Z to which potato was added is referred to as LINPACsa.

Potato was added to LINPAC by including new model expressions and parameters for potato. In this section the model expressions needed for potato in LINPAC are presented in the order in which they appear in the *Soilcrop* module. Changes made to LINPAC to run it in TIPS_Z will not be discussed. The parameters that were added to make LINPACsa are listed in section 2.3.4, the code for LINPACsa is added in Appendix 4. For every adaptation the line numbers of the fragment model text in Appendix 4 to which it applies are mentioned.

Some parts of the model were adapted for potato whilst the original section is still functional for other crops. The model differentiates between calculations meant for potato and for other crops by the existing crop parameter *Croper*. This is used in LINPAC to select either an annual (1) or perennial crop (2). In LINPACsa a third option for potato is introduced, indeterminate annual (3).

2.3.1 Initialisation and temperature sums

All temperature sums for development get a fixed value in LINPACsa. In LINPAC "local" cultivars were made by adjusting the developmental temperature sums to the temperature sum available in the growing season. In LINPACsa, the parameter listing is made per potato cultivar which makes it unnecessary to create these "local" parameters. *Tsm1* is initiated at a very high value, to be changed into the temperature sum at the reached at the moment tubers are initiated. The moment of tuber initiation is calculated as shown in section 2.3.3 (Appendix 4, line 299 to 312).

The temperature sum for emergence (*Tsmem*) was replaced by a fixed date of emergence called *Dayemobs*, because time between planting and emergence for potato is very hard to predict (Appendix 4, line 518 to 522) . For a good prediction many factors are lacking in the model, among which physiological age of seed potatoes, the actual soil temperature (which might greatly deviate from air temperature) and wetness of the soil.

2.3.2 Leaf area calculation

The leaf area growth in LINPACsa for potato is governed by the expolinear function from emergence until the end of the crop, unlike the leaf area growth in LINPAC that stops after *Tsm0* or *Tsm1* (Eqs 2.5 – 2.7). This is done to be able to simulate growth in the later stage of canopy development which can also occur in reality (DJ Jansen, Plant Research International, the Netherlands, pers. comm). After *Tsm0* the leaf area growth is slowed down (Eq. 2.8) and after *Tsm2* the leaf area starts dying off as a consequence of ageing (Eq. 2.9). *Tsm1* is no longer used as a parameter for leaf area growth in LINPACsa (Appendix 4 line 326-342 and line 554-585).

Equation 2.5 $$Tsumold = tb + ln(e^{LAI \times \frac{rm}{cm}} - 1)/rm$$

Equation 2.6 $$Lai = \frac{cm}{rm} \times \ln(1 + e^{rm \times ((Tsumold + Tmeff) - tb)})$$

Equation 2.7 $$cLai = Lai - OldLai$$

Equation 2.8 if Tsm >Tsm0 $$cLai = cLai \times \frac{Tsm3 - Tsm}{Tsm3 - Tsm0}$$ (Tsm3-Tsm)/(Tsm3-Tsm0) < 1 and > 0

Equation 2.9 if Tsm >Tsm2 $$cLai = cLai - Lai2 \times fLai3 \times \frac{Tsm - Tsm2}{Tsm3 - Tsm2}$$

2.3.3 Biomass and yield

In LINPAC the light use efficiency is reduced at sub and supra optimal temperatures (section 2.5). Whenever the average daily temperature is below or above the optimal range LUE will be reduced. For potato not the average daily temperature but the average daytime temperature (*Tmavd*) is used (Eq. 2.10). This is done because day time temperatures are assumed to be most limiting to the processes that make up the LUE. Further reasoning behind this is given in Appendix 5.

Equation 2.10 $$tmavd = tmmax - 0.25 \times (tmmax - tmmin)$$

Day length and temperature are the main factors that influence the moment of tuber initiation and the allocation to tubers (Driver & Hawkes, 1943; Bodlaender, 1963; Haverkort, 1990; Kooman & Haverkort, 1995;Van Dam et al., 1996). The allocation to storage organs in LINPACsa for potato is governed by *AllocNew*, which is determined by an exponential function of which the coefficients are dependent on day length and average temperature (Eq. 2.11). The allocation curve is based on Van Dam et al. (1996). *Biom1* is an assimilate pool that consists of biomass that can be reallocated, contained in the vegetative parts of the crop (Fig. 2.12). The allocation of new assimilates and reallocation of assimilates from *Biom1* is started at the moment of tuber initiation (Appendix 4 lines 621-653). Reallocation from vegetative crop parts is included because it is common in potato (DJ Jansen, Plant Research International, the Netherlands, pers. comm).

Equation 2.11 $$AllocNew = 1 - e^{-alphaAlloc \times (Tsm - Tsm1)}$$ AllocNew <1 and >0

Tubers are initiated when the development stage for tuber initiation (*DVSTI*) is 1, the development rate to tuber initiation is determined every day based on day length and temperature. When *DVSTI* = 1, *Tsm1* is set to the accumulated temperature sum at that moment. Then the fraction to be allocated to the tubers will be calculated (explained above), thus starting allocation to the tubers (Appendix 4 lines 916-922).

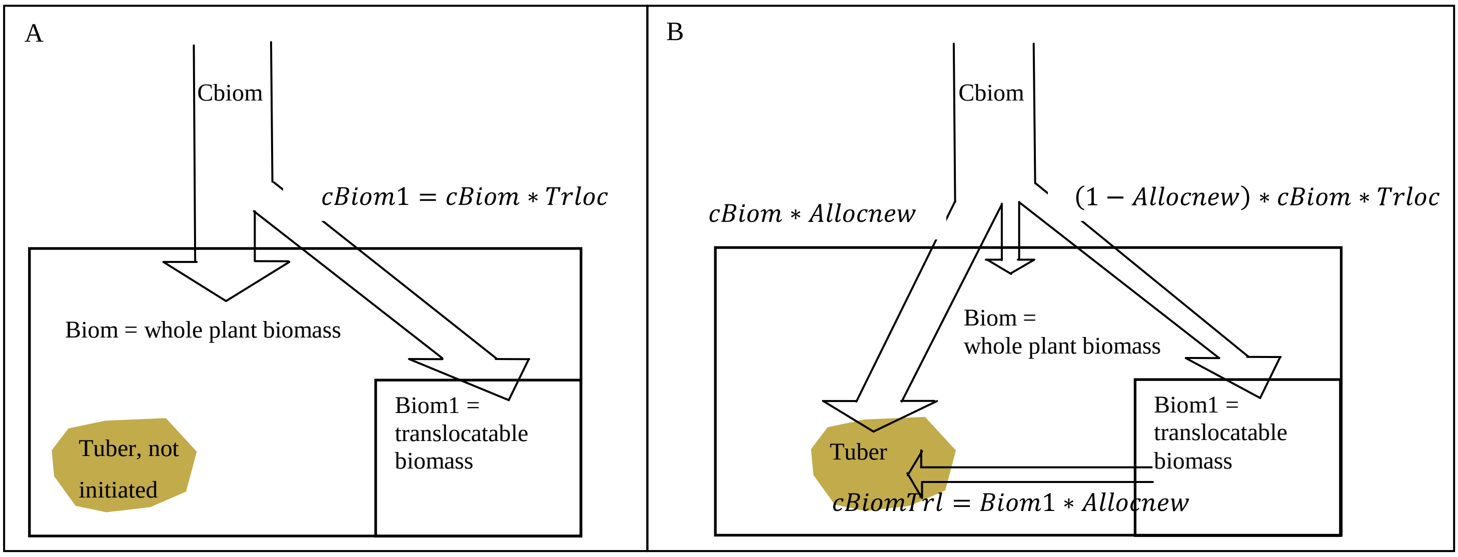


Fig 2.12. An overview of the allocation of new formed biomass (*Cbiom*) and reallocation of translocatable (*Biom1*) to the tuber. A. before tuber initiation B. after tuber initiation.

The slope of the allocation curve (*alphaAlloc*) is calculated as a function of daily average temperature and day length (Van Dam et al., 1996) (Eq. 2.12) (Appendix 4 lines 1048-1065).

Equation 2.12 $$alphaAlloc = AllocMn + \frac{AllocMx - AllocMn}{1 + e^{AllocA \times (xTmav - AllocBT) \times (xDL + AllocBDL)}}$$

alphaAlloc <AllocMx

The rate to tuber initiation (d^{-1}) (*DVRTI*) is calculated as a function of daily average temperature and day length (Van Dam et al., 1996) (Eq. 2.13) (Appendix 4 lines 1066-1076).

Equation 2.13 $$DVRTI = \text{xTmav} \times (1 + \text{SOIniBT} \times \text{xTmav}) \times \frac{1 + SOIniBDL \times xDL}{SOIniA}$$

The parameters used for calculation of the rate to tuber initiation and for calculation of *alphaAlloc* (the slope of the partitioning curve) were retrieved from Van Dam et al. (1996). In this paper measurements for cultivars Spunta and Désiree of the moment of tuber initiation (TI) and the slope of the allocation curve (α) were given for various temperatures and day length treatments (Fig 2.13). Because most data for calibration was gathered for cultivar Bintje the allocation curve was based on the cultivar most resembling Bintje in the research by Van Dam et al. (1996). Therefore the TI and α for cultivar Spunta were used for LINPACsa because the maturity class of Spunta (7) is closest to Bintje (6.5) (for Désiree 5.5). The maturity class is an indication of when a potato cultivar senesces and tubers ripen (NIVAP, 2007; Science and Advice for Scottish Agriculture, 2011).

To get to parameter estimates, firstly the relative effects of day length and temperature on TI and α were determined separately. A three parameter equation was then optimised to fit the observed TI's (parameter *SoIniBT* being the temperature effect and *SoIniBDL* the day length effect). Moment of tuber initiation was then turned into a rate (by dividing by *SOIniA*). Because the moment of tuber initiation was determined for fixed temperatures and day lengths by Van Dam et al. (1996) a development rate was introduced for LINPACsa to account for the effect of daily variance in temperature and day length. For α a more flexible equation was used with five parameters (parameter *AllocBT* being the temperature effect, *AllocBDL* the day length effect and *AllocMn* and *AllocMx* being the boundaries of the function). To calculate day length (daily) as a function of latitude and date, the function *CalcDayL* is used (Appendix 4 line 1077- 1122).

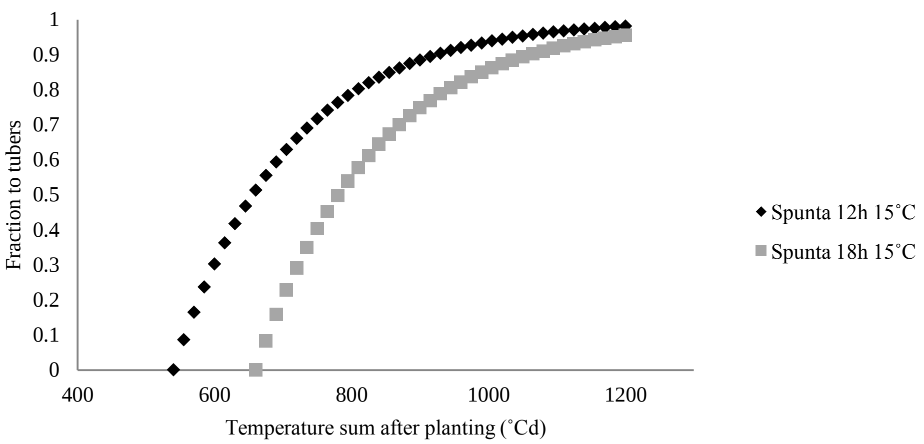


Fig. 2.13 Day length effect on allocation to tubers for cultivar Spunta under two day length regimes with the same temperature. In the short day length regime tubers are initiated earlier on and the curve is steeper, allocating more to the tubers in the beginning. Calculated based on parameters by Van Dam et al. (1996).

Some of the observations upon which the calibration is based were only measured in fresh weight. Therefore some expressions were added to the model to include the calculation of fresh tuber yield from the dry yield output parameter *Yield*. A logarithmic relation between tuber dry weight and fraction dry matter was found based on a fit of dry weight and dry matter fraction observations for cultivars Eersteling, Bintje and Innovator (Fig. 2.14). The new yield output parameter for fresh tuber yield (*FrYield*) is then calculated from this dry matter fraction *FrDMYield* (Appendix 4 lines 812-816). Because of a lack of further data on the relation between dry matter fraction and dry weight it is assumed that the relation is valid for all cultivars used in this research (*Alphayield* = 0.409, *Betayield* = -0.1521).

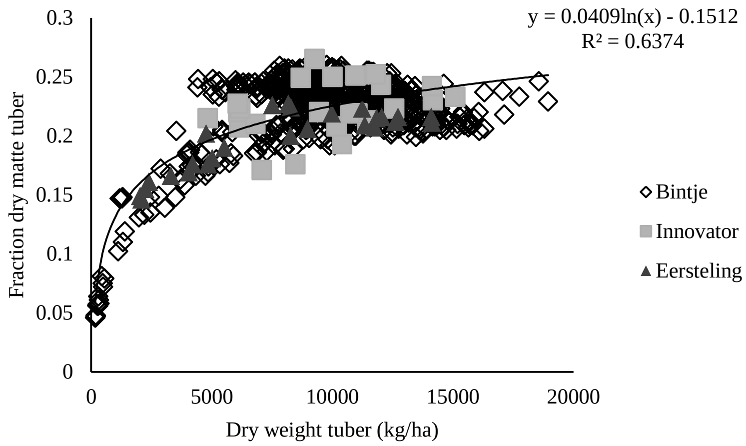


Fig. 2.14 Logarithmic fit of the relation between tuber dry weight and fraction dry matter in the tuber for Bintje, Eersteling and Innovator.

2.3.4 Additions to parameter listing

Dayemobs=	Input of emergence day	Day of year
FrYield =	Fresh tuber yield	kg ha^{-1}
FrDMYield =	Tuber yield over fresh tuber yield	-
alphaYield =	Slope of relation between dry and fresh tuber yield	-
betaYield =	Constant in relation between dry and fresh tuber yield	-
SOIniA=	Coefficient in determining the rate to tuber initiation	-
SOIniBT=	Relative effect of temperature on the rate to tuber initiation	-
SOIniBDL=	Effect of day length on the rate to tuber initiation	-
AllocMn=	Coefficient for determining the slope of the exponential allocation curve	-
AllocMx=	Coefficient for determining the slope of the exponential allocation curve	-
AllocA=	Coefficient in determining the slope of the exponential allocation curve	-
AllocBT=	Rel. effect of temperature on the slope of the exponential allocation curve	-
AllocBDL=	Effect of day length on the slope of the exponential allocation curve	-
DVRTI=	Rate to tuber initiation	d^{-1}
DVSTI=	Development stage tuber initiation 1=moment of tuber initiation	-
AllocNew=	Fraction allocated and reallocated to tubers	-
AlphaAlloc=	The slope of the exponential allocation curve	-

cBiomTrl=	Reallocated biomass from the reallocatable part of biom1	kg $ha^{-1}d^{-1}$
cBiom1=	Growth rate reallocatable assimilates in vegetative crop parts	kg $ha^{-1}d^{-1}$
xTsmLaiMx=	Auxiliary variable for Tsm0 when Croper <3	C°d
xDL=	Day length of a simulation day	h
CalcSOIni=	Name of the function that calculates rate to tuber initiation	-
CalcDayl=	Name of the function that calculates the day length of a simulation day	-
CalcTrLoc=	Name of the function that calculates the slope of the exp. allocation curve	-
xtemp=	Auxiliary variable for determining the slope of the exp. allocation curve	-
Tmavd=	Average daytime temperature	C°

2.4 Selection of field experiments

For calibration and validation of LINPACsa field experiments were selected. Cultivars Shepody and Innovator were chosen because of their use in the French fries industry, Bintje was chosen because it is widely used in field experiments and therefore many data are available. Eersteling and Russet Burbank were added to this research because they are included in field experiments for cultivars Shepody and Bintje. For Bintje and Eersteling most experimental results, soil and weather data were already compiled and formatted by employees of Plant Research International (PRI) and can directly be used in TIPS_Z. However, complete datasets from field experiments with Shepody and Innovator were not available and had to be compiled for this project. Missing weather and soil data had to be retrieved from other sources.

Below some important notes on the selection and compilation of experimental results and weather and soil data are given per field experiment. For all experiments without an observed emergence date, 14 days after planting is used as an estimate. Furthermore, capillary rise is not taken into account in the LINPACsa model and therefore the water available for plants in the field experiments may have been higher than just the water content between wilting point and saturation. From the field experiments selected for calibration and validation a selection was made to exclude treatments with fertilizer applications that were assumed to be below the amount required to attain the highest production level.

Aroostook Research farm, Maine, USA

A paper from 1991 (Porter & Sisson, 1991) was used for the fresh tuber weights (end harvest) for three years with cultivars Russet Burbank and Shepody. The weather data were based on measurements from a weather station at Caribou airport, approximately 25 km from the experimental location. All weather variables except for irradiation and precipitation were retrieved from Wunderground (2011). Irradiation data was taken from the US National Solar Radiation Database (US department of Energy, 2011). Precipitation data from the US National Weather Service proved to be more reliable than the precipitation data given by Wunderground (2011) when compared to the total precipitation for the growing season mentioned by Porter & Sisson (1991) (National Weather Service, 2011).

Based on the gravelly loam soil type mentioned in Porter & Sisson (1991) the soil data was retrieved from a USDA report (USDA, 2011). The available water capacity was recorded (9.1 inches=23,114 cm) and also rootable depth was given (80 inches = >2 m). Texture class was estimated to be 2 based on the description in Porter & Sisson (1991) and the USDA soil triangle. The slope class was estimated at 1 (<8%) and it was assumed there were no toxic soil conditions. All treatments above 200 kg/ha/N (225kg/ha N chemical fertilizer and more) were selected.

Droevendaal, the Netherlands

Data on field experiments from research farm Droevendaal was based on existing files from PRI (DJ Jansen, Plant Research International, the Netherlands, pers. comm). For 5 years between 1996 and 2000 for cultivars Bintje and Eersteling (only 1996 and 1997) the leaf area index (LAI), whole plant biomass (dry weight) and fresh and dry matter tuber weights (end harvest) were recorded. Irrigation data was incomplete. It was assumed that the crop did not suffer from water limitation throughout the experiment. In section 4.1 it is discussed whether this assumption is acceptable based on the results of the calibration. Different levels of N fertilizer application were used as treatments. Weather files were already present from KNMI station Eelde.
The soil data came from the website of the research farm. From the texture, bulk density and organic matter content, using a pedo-transfer function by Gupta and Larson (1979) the available water content was determined. The slope class was estimated at 1 (<8%) and it was assumed there were no toxic soil conditions. Only treatments with an initial fertilizer application of at least 200 kg/ha N were selected to prevent sub-optimal nutrient availability.

Treatments with a total application of at least 200 kg/ha N but spread out through the season were ignored. This was done because it could not be checked whether the applications spread over the season were timed correctly to meet the crop demand for nitrogen. Also the effect of application spread throughout the season can be very different from the effect of an initial application at the same total rate. It should be kept in mind that optimal fertilizer N applications for potato are not maximal applications. Desired application rates depend on soil type and have to be high enough to meet crop demand but not too high to ensure timely tuber imitation and ripening of the crop (Veerman, 2003).

Kibbutz Zeelim farm, Israel

Confidential information from HZPC (potato breeding company) on a field experiment in the years 2009 and 2010 was used. It includes fresh tuber weights (end harvest) and tuber dry weight percentages for cultivar Innovator. From this information the dry matter yields were calculated. The weather data from HZPC were substituted with estimations of vapour pressure. The assumption was made that early morning (minimum) temperatures can be used as an estimation of early morning dew point temperature, meaning that the air is saturated with dew in the morning. The resulting figures on vapour pressure resembled the ones measured in Tel Aviv and El Arish (Egypt), both approximately 80 km from the experimental location (Wunderground, 2011).

HZPC supplied the percentages of lutum and organic matter. From a soil map of Israel by Dan et al. (1975) the soil type was determined to be a Regosol. For estimation of the available water content, a comparable soil in Turkey was used (BH Janssen, Wageningen University, The Netherlands, pers. comm). By extrapolation of the relation between clay content and moisture content for a soil type in chapter 5 of Janssen (1970) (soil type Te) an available water content of 110 mm/m was determined. This is close (4 mm difference) to the available water content for a Dystric Regosol determined for the study area of this report based on Dijkshoorn et al. (2008) and Batjes (2005) (Appendix 7). The clay content measured at Kibbutz Zeelim matches with the Dystric Regosol from Argentina. Therefore the texture class (1) is based on the Dystric Regosol from Argentina. The slope class was estimated at 1 (<8%) and it was assumed there were no toxic soil conditions. All treatments were selected for calibration and validation, assuming plants were grown under best farm practice.

Kollumerwaard Research farm, the Netherlands

Confidential information from HZPC on a field experiment in the years 2008, 2009 and 2010 was used. It includes fresh tuber weights (end harvest) and tuber dry weight percentages for cultivar Innovator. From this information the dry matter yields were calculated. The weather data from HZPC were substituted with wind speed and vapour pressure from a weather station at Lauwersoog (KNMI, 2011), less than 10 km from the experimental location.

HZPC supplied the percentages of lutum (17%) and organic matter. From a digital soil map the soil type for the experimental location was determined. Soil samples belonging to this soil type with a lutum fraction around 17% typically had a lutum+ silt content of about 60%. Silt percentage was estimated at 43% and sand 40% (texture class 2) (Alterra, 2011). Available water content was determined based on lutum fraction and organic matter content using the program HERCULES (142mm) (Stolte et al., 1996). HERCULES determines the volumetric water contents for different hydraulic pressure heads for top soil and sub soil separately. It was assumed that the topsoil is half of the maximum rootable depth of potato (30cm) (FAO, 1998). Therefore the water content is an average of the estimates of the top soil and the sub soil. The slope class was estimated at 1 (<8%) and it was assumed there were no toxic soil conditions. All treatments were selected for calibration and validation, assuming plants were grown under best farm practice.

Lovinkhoeve, the Netherlands

Data on field experiments from Lovinkhoeve was based on existing files from PRI (DJ Jansen, Plant Research International, the Netherlands, pers. comm). The data include the fresh and dry matter tuber weights (end harvest) for 15 years between 1961 and 1978 for cultivar Bintje. Usually 8 treatments with different N application rates were done in 4 repetitions, however treatments differ a little in N application between years. For the period 1982 to 1990 (7 experimental years in this period) only the fresh tuber weights are known. Although also for these years N application was an experimental factor, there are two kinds of experiments per year of which the set-up is unknown because there are no files with management data. Per year there were experiments called H, with different N application rates and 3 repetitions and experiments called O, with different N application rates but without repetitions. Assuming the highest N application rates of all experiments are comparable, all experimental years were used. The missing experimental journal files for the years 1982 to 1990 were reconstructed based upon what was known from other files and assuming the same general set up as the years 1961 to 1978. The weather data were partly already available for the Swifterbant weather station, supplied by the Department of Meteorology of the Wageningen University added with data from de Bilt (KNMI, 2011). Missing years 1961 to 1964 were substituted with data from de Bilt (KNMI, 2011), missing years 1965-1974 and 1990 were substituted with data from Eelde (KNMI, 2011). Vapour pressure was calculated from minimum temperatures and highest relative humidity per day.

Soil data was retrieved from De Vos (1997). The slope class was estimated at 1 (<8%) and it was assumed there were no toxic soil conditions. Treatments with an initial fertilizer application of at least 180 kg/ha N were selected. The criterion for selection of N fertilizer treatments is slightly lower for Lovinkhoeve because this is a clayey soil. The supply of N from the soil will be higher, therefore the recommended N application rate is slightly lower (Veerman, 2003).

Simancas farm, Spain

Confidential information from HZPC on a field experiment for the years 2008, 2009 and 2010 was used. It includes fresh tuber weights (end harvest) and tuber dry weight percentages for cultivar Innovator. From this information the dry matter yields were calculated. The weather data from HZPC were substituted with wind speed and vapour pressure from a weather station at Valladolid Airport, approximately 25 km from the experimental location. The first three days after planting in 2008 there was no weather station at the location. Because no crop was present yet on these first days, weather variables are not essential and therefore the first three days of the weather file have been extrapolated from the executive days. The total precipitation for 2008 from the weather data file supplied by HZPC proved to be almost twice as high as the year 2009 and 2010. While observed yields in 2008 were equal or less then the yields observed in 2009 and 2010. During calibration of the Simancas experiment the number of water limited growing days was three times higher in 2009 and two times higher in 2010. Therefore it was assumed that the precipitation in the weather file for 2008 is an overestimation of reality and the 2008 experiment was excluded from calibration and validation.

HZPC supplied the percentages of lutum (17%) and organic matter. Based on the 17% lutum only texture classes 1 and 2 are possible, as the location is close to a river (clay expected) and no other information on texture is available, the texture class is estimated to be 2 (1 is very coarse >65% sand). Available water content was determined based on lutum fraction and organic matter content using the program HERCULES (Stolte et al., 1996). HERCULES determines the volumetric water contents for different hydraulic pressure heads for top soil and sub soil separately. Assuming the topsoil is half of the maximum rootable depth of potato (30cm) the water content is an average of the estimates of the top soil and the sub soil (145mm) (FAO, 1998). The slope class was estimated at 1 (<8%) and it was assumed there were no toxic soil conditions. All treatments were selected for calibration and validation, assuming plants were grown under best farm practice.

2.5 Parameterisation

Before calibration of LINPACsa initial parameter values were determined. Not all parameters were optimised by automated calibration of the model. Parameter values established reasonably well in literature were excluded from calibration to keep the automated process simple and manageable. Moreover, with more variables included in calibration, the model fit is expected to be better but the explanatory power of the model will be less. Below, the fixed initial values chosen for some of the parameters are given (Table 2.3). The initial values of parameters included in calibration and, more importantly the bounds within which these values were allowed to fluctuate, are given in section 2.6.

Table 2.3 Values of parameters not to be calibrated, sources on which they were based and further comments on the values.

Parameter and value	**Source(s)**	**Comments**
Kpar = 1.0	(Spitters & Schapendonk, 1990; Kooman & Spitters, 1995)	Extinction coefficient
Tmbase = 2.0°C	(Spitters & Schapendonk, 1990; Kooman & Haverkort, 1995)	Base temperature
Lue = 3.0 g MJ^{-1}	(Van Delden et al., 2001; Wolf, 2000)	Light use efficiency Spitters & Schapendonk (1990) mentioned 2.7.
Flue = 1.0	-	Flue 1.0 means there is no reduction of LUE due to ageing of the crop. Based on LINTUL2p.
Tmt1-Tmt4 = 2,18,24,35°C	(Kooman & Haverkort, 1995)	Temperature effect on LUE (see section 2.2.3). From fig. 3 of the paper.
Trloc = 0.5	-	Half of the vegetative biomass can be translocated to the tubers. This is an assumption.
Rdepth = 0.5 m	(Wolf, 2002)	The maximum rooting depth for potato is 0.4 m in the LINTUL2p model. However, Wolf (2002) gives 0.5 m as a rooting depth of potato. The highest value is used to make sure that the parameter is not limiting.

2.6 Calibration and validation

The LINPACsa model was calibrated and validated using the TIPS-Z modelling environment (Jansen, 2002). Calibration was done based on field experiments (section 2.4). The automated procedure minimises the difference between observations of field experiments and outcomes simulated by the model by adjusting the values of model parameters. The calibration can be based on multiple outputs at once (e.g. LAI, whole plant biomass, tuber yield). Values of parameters to be calibrated can be varied within bounds given by the user to make sure values remain within a realistic range and therefore keep their explanatory value.

Below an overview is given of the parameters that were included in the calibration (Table 2.4). The meaning of the parameters is given in Appendix 3. The parameters are grouped in LAI parameters (underlined), yield parameters (*italics*) and water limitation parameters. For most parameters the boundaries with which their values were allowed to be changed during calibration are given by the relative change (α) (Equation 2.14). To avoid the calibration to generate 0 values (causing an error when the parameter is a denominator), α was kept above -1.0. For some parameters the upper and lower boundary within which the value is allowed to change are given as absolute values.

Equation 2.14 $$new\ parameter = old\ parameter + (old\ parameter\ \times \alpha)$$

The parameter C*ropstday* was added for the sake of calibration, this parameter gives the observed day of emergence. In most experiments this observation has not been included and for other experiments it is not clear how precise the observation was. Because of its importance for the LAI curve (the beginning of the curve) *Cropstday* was calibrated. The parameter value was allowed to fluctuate between 8 days earlier or later. Looking at the soil types in the experimental data, those with the same texture class have a spread of almost 200 mm in available water content. This can be explained by the fact that for most experimental locations no direct measurements of available water content were done and different methods were used to determine available water content (section 2.4). Therefore available water content was included for calibration to match the available water content with observed yields. The parameter value was allowed to deviate 105mm from initial values.

Table 2.4 Parameters to be calibrated and the boundary between which their values can fluctuate in the automated calibration. The upper and lower boundary are either given as the relative change of the parameter value (α) or as the absolute upper and lower boundary of the parameter value (the kind of boundary is then given as "between values"). The parameters that are underlined are the LAI parameters, the parameters in italics are the yield parameters the last parameter is for water reduction.

Parameter	**Kind of boundary**	**Lower boundary**	**Upper boundary**	**Remarks**
Tb	α	-0.99	1.0	Original value 130
Cm	α	-0.99	1.0	Original value 0.0155
Rm	α	-0.99	1.0	Original value 0.02
Tsm0tb	α	-0.99	1.0	The role of temperature sums for LINPACsa has changed. Deviating values were expected, therefore parameters were allowed to change 100%. Original value: 380°Cd
Tsm2tb	α	-0.99	1.0	The role of temperature sums for LINPACsa has changed. Deviating values were expected, therefore parameters were allowed to change 100%. Original value: 700°Cd
Tsm3tb	α	-0.99	1.0	The role of temperature sums for LINPACsa has changed. Deviating values were expected, therefore parameters were allowed to change 100%. Original value: 2500°Cd
Flaitb	Between values	0	1.0	Meaning that the fraction of leaves that has died at the at end of the crop season is set between 100% and 0%
SOIniA	α	-0.2	0.2	Original value: 200.074
SOIniBT	α	-0.05	0.05	Original value: -0.0313
SOIniBDL	α	-0.05	0.05	Original value: -0.0243
AllocMn	α	-0.1	0.1	The set of parameters for allocation proves to be very sensitive and therefore relative change is kept at 10%. Original value: -2.5621
AllocMx	α	-0.1	0.1	The set of parameters for allocation proves to be very sensitive and therefore relative change is kept at 10%. Original value: 2.8063
AllocA	α	-0.1	0.1	The set of parameters for allocation proves to be very sensitive and therefore relative change is kept at 10%. Original value: 0.00023
AllocBT	α	-0.99	1.0	The temperature and day length coefficients for allocation are less sensitive then the other parameters for allocation, therefore change is set at 100%. Original value: 9.4579
AllocBDL	α	-0.99	1.0	The temperature and day length coefficients for allocation are less sensitive then the other parameters for allocation, therefore change is set at 100%. Original value: 2.7033
Dlaitb	Between values	-1.0	0	In the LINPAC parameter file values of -100% can be found (meaning all leaves die when there is a water shortage)
Trcrtb	Between values	6	10	LINPAC original values between 5 and 8. In LINTUL2p (Huber, 2010) the value for potato is 8. Therefore the value is allowed to fluctuate around 8.

For validation of the model, treatments of experiments were selected. These treatments were not included in the automated calibration in order to compare the simulated and observed outcomes of these treatments to evaluate the performance of the model after calibration of the parameters. Because of the many experimental years available for cultivar Bintje, for validation data from two years were used. A year with average rainfall and temperatures in the growing season (1969) and a somewhat more extreme year (1971, fourth driest growing season in the weather dataset) were used to test model performance. For the experiments with other cultivars less data was available, therefore one treatment per experimental year was used for validation. The treatment to be used for validation was selected from the treatments by using the Microsoft Excel 2010 function for generating random numbers (Appendix 6).

To get good results from the calibration procedure not all parameters and all experiments were used for calibration at once. Because most parameters selected to be calibrated are dependent on others it is important to first have a clear idea about one parameter value before adjusting the next one. The parameter values that determine the shape of the LAI curve for example are important for simulation of light interception which in turn determines yield. Although calibrating all parameters at once does not necessarily have to lead to a less accurate estimate of parameter values, the stepwise approach is preferred here because it could help prevent errors because of interdependent parameters. Also a stepwise approach gives a better insight in the calibration process.

Automated calibration of LINPACsa was executed in 3 stages (Table 2.5) (Fig. 2.15). After each stage the calibrated parameter values for each cultivar or location were changed in the parameter listing so the next stage used the new parameter values. Parameters for Bintje (and Eersteling) were calibrated first because for these cultivars most observations were done (LAI, whole plant biomass and yield). LAI measurements for Bintje (and Eersteling) were used to calibrate LAI parameters in stage 1 (non-water limited simulation). In stage 2 the calibrated values for LAI parameters were used, parameters for water limitation (Lovinkhoeve experiment, a non-irrigated field experiment included) and parameters for allocation to tubers were calibrated. The parameters found for Bintje in stages 1 and 2 were used for the cultivars in stage 3. In this stage parameters for LAI, water limitation and allocation to tubers were calibrated for Innovator, Shepody and Russet Burbank. The stages of calibration will be used in the results section to distinct between calibration results.

Table 2.5 A list of all separate steps of calibration of LINPACsa. The parameters in bold are calibrated per experimental location, the underlined parameter is calibrated per combination of cultivar, sowing date and experimental location. [1]Only calibrated for Lovinkhoeve.

Stage	Calibration for cultivars	Experiments included in calibration	Parameters to calibrate	Parameters calibration is based on
1	Eersteling, Bintje	Droevendaal all years (non-water limited model version)	LAI parameters (see table 2.4), <u>cropstday</u>, **reltotalwatcont, availwatcont**, Dlai, trcr	LAI
2	Eersteling, Bintje	Droevendaal all years and Lovinkhoeve all years (last site rain fed model version)	Yield parameters (see table 2.4), **reltotalwatcont[1], availwatcont[1],** <u>cropstday</u>[1]	Tuber yield, fresh tuber yield, plant dry weight, fraction dry matter
3	Innovator, Shepody, Russet Burbank	Aroostook, Kibbutz Zeelim, Simancas and Kollumerwaard	LAI parameters (see table 2.4), <u>cropstday,</u> Yield parameters (see table 2.4), **reltotalwatcont, availwatcont**, Dlai, trcr	Tuber yield, fresh tuber yield, fraction dry matter

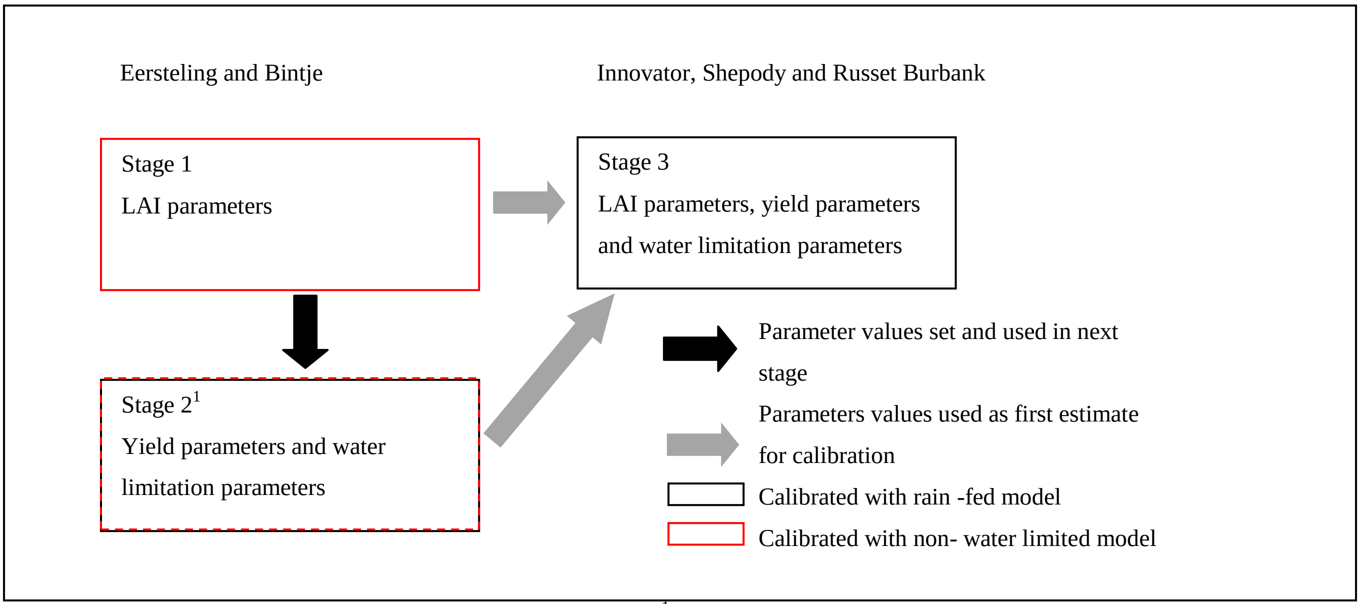


Fig. 2.15 A scheme of the sequence of calibration for LINPACsa. [1] For Lovinkhoeve (only Bintje) rain-fed model version, for Droevendaal non- water limited model version.

2.7 Simulation

For simulation, weather data for two weather pixels (half a degree by half a degree in the geographical coordinate system) that overlap with the largest part of the study area was used (Fig. 2.16). This weather data is different from the data mentioned in section 2.1.4, it is based on integration of data from several weather stations. Average monthly weather data was converted into daily weather by linear interpolation for the years 1981-2009 (courtesy of JG Conijn, PRI, Wageningen, the Netherlands). However, to keep simulation and analysis of results manageable, simulation was based on a selection of nine recent weather years (2001-2009). For the same reason, only main soil types per weather pixel were used. Soil data was gathered from two soil maps (Appendix 7). The Calcaric Regosol was only found in the north most pixel, the Haplic Phaeozem was found in both pixels according to the soil maps (Table 2.6). From a farmer who grows potatoes in Villa Dolores also some soil properties were retrieved (M Pasman, Villa Dolores, Argentina, pers. comm). The soil texture distribution (57% sand, 32% silt, 11% clay) most closely resembles that of the Haplic Phaeozem.

Table 2.6 Soil types, their specific parameters and their distribution within the area.

Soil type	**Distribution**	**Slope class**	**Texture class**	**Rootable depth (m)**	**Available water content (mm/m)**
Haplic Phaeozem	In both weather pixels	1	2	1.0	126
Calcaric Regosol	Weather pixel 175190 only	1	1	1.0	88

Firstly simulation runs were made for Innovator to investigate the non-water limited yield for afore mentioned soil types, weather years and weather pixels for two planting seasons. Also the 85% irrigation yields for all 5 cultivars used in this report were simulated for the same weather and soil inputs. For both simulations, average planting and harvest dates were used; late season planting day 52, harvest day 227, medium early season planting day 209 harvest day 332 (section 2.1.4). The 85% irrigation level was simulated by 85% of the irrigation needed to uplift water limitation. Therefore actual transpiration can drop to 85% of potential at minimum leading to a maximum reduction (by the ratio actual over potential transpiration) of 15% of LAI, biomass and yield in case of water shortage.

Fig. 2.16. The area of interest and overlap with two weather pixels. Interpolated weather data is produced that is representative for these pixels of half a degree by half a degree.

To investigate the influence of planting and harvest date on yield and irrigation use efficiency for Innovator, simulation runs were made at the 85% irrigation level using different planting and harvest dates. All possible combinations of four planting dates (1 week intervals) and two harvest dates (earliest and latest date) per season were investigated. The dates were based on planting and harvest dates as were discussed in section 2.1.4. Because a good relation between planting date and emergence date was not established for LINPACsa (section 2.3.1) the emergence date was estimated at 14 days after planting (Table 2.7). The influence of plant- harvest date combinations is also investigated for afore mentioned weather years and two planting seasons but only for weather pixel 175190 with the two main soil types.

Table 2.7 Scheme of simulation with varying plant- harvest date combinations (DOY stands for day of year).

Run	**Cropping season**	**Planting date (DOY)**	**Emergence date (DOY)**	**Harvest date (DOY)**
1	Late	41	55	181
2		41	55	273
3		48	62	181
4		48	62	273
5		55	69	181
6		55	69	273
7		62	76	181
8		62	76	273
9	Medium early	196	210	305
10		196	210	359
11		203	217	305
12		203	217	359
13		210	224	305
14		210	224	359
15		217	231	305
16		217	231	359

2.8 Additional calculations and statistical analysis

The non- water limited fresh tuber yields and actual fresh tuber yields for Villa Dolores found in literature were used to determine absolute and relative yield gaps. The actual fresh tuber yield for the best practice farmer and for the whole area determined by Caldiz (1999) were used (section 2.1.4). The relative yield gaps were then compared to values found in literature. From the simulations at the 85% irrigation level, for 5 cultivars and for different plant- harvest date combinations for Innovator, the sums of irrigation and dry matter tuber yields were used to calculate irrigation use efficiency (IUE) (Eq. 2.15).

Equation 2.15 $$IUE = \frac{dry\ tuber\ yield}{irrigation\ applied} \quad \text{in kg l}^{-1}$$

A Student's T-test was used to compare the non- water limited fresh tuber yields with literature values. T-tests were also used to compare observations from the Lovinkhoeve experiment for the validation years 1969 and 1971 to the values calculated by the model. The other calibration and validation fits were analysed by comparing the intercept and the slope of the linear regression line belonging to the observed and calculated values to the intercept (=0) and slope (=1) of the 1:1 line. No significant difference in intercept and slope means that the fit of the observed and calculated values is comparable to the ideal fit for calibration. A difference in intercept indicates a systematic deviation between calculated and observed values. A difference in slope indicates an increasing or decreasing deviation between calculated and observed values. This comparison was done with a two tailed confidence interval in Microsoft Excel 2010.

For the analysis of the fresh tuber yields and irrigation use efficiencies for all simulations at 85% irrigation level two-way ANOVA's were used in order to compare the effect of two factors. Statistical analysis for all tests mentioned before, except for the regression intercept and slope test, was done with IBM SPSS Statistics package v19. Firstly, the data were tested for normality using a combination of the q-q plot and the Shapiro Wilk test (for less than 50 samples) or Kolmogorov Smirnova test (more than 50 samples). Homogeneity of variance was tested for the ANOVA's with the Levene's test. Test outcomes were considered significant when $P<0.05$.

3 RESULTS

3.1 Calibration and validation

In this section model outputs such as LAI, whole plant biomass and fresh tuber yield are compared to the values of these crop characteristics observed in the field experiments upon which calibration and validation was based. The order of calibration, and experiments and parameters involved are discussed in section 2.6. The results shown here are based on the parameter listing that was optimised by automated calibration.

In field experiments, for some days multiple observations were done on the same cultivar. These observations were done for different treatments. Either different nitrogen treatments were used or same treatments were repeated. There is a large variance between the values observed for these different treatments on the same day. However, no nitrogen effects are included in LINPACsa and nitrogen treatments selected were all assumed to be optimal. Therefore the model will not be able to calculate different values for these treatments. In the process of automated calibration, the parameter values will be optimised to reach a calculated output equal to the average of the observed values for one day. Therefore, in the result graphs the average of multiple observations is used and compared with the calculated value. Figures including all observations (no averages) on one cultivar on the same day are given in Appendix 9.

3.1.1 Calibration stage 1

In calibration stage 1 LAI calculated by the non-water limited model version is compared to LAI observed in the Droevendaal experiment (Fig. 3.1). The intercept and slope of the regression belonging to the calculated and observed LAI values differ significantly from those of the 1:1 line (Appendix 8, Table 1).

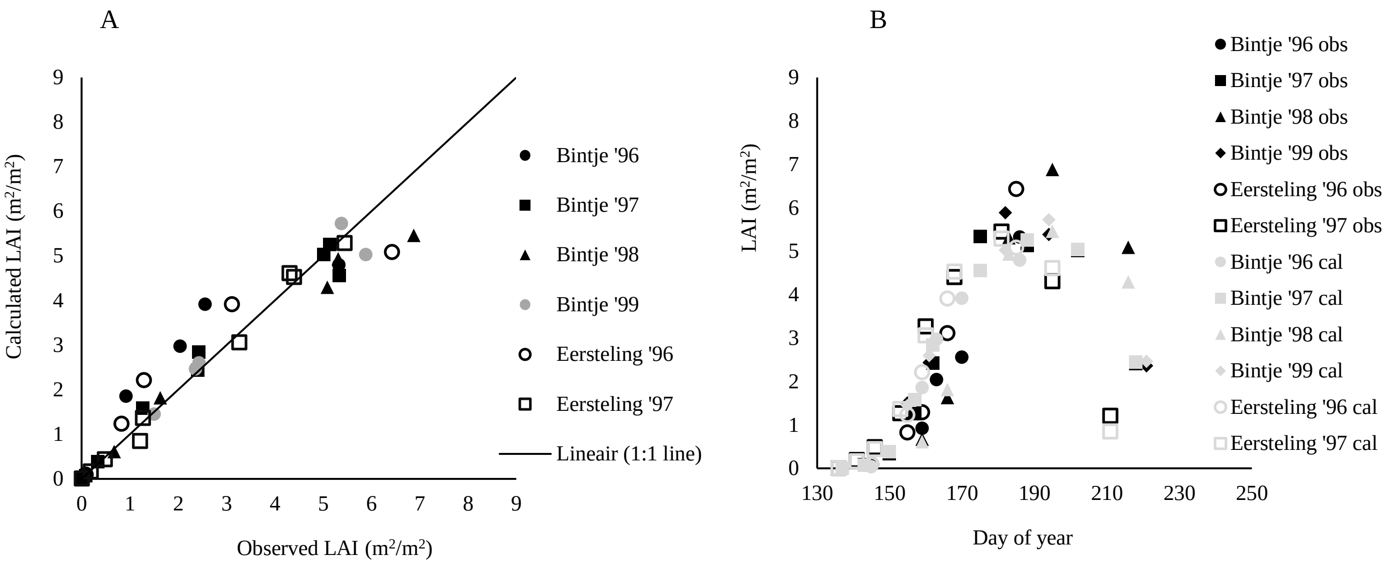


Fig. 3.1 Fit of the non-water limited model for LAI for the Droevendaal experiment. A Relation between observed LAI values and LAI values calculated by the model. B Relation between the day of year and observed (dark markers)- and calculated LAI values (grey markers).

3.1.2 Calibration stage 2

Whole plant biomass (dry matter) calculated by the non-water limited model version is compared to whole plant biomass observed in the Droevendaal experiment (Fig. 3.2). The intercept and slope of the regression belonging to the calculated and observed whole plant biomass do not differ significantly from those of the 1:1 line (Appendix 8, Table 2). Model underestimations of up to 4 tonnes occur. Differences between observations for whole plant biomass for different treatments on the same day are maximally 1 tonne (Appendix 9, Fig. 2).

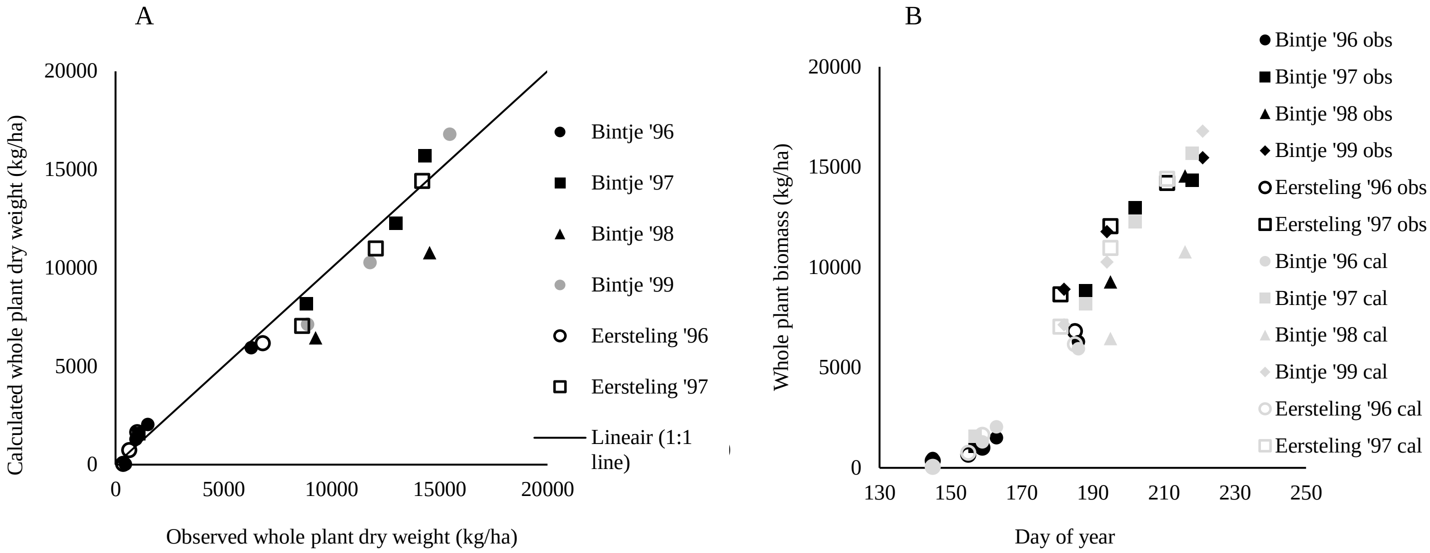


Fig. 3.2 Fit of the non-water limited model for whole plant biomass for the Droevendaal experiment. A Relation between values calculated by the model and observed values. B Relation between the day of year and observed (dark markers)- and calculated values (grey markers).

Fresh tuber yields calculated by the rain fed model version are compared to tuber yields observed in the Lovinkhoeve experiment (Bintje) (Fig. 3.3). The intercept and slope of the regression belonging to the calculated and observed fresh tuber yield differ significantly from those of the 1:1 line (Appendix 8, Table 3). Mostly model deviations occur of around 10 tonnes (1973 even almost 20 tonnes) (Appendix 9, Fig. 3).

There is an increasing trend in the average observed fresh tuber yields for the Lovinkhoeve experiment although the correlation is weak. The fresh tuber yields calculated for the Lovinkhoeve experiment show a nearly horizontal trend line (Fig. 3.4).

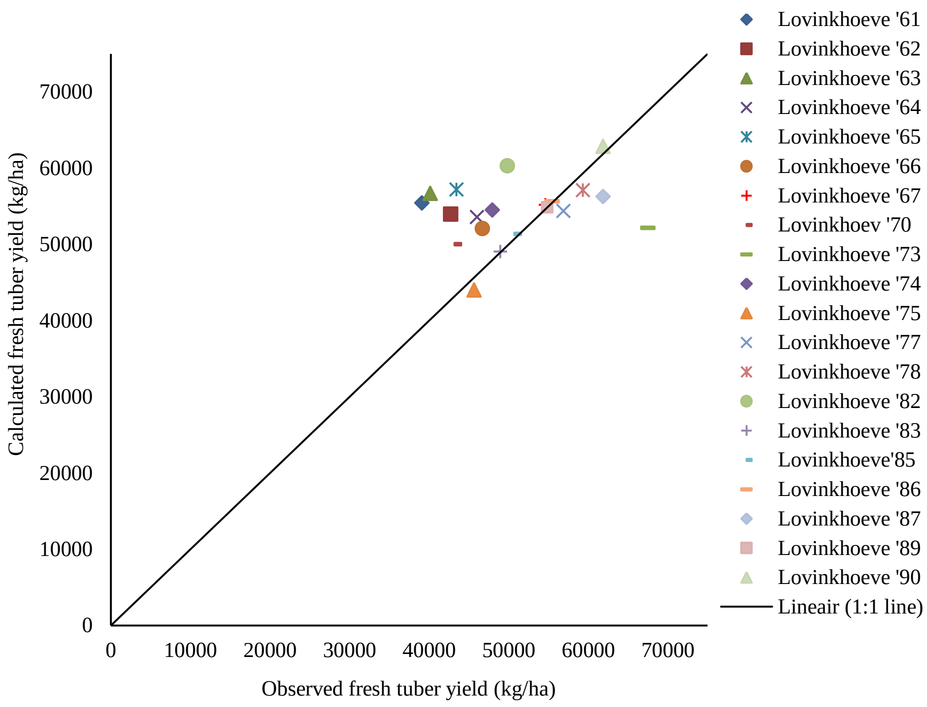


Fig. 3.3 Fit of the rain fed model for fresh tuber yield of Bintje in the Lovinkhoeve experiment.

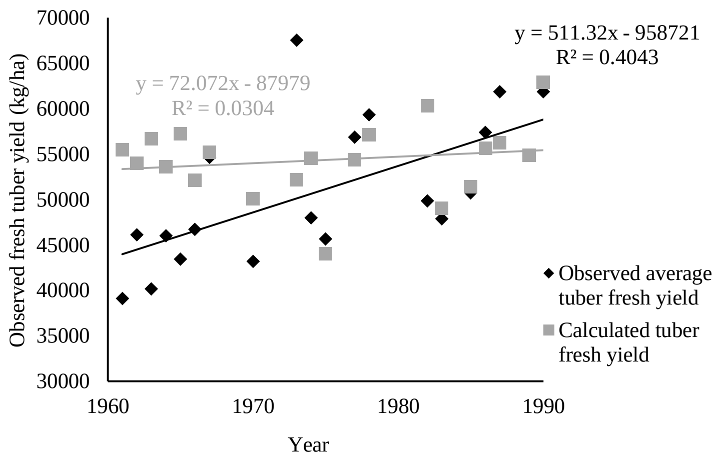


Fig. 3.4 Trend in observed and calculated average fresh tuber yield for Bintje in the Lovinkhoeve experiment.

Fresh tuber yields calculated by the non-water limited model version are compared to tuber yields observed in the Droevendaal experiment (Fig. 3.5). The intercept of the regression belonging to the calculated and observed fresh tuber yield do not differ significantly from the intercept of the 1:1 line, however the slope of the regression line for the fit is slightly lower than 1 (Appendix 8, Table 4). Observations of various treatments for one day differ almost 9 tonnes (Bintje, 1998), (Appendix 9, Fig. 4).

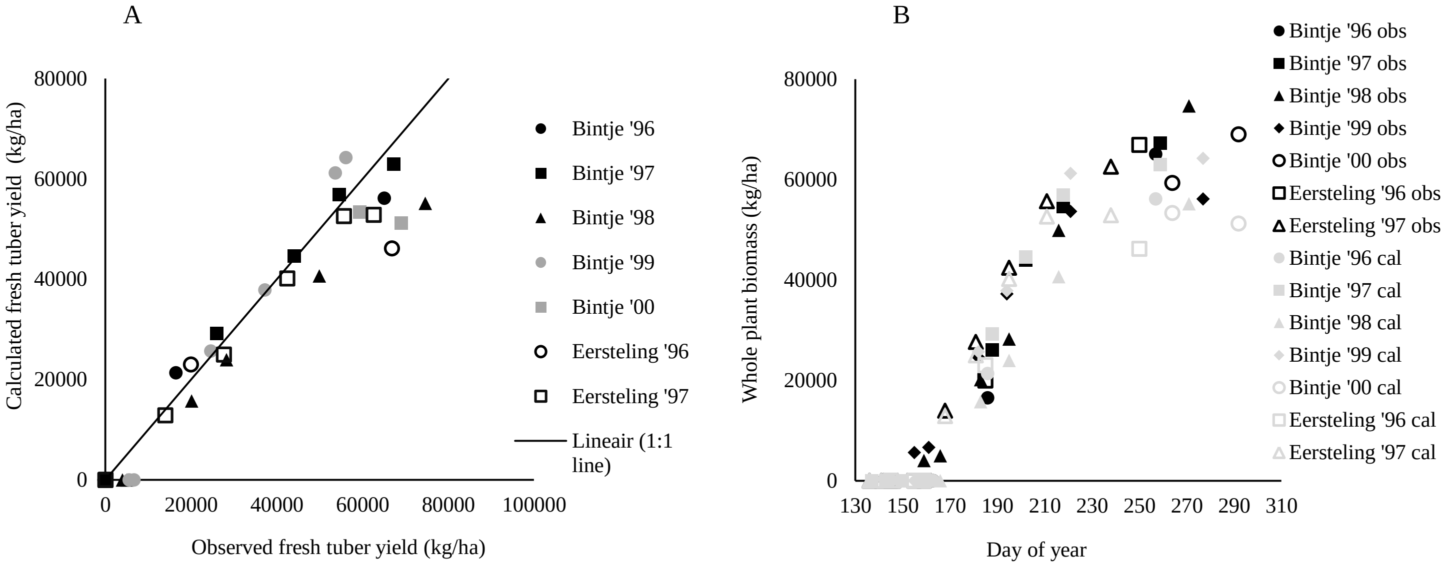


Fig. 3.5 Fit of the non-water limited model for fresh tuber yield for the Droevendaal experiment. A Relation between values calculated by the model and observed values. B Relation between the day of year and observed (dark markers)- and calculated values (grey markers).

3.1.3 Calibration stage 3

Fresh tuber yields calculated by the rain fed model version are compared to tuber yields observed in the experiments with Innovator (Fig. 3.6). The intercept and slope of the regression line through the calculated and observed LAI values are not significantly different from those of the 1:1 line (Appendix 8, Table 5). Most of the observations differ more than 5 tonnes on the same day (Appendix 9, Fig. 5).

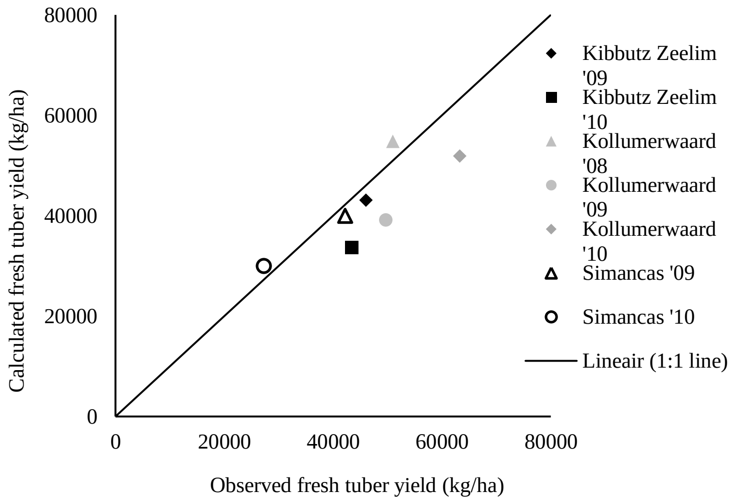


Fig. 3.6 Fit of the rain fed model version for fresh tuber yield for all experiments with Innovator.

Fresh tuber yields calculated by the rain fed model version are compared to fresh tuber yields observed in the Aroostook experiment (Fig. 3.7). The intercept and slope of the regression line through the calculated and observed LAI values are not significantly different from those of the 1:1 line (Appendix 8, Table 6). There is a difference of over 10 tonnes between two observations made one day after each other (Russet Burbank, 1987), (Appendix 9, Fig. 6).

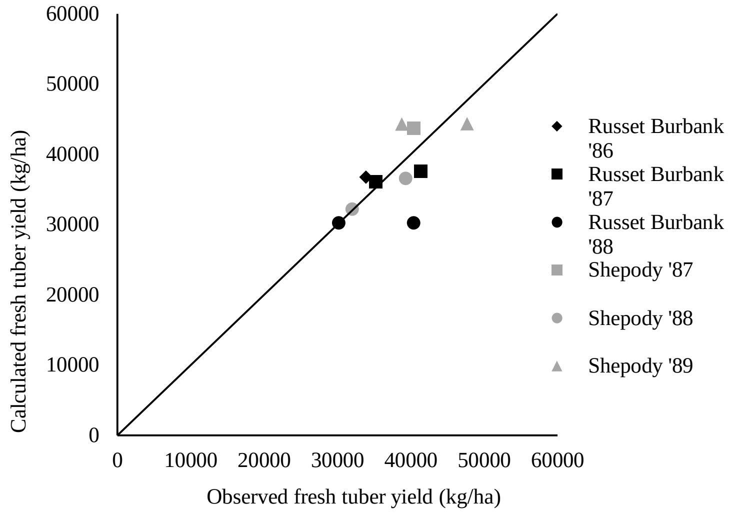


Fig. 3.7 Fit of the rain fed model version for fresh tuber yield for the Aroostook experiment.

3.1.4 Calibrated parameter values

The parameter values obtained with the automated calibration of the LINPACsa model are listed per cultivar (Appendix 10). Also time to emergence per cultivar and available water content per experimental site are given in this appendix. The LAI parameters are used to simulate the potential LAI curves (no water limitation) for all cultivars for a standard weather year (de Bilt, 2011) with the non-water limited model version (Fig. 3.8). An estimate was made of a representative emergence day for the Netherlands (day 133 ,7th of May). The fact that planting dates for these cultivars are different in practice was ignored to be able to compare the cultivars under similar conditions.

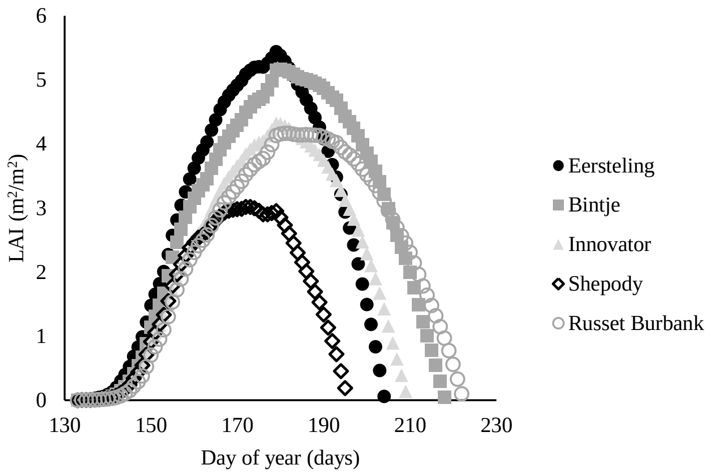


Fig. 3.8 LAI curves for five cultivars based on the calibrated LAI parameters and weather data from De Bilt, 2011.

The canopy lifespan is longest for Russet Burbank and Bintje, the canopy of Shepody and Eersteling senesces earlier and Innovator has an intermediate canopy lifespan. The canopy of Bintje is above LAI 3 for the longest period, followed by Eersteling and Russet Burbank, then Innovator. Shepody barely reached values above 3.

3.1.5 Validation

Average observed fresh tuber yields for the validation years 1969 and 1971 for the Lovinkhoeve experiment are 50389 kg/ha and 51225 kg/ha, respectively. The fresh tuber yields simulated by the rain fed model version are 55011 kg/ha for 1969 and 53724 kg/ha for 1971.

For the experiments with Innovator, per year one treatment was selected for validation (Fig. 3.9). The intercept and slope of the regression line belonging to the observed and calculated fresh tuber yields for the validation treatments are not significantly different from those of the 1:1 line (Appendix 8, Table 7).

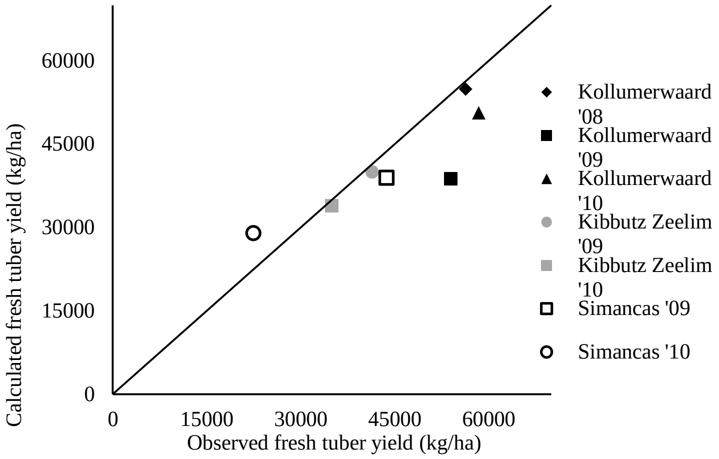


Fig. 3.9 Fit of the rain fed model version for fresh tuber yield for validation treatments with Innovator.

For the Aroostook experiment (Fig. 3.10) the intercept and slope of the regression line belonging to the observed and calculated fresh tuber yields for the validation treatments are also not significantly different from those of the 1:1 line (Appendix 8, Table 8).

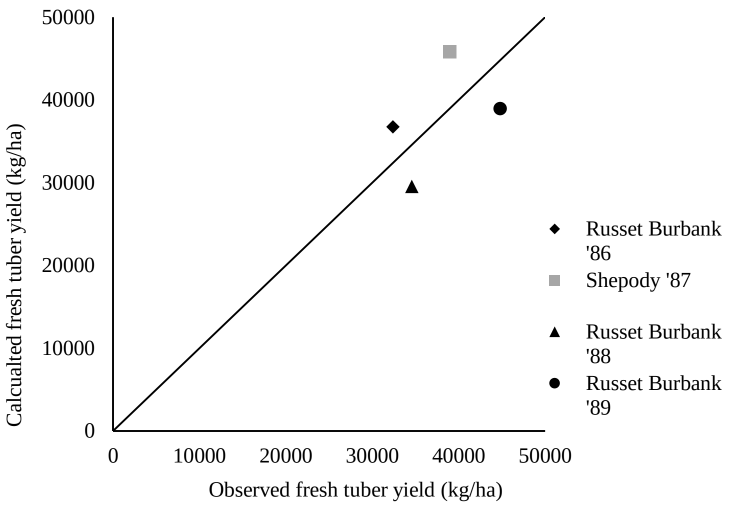


Fig. 3.10 Fit of the rain fed model version for fresh tuber yield for validation treatments of the Aroostook experiment.

3.2 Simulated yields for Villa Dolores

3.2.1 Non-water limited yields

Non-water limited fresh tuber yields were simulated for cultivar Innovator for two cropping seasons in two weather pixels. The averages over 9 weather years were compared to a similar study in literature for potato in Villa Dolores (in which no cultivar specific parameters were used) (Table 3.1). The potential yield found by Caldiz (2000) for the late season is not significantly different from the yields simulated with LINPACsa for both weather pixels. For the medium early season the potential yield found by Caldiz (2000) differs significantly from yields simulated with LINPACsa (using Students T-test, Appendix 11).

Table 3.1 Nine year average non-water limited fresh tuber yields for Innovator in two cropping seasons and two weather pixels and the potential production according to Caldiz (2000) (cultivar not specified).

	Medium early	**Late**
LINPACsa simulation Weather pixel 175190	65214	48704
LINPACsa simulation Weather pixel 175910	65031	48500
Caldiz (2000)	55000	47000

3.2.2 Yields for 5 cultivars at 85% irrigation level

Simulated fresh tuber yields for the late cropping season at the 85% irrigation level on two different soil types and in two weather pixels (combined into 3 “conditions” of soil type and weather) were averaged over nine weather years. There is a significant effect of cultivar. Of the five cultivars included, fresh tuber yields are highest for Innovator over both soil types and both weather pixels (Fig. 3.11) (Appendix 12). Lowest yielding is Russet Burbank followed by Shepody, Eersteling and Bintje.

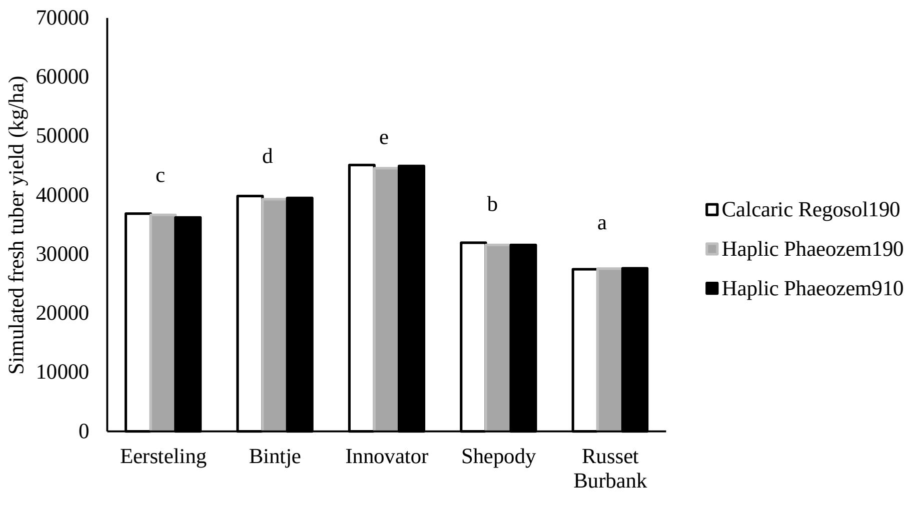


Fig. 3.11 Average fresh tuber yields for five cultivars and three combinations of soil type and weather pixel in the late cropping season simulated with the 85% irrigation model version ($LSD_{0.05}$ = 1831).The letters indicate significant differences.

For the medium early season Russet Burbank was taken out. For some simulation years yields for this cultivar were 0 whilst for other cultivars realistic yields were simulated. This is probably caused by parameter values for

Russet Burbank that are not robust enough for simulation in Villa Dolores (see 4.3) (Fig. 3.12). In general the fresh tuber yields for the medium early season are about 10 tonnes higher than the fresh tuber yields in the late season. There is only an effect of cultivar (Appendix 12), no significant effect of soil or weather pixel was found. Again Innovator yielded highest. With absence of Russet Burbank, Shepody is the lowest yielding cultivar, followed by Eersteling. No significant difference between Bintje and Innovator is found.

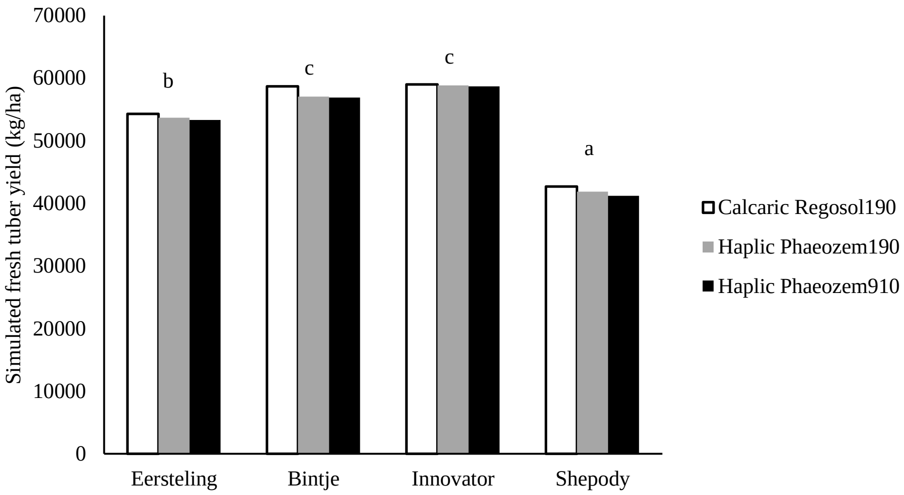


Fig. 3.12 Average fresh tuber yields for four cultivars and three combinations of soil type and weather pixel in the medium early cropping season simulated with the 85% irrigation model version ($LSD_{0.05}$ = 2893). The letters indicate significant differences.

3.2.3 Yields for different plant- harvest day combinations at 85% irrigation level

The average fresh tuber yield simulated for Innovator for 9 years, four planting dates and two soil types shows a significant effect of planting day (Fig. 3.13) (Appendix 13). Yields are higher with earlier planting day. This effect is only significant if the difference in planting day is at least 14 days. The crop is observed to fully senesce during simulations at the end of the cropping season, for all planting dates regardless of harvest date.

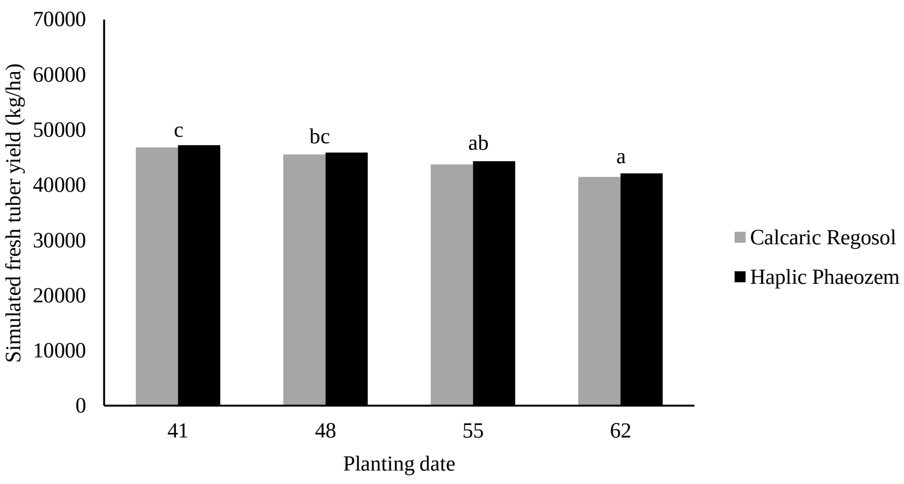


Fig. 3.13 Average fresh tuber yields for Innovator in the late season at four different planting dates with two soil types simulated with the 85% irrigation model version ($LSD_{0.05}$ = 2637). The letters indicate significant differences.

There is no significant difference between the simulated average fresh tuber yields of Innovator for 8 different plant- harvest date combinations on two soil types in the medium early cropping season (Fig. 3.14) (Appendix 13).

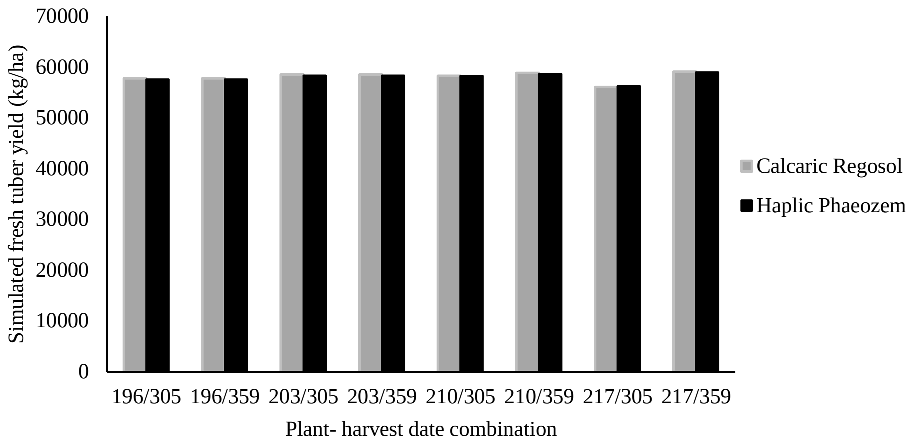


Fig. 3.14 Average fresh tuber yields for Innovator in the medium early season at 8 different plant-harvest date combinations with two soil types simulated with the 85% irrigation model version.

3.3 Irrigation use efficiencies for Villa Dolores

Irrigation use efficiencies (IUE) in kg dry tuber yield per litre irrigation applied (Eq. 2.15, section 2.8) for the late season are highest for Shepody and Innovator, followed by Bintje and Eersteling. Russet Burbank showed lowest IUE. The Calcaric Regosol resulted in lowest IUE and there was little effect of weather pixel when comparing the Haplic Phaeozem in weather pixel 190 and 910. However, the homogeneity of variance assumption does not apply for the average IUE of five cultivars in the late cropping season (Fig. 3.15) (Appendix 14). Therefore no further statistical analysis is done and the significance of the afore mentioned differences cannot be indicated.

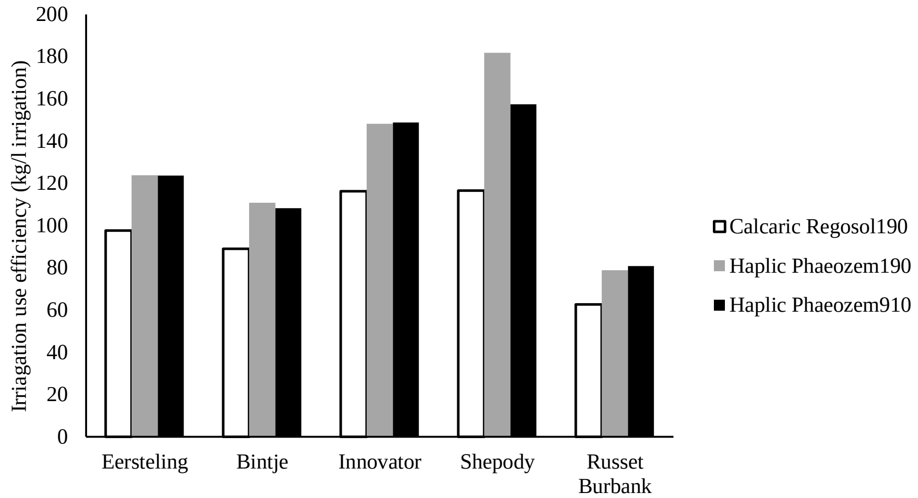


Fig. 3.15 Irrigation use efficiencies for 5 cultivars in the late season on two different soil types within two different weather pixels based on the outcomes of the simulation with the 85% irrigation model version.

For the medium early season there is an effect of cultivar and an effect of soil type- weather pixel combination on IUE (Fig. 3.16) (Appendix 14). Innovator has the highest IUE with 56.6 kg/l irrigation averaged over the combinations of soil type and weather pixel. Only Bintje is significantly lower in water use efficiency. The Haplic Phaeozem in weather pixel 910 has a higher IUE than the Calcaric Regosol in pixel 190, however not significantly higher than the Haplic Phaeozem in weather pixel 190. Irrigation use efficiencies are lower compared to the late season in all cases, Russet Burbank not included.

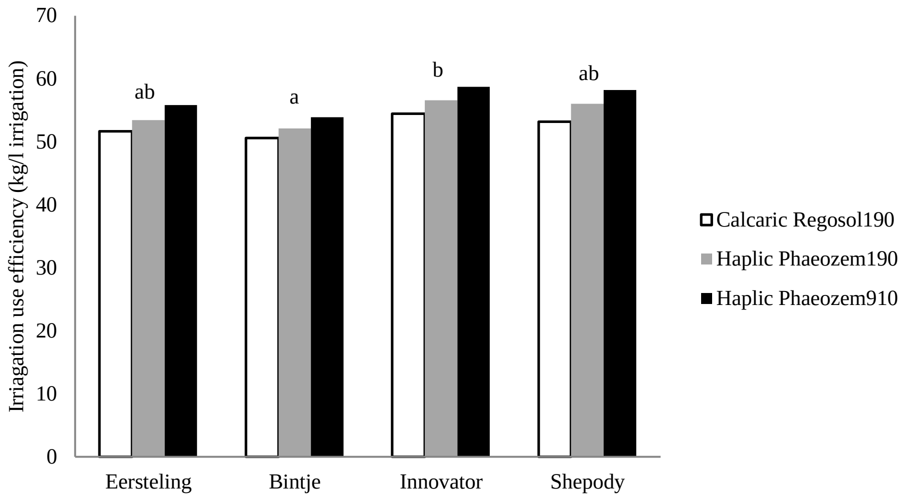


Fig. 3.16 Irrigation use efficiencies for 5 cultivars on two different soil types within two different weather pixels in the medium early season based on the outcomes of the simulation with the 85% irrigation model version ($LSD_{0.05}$ = 4.373).

Irrigation use efficiencies for the different planting dates in the late season are highest for the earliest planting dates. The Calcaric Regosol resulted in lowest irrigation use efficiencies. However, the homogeneity of variance assumption does not apply for the average IUE for four planting dates in the late cropping season (Fig. 3.17) (Appendix 15) Therefore no further statistical analysis is done and the significance of the afore mentioned differences cannot be indicated.

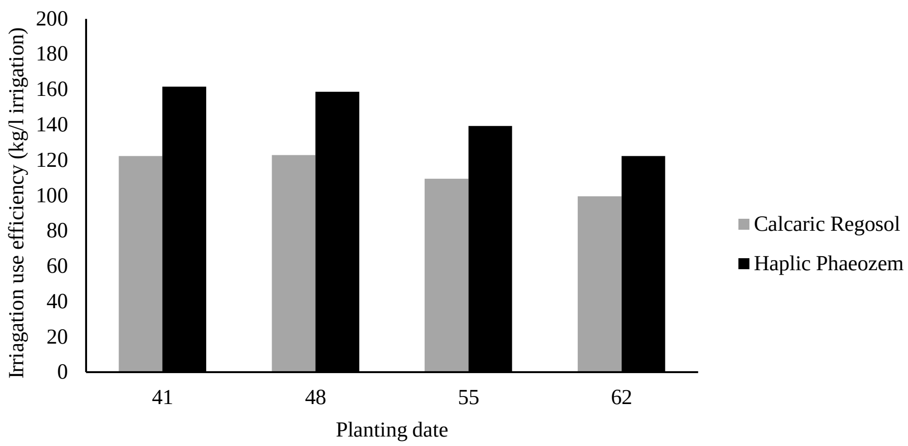


Fig. 3.17 Irrigation use efficiencies for Innovator at 4 planting dates on two different soil types in the late season based on the outcomes of the simulation with the 85% irrigation model version.

For Innovator at 8 plant- harvest day combinations in the medium early season there is an effect of soil type on IUE (Fig. 3.18) (Appendix 15). On average highest IUE is attained on the Haplic Phaeozem.

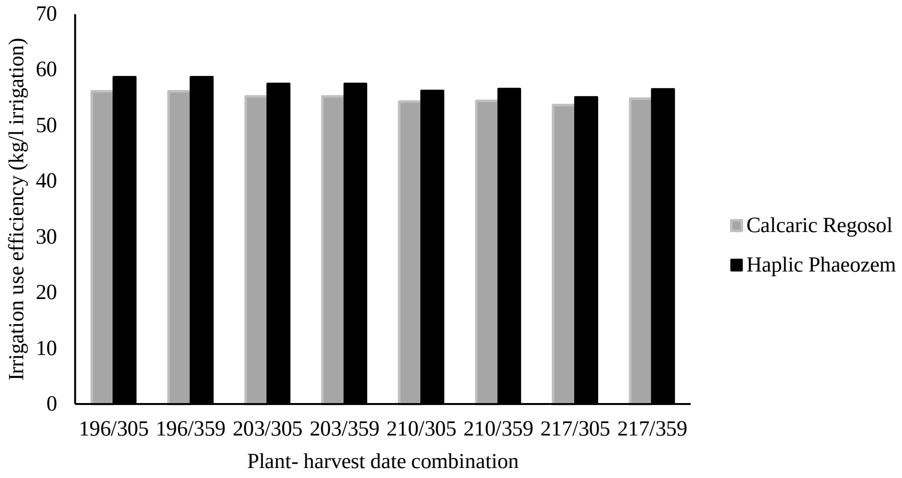


Fig. 3.18 Irrigation use efficiencies for Innovator at 8 plant- harvest day combinations on two different soil types in the medium early season based on the outcomes of the simulation with the 85% irrigation model version.

4 DISCUSSION

4.1 Data and input parameters

During collection of data for calibration and validation a substantial part of the required information had to be estimated or derived. Therefore the correctness of some essential information is uncertain. Incorrect data can lead to a less accurate calibration and therefore a less valid parameter listing for the model.

Information on irrigation applied during the Droevendaal experiment was missing. Therefore the assumption was made that enough irrigation had been applied to prevent water limitation. If the assumption is wrong, this can lead to parameter values that calculate a non-water limited yield lower than would have occurred in a genuine non-water limited experiment. The model underestimated the observed fresh tuber yield of the Droevendaal experiment, though no water limitation was included in the model calculations. Therefore it seems unlikely that the observations were from a crop that suffered water limitation.

Exact emergence dates were missing for most experiments. Although emergence day was calibrated for reasons mentioned in 2.3.1, observed emergence dates could have improved the calibration of other parameter values. Emergence date is the start of the LAI curve, when this is known one less parameter will have to be calibrated, making the calibration of the other LAI parameters more accurate.

The soil hydrological properties for all experiments had to be estimated or retrieved from other sources. Therefore the classification of soil texture and especially plant available water content (between field capacity and wilting point) might deviate from reality. For many experimental locations, data on soil chemical properties are available but soil hydrology is less determined, probably because it takes more effort to measure the water content at different hydraulic pressures. Without accurate estimations of soil available water content the rain fed model version will simulate more (available water content is higher in reality) or less water limitation in comparison with reality. Therefore plant available soil water content was allowed to be corrected by calibration.

Weather data used is in general reliable. For Aroostook the weather files resembled the weather described in the paper from which the other experimental data were derived. For Simancas, part of the data was retrieved from a commercial website whilst the other part came from HZPC. The precipitation data from HZPC for 2008 were found to be too high compared to the other weather years while yield for 2008 was comparable to yields of other years. The year 2008 was therefore excluded from calibration and validation. For Kibbutz Zeelim the vapour pressure was estimated and compared to nearest weather stations (approximately 80 kilometres). The weather data from Simancas and Kibbutz Zeelim might deviate from reality, despite this the data were considered good enough to simulate crop growth for these experiments.

The management circumstances were not clear for any of the field experiments. The assumption is made that plants in all treatments selected were grown under best management practice. However, for none of the experiments there has been direct communication with the on-site manager. Also it is not known whether seed potato quality, macro and micronutrient application, weed and pest management, tillage, planting and harvest were optimal.

Also for simulation of yields for Villa Dolores the validity of some data was questionable. The weather data are based on interpolation of information from multiple stations, it is not known which stations in the area were used. Also the daily weather figures are derived from monthly data and interpolated leading to a significant error in simulation. Furthermore is assumed that the simulations give an indication of average yields over a nine year period and do not represent the yields for a particular year. It is assumed that the soil types from the soil maps are representable for Villa Dolores. However, it is not known whether the soil types used for simulation match with the soil types used for potato cultivation in the area.

4.2 Model performance

4.2.1 Calibration stage 1

Although planting density is not included in the model, some parameters that determine the initial LAI were included in calibration (*cm*, *rm* and *tb*). Therefore the planting densities used in the experiments are taken up implicitly in the parameter listing per cultivar. This means that for correctness, when simulating for planting densities other than used for calibration in this research, a new calibration should be performed with an experiment with the desired planting density for simulation. For practical reasons it might be better to assume that a small difference in planting density will have a negligible effect on the total simulation.

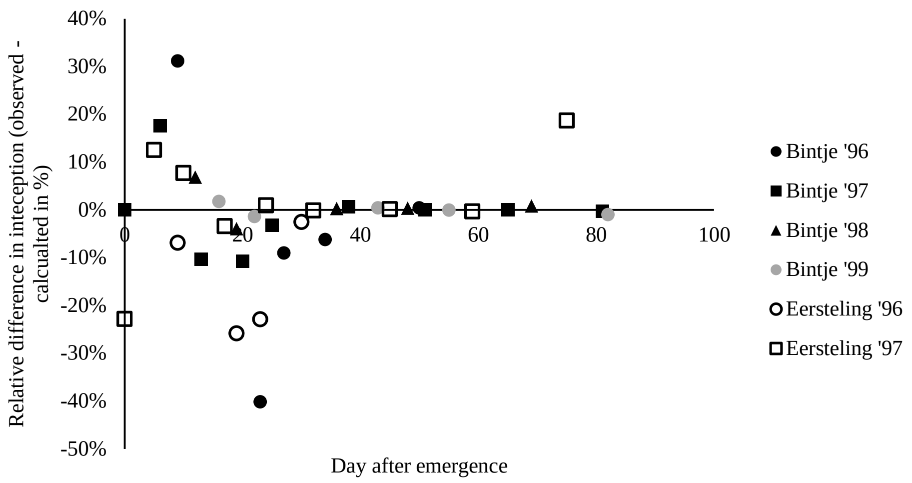


Fig. 4.1 Relative difference in radiation interception between observations and model calculations for the Droevendaal experiment based on LAI values and extinction coefficient 1.0.

The regression fit for LAI for Bintje and Eersteling in the Droevendaal experiment was significantly different from the 1:1 line. This indicates that the model fit deviated significantly from the ideal fit. Looking at the coefficients of the regression line though, the confidence intervals for the intercept and the slope only deviate 0.1 (lower bound) and 0.05 (higher bound) from the 1:1 line (Appendix 8, Table 1). More importantly, the difference between radiation interception based on the LAI values for observations and calculations is very small. The difference in radiation interception for the observed and calculated LAI values is expressed as a percentage of the observed values (Fig. 4.1). Especially the underestimations by the model (positive differences) are small except for one measurement for Eersteling in 1997. The large deviations at the beginning of the season are a reflection of the method of comparing differences rather than an indication of the model fit. Because of the small values at the start of the season (until approximately 20 days after emergence), small absolute deviations cause large relative deviations. Based on the fit of the LAI values and the small deviation in radiation interception the new parameter values for LAI are considered acceptable.

4.2.2 Calibration stage 2

The fit for whole plant biomass for Eersteling and Bintje in the Droevendaal experiment was good, the regression line for the observed and calculated values was not significantly different from the 1:1 line. However, there was a large deviation between observed and calculated values. The relative deviation for whole plant biomass has become bigger than the relative deviation for radiation interception (Fig. 4.2, compare Fig. 4.1). This is not to be expected as leaf area is directly related to biomass production and therefore deviations in LAI should be of the same magnitude as deviations in whole plant biomass. Generally the calculated values underestimate (positive deviation) the observed values. Also the relative difference between calculated and observed values shows a decreasing trend against the day after emergence. The decreasing trend implies that the whole plant biomass in the model grows faster than in reality. Possible explanations for the larger deviations in comparison with LAI and the decreasing trend towards the end of the growing season are given in section 4.2.3.

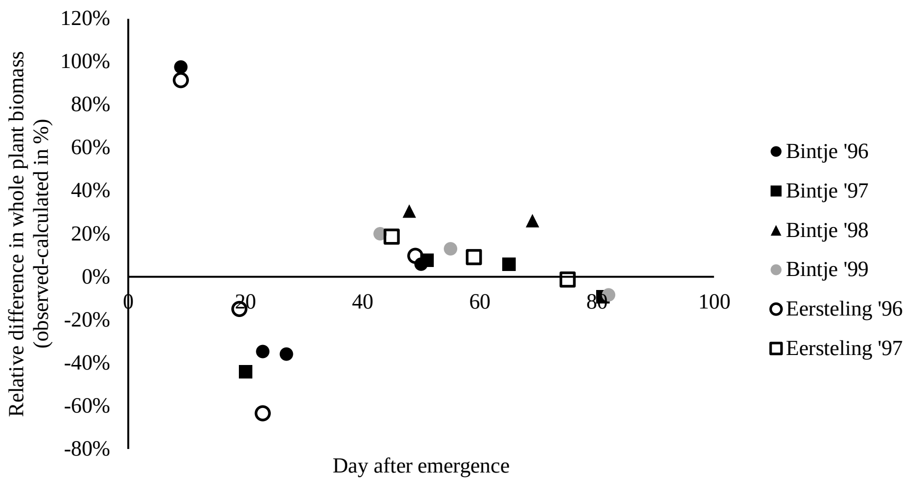


Fig. 4.2 Relative difference between observations and calculations of whole plant biomass for the Droevendaal experiment.

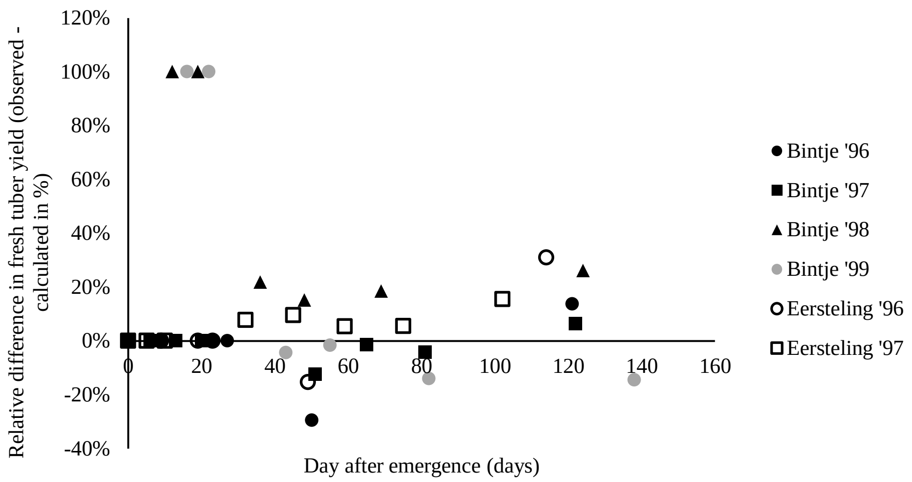


Fig. 4.3 Relative difference between observations and calculations of fresh tuber yields for the Droevendaal experiment.

The slope of the regression line for observed and calculated fresh tuber yields for the Droevendaal experiment was significantly lower than 1 meaning the calculated values were increasingly underestimating the observations. The relative difference compared to the observed fresh tuber yields was even greater (Fig. 4.3) than for the whole plant biomass. The deviations for whole plant biomass might have been amplified by slightly sub-optimal values for the parameters governing allocation and reallocation to the tubers. Also there might have been a degree of error between measurements of whole plant biomass (slightly lower) and final yield (slightly higher).

For the Lovinkhoeve the calculated values did not match with the observed values (Fig. 3.3). The spread in observations within the years was large (Appendix 9, Fig. 3) and also between years there was a slightly increasing trend in average observed yield. This trend was not found in the model calculated fresh tuber yields calculated by the model. Therefore the increasing trend cannot be explained by climate change (more favourable weather circumstances in the last couple of decades). Climate change should have led to increased calculated fresh tuber yields as weather is included in the model. A change in cultivar properties (higher yielding cultivar) over the past decades can be ruled out as potato cultivars are propagated vegetatively once a cultivar is developed.

The management, however is not included in the model, because this is assumed to be the same over the years. The increase in fresh tuber yield over the years could be caused by improvements in management that occurred over the 3 decades in which the experiment was conducted. As was already mentioned, most of the management information is missing. Changes in management that could have improved yields are: better treatment of seed tubers, better nutrient, pest and weed management, better harvest procedures, increased drainage capacity (waterlogging not taken up in model) and better soil structure.

The data for Lovinkhoeve should have been analysed before they were used for calibration of the model. The experimental conditions could have been investigated. If management did in fact improve, the trend could have been included in the model as a time dependent management coefficient.

4.2.3 Light use efficiency, nitrogen and potential yield

The relative model deviations for the radiation interception for the Droevendaal experiment in calibration stage 1 were smaller than the relative deviations for whole plant biomass in calibration stage 2 (see 4.2.2). One possible explanation for this can be found in the light use efficiency mechanism in the model. The fraction intercepted radiation is linearly related to the whole plant biomass by multiplication with a constant LUE and the incoming PAR. The value chosen for LUE might have been too low leading to a structural underestimation of observed plant biomass. For the LUE of potato the value of 3 is among the highest found in literature (Table 4.1). The LUE value might have been too low for the Droevendaal experiment but based on the majority of the literature found, for now it is assumed the LUE values was valid.

A mechanism leading to a lower LUE is the reduction due to temperature, whenever temperatures are sub- or supra optimal LUE is reduced (section 2.2.3). This effect is already weakened for low temperatures by introducing a daytime average temperature (section 2.3.3). In literature it is generally accepted there are sub –and supra-optimal temperatures for LUE (Went, 1944; Dwelle et al. 1981; Winkler, 1971; Kooman & Haverkort, 1995; Markovskaya et al. 1996). Therefor it is not likely that the model underestimation is caused by an erroneous inclusion of this mechanism.

Table 4.1. Values found for LUE in literature.

Source	LUE
Spitters (1987)	2.4
Van Delden et al. (2001)	3.0
Wolf (2000)	3.0
Spitters & Schapendonk (1990)	2.7
Griffin et al. (1993)	3.5 (vegetative) 4.0 (generative)

An alternative explanation would be measurement error. Reported LAI observations might have been too low or whole plant biomass observation might have been too high, especially towards the end. For a clear explanation for the structural underestimation of whole plant biomass by the model further research will have to be conducted.

The decreasing trend in the relative difference between the observed and the calculated whole plant biomass can be caused by a decreasing LUE towards the end of the growing season in reality which is not taken up in the model. Generally in literature it is found that LUE for potato is rather constant (Allen & Scott, 1980; Burstall & Harris, 1986; Spitters, 1987; Jeffries & Mackerron, 1989) or even increases after tuber initiation (Griffin et al., 1993; Spitters, 1990; Spitters & Schapendonk, 1990). However, some literature states that N limitation can also cause LUE decline (Van Delden, 2001; Shah et al., 2004). Also, most of the literature stating LUE is constant does not consider severe N limitation. Vos & Van der Putten (1998) and Van Delden (2001) showed that in case of N limitation photosynthesis is maintained at a high level and leaf size is reduced first, if N supply is very limiting LUE is decreased.

The treatments of the Droevendaal experiment selected for calibration all had only one initial N application. Therefore, at the end of the season N limitation could have occurred causing a lower LUE. In LINPACsa there is a parameter that indicates the decrease of LUE until a certain fraction of the original value at the end of the crop season (*Flue*). This parameter was set to 1 in LINPACsa. To investigate whether LUE might have been decreased at the end of the growing season a second calibration sequence was performed for Bintje in the Droevendaal experiment. For several treatments with initial N application levels of 0, 100, 200 and 300 kg/ha (also treatments not selected for calibration and validation) of the Droevendaal experiment the LAI parameters were calibrated per treatment.

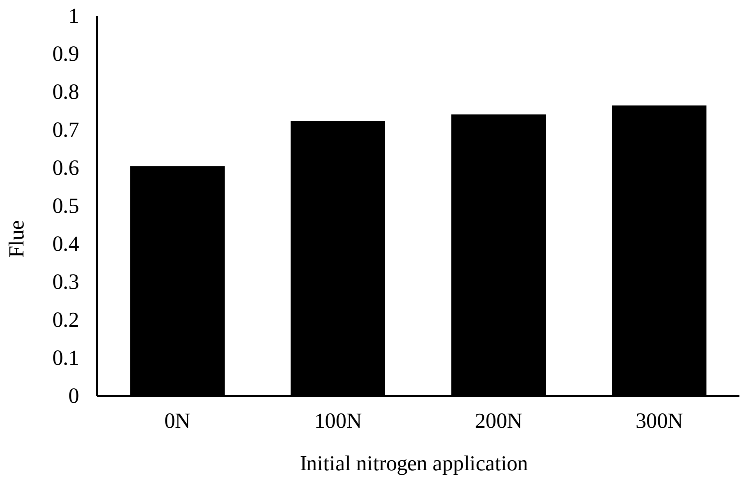


Fig. 4.4 Fraction of original LUE left at the end of the growing season in response to initial nitrogen fertilizer application.

The calibrated values for the LAI parameters per treatment were then used for a second calibration round. In this round *Flue* was calibrated per treatment so it could be determined whether LUE decreased at the end of the season and whether this was correlated with N application (Fig. 4.4). Looking at the results there seems to be a trend indicating that lower initial applications lead to a lower *Flue* meaning the LUE decreased at the end of the growing season. This trend, however did not prove to be significant (Appendix 16). Judging by the Shapiro-Wilk test the data were not normally distributed, however in the q-q plot the residuals do not show a great deviation from normality. Also the one way ANOVA is reasonably robust and can handle a degree of non-normality (EPJ Boer, Wageningen University, the Netherlands, pers. comm).

Although no significant effect of nitrogen application rate was found, LUE showed a decreasing trend with decreasing initial fertilizer application. This effect was not accounted for in the model. Despite the non – significant results, for future use it would be wise to also include *Flue* in calibration. Also for further use of the parameter listings obtained in this report it is wise to recalibrate for *Flue*.

As was mentioned in the introduction, field experiments for determining potential yield are dependent on the optimum amount of nitrogen fertilizer. Therefore the highest production level modelled in this report is called non-water limited. Judging by the calibration on *Flue* this was a good assumption. Although not significant, the effect of nitrogen application on *Flue* indicates that the treatments selected for calibration of the model could indeed have been limited by nitrogen. The application level of 200 kg N ha^{-1} resulted in a slightly lower *Flue* than the 300 kg N ha^{-1} application. Therefore the selection criterion for treatments used in calibration might have been too low to claim the model was calibrated for potential production.

4.2.4 Calibration stage 3

For Innovator, Shepody and Russet Burbank the intercepts and slopes of the regression lines belonging to the observed and calculated fresh tuber yields were not significantly different from those of the 1:1 line. Most model deviations were within 10% of the observed values. For Innovator, on four occasions the calculated values were 25% lower than the observed values. For Shepody and Russet Burbank on one occasion the calculated value was 25% lower than the observed value. The large differences in observations within the same year for similar treatments with one cultivar indicate that a large measurement error has to be taken into account for all three cultivars.

4.2.5 Calibrated parameter values

The LAI curves are generally in line with expectations considering the maturity classes for the cultivars used. The maturity class is an indication of when a potato cultivar senesces and tubers ripen. The lower the maturity class, the later the potato crop senesces, the longer canopy lifespan. When ranking the cultivars according to maturity class from low to high and comparing this to their rank bycanopy lifespan found in section 3.1.4, only Shepody has a canopy life span that is lower than would be expected (Table 4.2).

A possible explanation for the unexpectedly low canopy life span of Shepody is the fact that no LAI observations were used for the calibration of the cultivar specific LAI parameters. However, not only for Shepody but also for Russet Burbank (same experiment) and Innovator no LAI observations were used and those cultivars do have a canopy lifespan that is in line with their maturity class. Especially for Shepody recalibration with a field experiment including LAI observations is recommended.

Table 4.2 Ranking of cultivars by maturity class and their rank by canopy lifespan as calculated in section 3.1.4 (NIVAP, 2011; Science and Advice for Scottish Agriculture, 2011). The later the cultivar; the lower the maturity class.

Cultivar	Maturity Class	Rank canopy lifespan in simulation
Russet Burbank	5.5	1
Shepody	5.75	5
Bintje	6.5	2
Innovator	7	3
Eersteling	9	4

4.2.6 Validation

For Bintje the years 1969 and 1971 of the Lovinkhoeve experiment were used for validation of fresh tuber yields. The calculated values overestimated observed values by 9% and 5%, respectively. For Innovator the relative differences between calculated and observed fresh tuber yields were under 20% except for an overestimation for one year of the Simancas experiment (29%) and an underestimation in the Kollumerwaard experiment (28%). For Shepody and Russet Burbank relative over- and underestimations of the fresh tuber yield by the model were all within 20%.

Compared to literature a deviation of simulated dry matter tuber yields of 10-20% of the observed values is common (generally 5-20% for Russet Burbank, Johnson et al., 1988) (majority within 20% for various cultivars and climates, Griffin et al., 1993) (18% and 28% for Maris Piper, Huber, 2010). The validation results in this report are thus in line with some other model validations. For Innovator, Shepody and Russet Burbank the intercepts and slopes of the regression lines for the calculated and observed fresh tuber yields were not significantly different from the ones for the 1:1 line.

Because of the high variance in observations for similar treatments within a year it might have been better to also select a whole year in the experiments for Innovator, Shepody and Russet Burbank. That way the variance that cannot be explained by the model (for the same treatment and the same weather year) is replaced by variance that can be explained by the model (variance in weather between years).

For validation of Bintje the year 1969 was chosen because it was average in temperatures and rainfall, 1971 was chosen because it was one of the extreme dry years. Despite of this difference the relative overestimations by the model are almost equal indicating that the model can handle variation in weather relatively well.

4.3 Simulated yields for Villa Dolores

During simulation runs for the medium early season, the auxiliary parameter for allocation and reallocation, *AllocNew*, for Russet Burbank did not always reach a value above zero. The combination of parameters for the temperature and day length effects on *AllocNew* was obtained by calibration with an experiment in Northern America. The combination of parameter values proved not to be robust enough to be valid for the conditions in Villa Dolores. Adding experiments to the calibration with conditions more resembling those used for simulation, might create a parameter listing for Russet Burbank that will result in a correct calculation of the allocation parameter and therefore a more realistic yield.

The parameters for Innovator, Shepody, Bintje and Eersteling proved to be more robust, *AllocNew* did reach 1. Also the parameters used to calculate the temperature and day length dependent auxiliary variable *DVRTI* (rate to tuber initiation) for Russet Burbank proved more robust than the allocation parameters. The moment of tuber initiation was comparable to that of other cultivars. Because the zero value for *AllocNew* for Russet Burbank did not lead to any yields, this cultivar was excluded from simulation for the medium early season.

For both the simulation with 5 cultivars and the simulation with plant-harvest date combinations in the medium early season the normality of residuals test proved to be significant for the fresh tuber yields (both Kolmogorov-Smirnova and Shapiro-Wilk)(Appendixes 12 and 13). Although according to this test the assumption of normality is not justified, in the q-q plot the residuals do not show a great deviation from normality. Also the two way ANOVA is reasonably robust and can handle a degree of non-normality (EPJ Boer, Wageningen University, the Netherlands, pers. comm). Therefore it was assumed that the ANOVAs were valid to be used for analysis of the fresh tuber yields for the medium early seasons of both the 5 cultivars and the plant- harvest date combinations simulations.

4.3.1 Non-water limited yields

The fresh tuber yield simulated by the non-water limited model version for the late season with Innovator (both weather pixels) in Villa Dolores proved to be similar to the yield mentioned in literature. The fresh tuber yield for the medium early season was significantly higher than the yield mentioned in literature. Probably Caldiz (2000) used a shorter period for the medium early growing season compared to the period used in this report because different methods were used to define the length of the growing season. Caldiz (2000) used temperature boundaries to select a growing season (maximum temperature, 30°C) whereas fixed dates were used in this report. Besides a difference in defining the length of the growing season some other factors in the simulation of Caldiz (2000) might cause a difference. No cultivar specific model was used and other weather years were used (before 1992).

To compare actual yields for Villa Dolores to other potato production areas the relative yield gap is used (Table 4.3). The absolute yield gap is determined for the best practice farmer (a commercial pivot irrigated farm) and for the average production in the whole area according to Caldiz (2000). The non-water limited yields for Innovator averaged over the two weather pixels are used.

Table 4.3 The yield gaps for both cropping seasons for the best practice farmer and for the average of the area based on the non-water limited fresh tuber yield in tonnes ha^{-1}. Also the yield gap relative to the non-water limited fresh tuber yield is given.

	Actual fresh tuber yield		**Non- water limited fresh tuber yield**		**Yield gap**		**Relative yield gap**	
Season	Late	Medium early	Late	Medium early	Late	Medium early	Late	Medium early
Farm best practice	24-32	32-42	48.602	65.123	17-25	23-33	35%-51%	35%-51%
Average for area	18	25	48.602	65.123	30	40	61%	61%

Huber (2010) found relative yield gaps for potential yield of 58% and 59% (maturity groups medium early and medium late respectively) for a commercial farm in Poland. From Caldiz (2000) similar relative yield gaps are found for Villa Dolores, 62% in the late season and 55% in the medium early season. Hengsdijk & Langeveld (2009) found a relative yield gap of 62% for Western Europe based on FAO statistics and potential yields based on expert knowledge. For former Soviet union states and Eastern and Central Europe they found 84% and 88% yield gaps respectively. From literature it can be concluded that the average productivity in Villa Dolores expressed relatively to the areas potential is at the same level as Western Europe. The best practice farm is more productive than a commercial farm in Poland. The average productivity in the area is lagging behind the best performance with 10-26% (relative yield gap) compared to the best performing farm.

Prudency is required with these conclusions as they are based on different methods to estimate or calculate production levels. Also, in literature the yields given are claimed to be the potential yield. The LINPACsa model is not simulating potential yield, but a non-water limited yield which is lower than potential. How much lower is not known. Therefore, the yield gap for Villa Dolores should be larger than calculated in this research if true potential yields were to be used.

4.3.2 Yields for 5 cultivars at 85% irrigation level

The fresh tuber yields simulated at the 85% irrigation level were generally 10 tonnes higher in the medium early season compared to the late season. This difference between seasons was already mentioned in the agro ecological description of Villa Dolores. Simulation year 2009 was analysed (other years could not be analysed because of time constraints). In the analysis it was found that maximum LAI was lower but the canopy lifespan was longer for the medium early season. The total global radiation received by the crop was 28% higher in the medium early season. Part of this higher global radiation received can be explained by a longer canopy lifespan (22% longer). The rest of the difference in total global radiation is caused by an increase in radiation in the medium early season. Averaged over the growing season radiation was higher in the medium early season compared to the late season in which the radiation decreases in the course of the season. The higher radiation received accounted for the difference in intercepted radiation between both seasons. The lower peak LAI values in the medium early season apparently did not cause a significantly lower interception of received radiation levels. In general a lower maximum LAI, if still over 3, cannot be considered disadvantageous because the additive interception by additional LAI is very low.

The higher maximum LAI and shorter canopy lifespan in the late season can be explained by the higher temperatures in the beginning of the late season. With higher temperatures, LAI builds up faster but also the temperature sum at which leaf area starts decreasing is reached faster. The high temperatures at planting were already mentioned as a restraint in the agro ecological description. This proves that the model performed well in simulating the difference between growing seasons in Villa Dolores.

Innovator yielded highest in both seasons, in all conditions. No effect of soil or weather conditions was found. Apparently the difference in weather data between weather pixel 175190 and 175910 did not result in a significant difference in yield. A difference in soil types could have resulted in a significant difference in yield because a comparatively lower water content leads to water limitation sooner, causing a reducing effect on LAI and yield. However, this difference in soil types only becomes apparent in case of water limitation. From an analysis of the 2009 simulation year for both cropping seasons it becomes clear that for weather pixel 175190 on the Haplic Phaeozem less water limited growing days occurred than on for the Calcaric Regosol. The latter soil type is lowest in available water content. Also the summed reduction factor (cumulative *TrRat*) for LAI and yield caused by water limitation was lower on the Haplic Phaeozem. Despite the differences, the crops in the simulation did not suffer enough water limitation to result in a significant yield difference between the soil types.

The difference in water limitation between soil types was reduced by irrigation. Irrigation was applied to keep LAI and yield reduction under or equal to 15%, keeping yield differences between soil types small.

4.3.3 Yields for different plant- harvest day combinations at 85% irrigation level

There was an effect of planting date in the late season. The four combinations with the late harvest date in the late cropping season were not included as the later harvest date did not influence yield. The canopy had already died before the early harvest date. The yields were highest for the earliest planting dates and decreased with increasing planting date. In an analysis of the simulation for 2009 it became clear that the difference was not caused by the allocation and reallocation to the tuber. There was a decreasing trend in received global radiation with increasing planting date. There was no clear effect of planting date on canopy lifespan or water limitation. With the decreasing radiation in the late season it is assumed the earlier planting dates lead to higher yields because the higher radiation at the start of the season is utilized.

For the medium early season no significant effect of planting and harvest date combination was found. The yields did show a slight increase with increasing planting date. For the two latest planting dates the early harvest date caused lower yields because the crop canopy was not fully senesced on this date. The global radiation received by the crop was increasing with time. However, the additional radiation received by the crop might have been offset by the shorter canopy lifespan at later planting dates. The canopy lifespan decreased with later planting date due to increasing temperatures over the season. At later planting dates the temperature sum for leaf area decrease was reached faster resulting in a shorter canopy lifespan.

4.4 Irrigation use efficiencies and maximal and optimal production

Because the assumption of homogeneity of variances was not valid no statistical analysis was done for the irrigation use efficiencies for the late season with 5 cultivars and for the late season with different plant- harvest date combinations. Only the medium early seasons will be discussed in detail here.

Irrigation use efficiency (Eq. 2.15, section 2.8 for definition) in the medium early season was lower than in the late season in all cases. This is caused largely by the higher temperatures in the medium early season. This is in line with what was found on irrigation in the agro ecological description of Villa Dolores.

Soil type had an effect in all simulations in the medium early season. It is apparent that on Haplic Phaeozems the production of tuber yield (dry matter) per litre water is higher than on Calcaric Regosols. This is due to the higher available water content of the Haplic Phaeozems. Innovator had the highest IUE and was also the highest yielding cultivar in all cases. However, the IUE does not seem to be connected with productivity of a cultivar. Bintje yielded second highest but had the lowest IUE in the medium early season. Also Shepody yielded lowest (ignoring Russet Burbank) but had the second best IUE. The parameter values calibrated indicate that Innovator is an efficient, high yielding cultivar whereas for Shepody and Bintje high yields are inversely related to efficiency. Further analysis on this presumed inverse relation of IUE and yield was not done because of time constraints but is recommended.

There was no significant effect of plant-harvest date combination on the IUE in the medium early season. Already it was concluded that there is also no effect of plant-harvest day combination on fresh tuber yield in the medium early season.

Combining the results on fresh tuber yield and IUE a scheme has been made with the maximal and optimal production (Table 4.4). For maximal production a ranking was made of the highest fresh tuber yields, for optimal production a ranking was made of the highest irrigation use efficiencies. Optimal production is thus defined as the highest production per litre of irrigation used. The rankings only give the combinations of cultivar, soil type, planting day, harvest day and season that were simulated in this report. Unless noted otherwise the weather pixel used is 175190. The significant differences for plant- harvest date combinations are obtained with only one cultivar, only for Innovator different plant- harvest date combinations were explored. Another cultivar combined with different plant- harvest date combinations might have led to higher productions, especially Shepody with optimal production.

Table 4.4 Combinations of growing conditions ranked by maximal (highest fresh tuber yield) and optimal (highest irrigation use efficiency) productions.

<table>
<tr><th>Goal</th><th>Season</th><th>Rank</th><th>Cultivar</th><th>Soil type</th><th>Plant- harvest day combination</th><th>Fresh tuber yield/IUE</th></tr>
<tr><td rowspan="6">Maximal production</td><td rowspan="3">Medium early</td><td>1</td><td>Innovator[1]</td><td>Calcaric Regosol[2]</td><td>217/359[2]</td><td>59123</td></tr>
<tr><td>2</td><td>Innovator[1]</td><td>Haplic Phaeozem[2]</td><td>217/359[2]</td><td>58999</td></tr>
<tr><td>3</td><td>Innovator[1]</td><td>Calcaric Regosol[2]</td><td>209/332[2]</td><td>58975</td></tr>
<tr><td rowspan="3">Late</td><td>1</td><td>Innovator</td><td>Haplic Phaeozem[2]</td><td>41/181[1]</td><td>47217</td></tr>
<tr><td>2</td><td>Innovator</td><td>Calcaric Regosol[2]</td><td>41/181[1]</td><td>46801</td></tr>
<tr><td>3</td><td>Innovator</td><td>Haplic Phaeozem[2]</td><td>48/181[1]</td><td>45875</td></tr>
<tr><td rowspan="6">Optimal production</td><td rowspan="3">Medium early</td><td>1</td><td>Innovator[1]</td><td>Haplic Phaeozem</td><td>196/305[2]</td><td>58.73</td></tr>
<tr><td>2</td><td>Innovator[1]</td><td>Haplic Phaeozem[1,3]</td><td>209/332[2]</td><td>58.71</td></tr>
<tr><td>3</td><td>Shepody[1]</td><td>Haplic Phaeozem[1,3]</td><td>209/332[2]</td><td>58.20</td></tr>
<tr><td rowspan="3">Late</td><td>1</td><td colspan="3" rowspan="3">No statistical analysis done</td><td rowspan="3">Average season: 123</td></tr>
<tr><td>2</td></tr>
<tr><td>3</td></tr>
</table>

[1]Factor leading to highest fresh tuber yield/ irrigation use efficiency but not significantly different from the level yielding second best to this level.

[2]No significant effect of this factor on yield

[3]Weather pixel 910

5 CONCLUSIONS

Developing a model version of LINPAC for potato

- For calibration of a crop growth model it is essential to be sufficiently certain about the correctness of data used. Also the assumption that the field experiments used were performed with the best management possible should be checked for correctness. In reality it proves very difficult to find all required information on field experiments. Therefore data collection for calibration of a model should not be underestimated. For researchers involved in field experiments it is important to not only carefully describe the measured results but also the circumstances in which the field experiment was performed.
- Good soil hydrological data (pF curves) are essential for the calibration of a crop growth model that includes the water content of the soil. These measurements are not readily available, not even for experimental farms.
- For the Lovinkhoeve experiment a trend of increasing yields was found likely to be caused by improvement of management. This was done by ruling out climate change by comparing the trend in observations with the trend in values calculated with LINPACsa. Before calibration, experimental data has to be checked for any trends over the years. If the cause of the trend cannot be or is not taken up in the model the data should not be used.
- It is impossible to determine potential or water and nutrient limited production levels for potato without considering optimal nitrogen application. For this report the nitrogen applications in the field experiments used are not assumed to have been optimal and therefore the highest production level modelled was deliberately called non-water limiting rather than potential.
- The experiments used for calibration showed a large variation in observed values within years for similar treatments. These variations affected calibration results, causing a large uncertainty of the model.
- For validation whole experimental years should have been selected and not just single treatments within years. Variation between treatments cannot be simulated if the season lengths and soil and weather conditions are equal between these treatments. This will lead to unnecessarily bad validation results. Variation between years caused by different soil and weather conditions and season lengths can however be simulated by the model.
- For all cultivars, except Shepody, the LAI parameters resulted in LAI curves that are in line with the maturity classes.
- The performance of LINPACsa is comparable to the performance of other potato growth models in literature. Especially the parameters for light use efficiency (*Lue, Flue*) can be (re)calibrated in order to improve model performance for the cultivars used in this report. Performance of the model in a region other than included in calibration and validation was overall good although for Russet Burbank the allocation parameters did not prove robust enough for valid simulation. Further calibration of the model with field experiments from other regions will be needed to improve the validity of the parameters for Russet Burbank.

Productivity and yield gap and of the potato sector in Villa Dolores

- The relative yield gap for the average production in Villa Dolores is comparable to a highly productive area like Western Europe. A good performing commercial farm in Villa Dolores had an even better relative yield gap compared to literature. Because of differences in the methods to determine these yield gaps some prudence is needed for this conclusion.
- Innovator was the highest yielding of the cultivars involved in all simulations.
- No significant effect was found of soil type or weather conditions on the fresh tuber yield, despite the higher available water content of Haplic Phaeozems compared to Calcaric Regosols. The irrigation level of 85% probably caused the difference in yield between soil types to be too small to cause significant differences in yield.
- In the late season an earlier planting date led to higher fresh tuber yields because the dropping radiation levels were better utilized by earlier canopy cover.
- In the medium early season no effect of planting date on fresh tuber yields was found. The earliest harvest date was however limiting for the two latest planting dates because the crop canopy had not fully senesced at harvest.
- The highest fresh tuber yields were attained in the medium early season with the latest planting and harvest dates (day 217 and 359) on a Calcaric Regosol with cultivar Innovator. In the late season highest fresh tuber yields were attained with the earliest planting and harvest dates (day 41 and 181) on a Haplic Phaeozem with Innovator.

Water use efficiency of the potato sector in Villa Dolores

- Irrigation use efficiency in the medium early season was lower than in the late season in all cases. This is caused largely by the higher average temperatures in the medium early season
- In the medium early season irrigation use efficiencies of Innovator and Shepody were highest.
- In the medium early season generally irrigation use efficiency was higher on Haplic Phaeozems because of higher available water content of this soil type.
- The highest irrigation use efficiencies were attained with Innovator in the medium early season on a Haplic Phaeozem with the earliest planting and harvest dates (day 196 and 305). Irrigation use efficiencies for the late season were higher but not analysed statistically.

General recommendation

- The influence of the various management choices (planting and harvest day, growing season, cultivar) on the yield and use of irrigation water as found in this report could and should be used by growers, the processing industry and policy makers to improve the sustainability and profitability of the potato production chain in Villa Dolores.

6 REFERENCES

Allen EJ, Scott RK. 1980. An analysis of growth of the potato crop. *Journal of Agricultural Science, Cambridge* **94**: 583-606.

Alterra. 2011. *Digital soil information for the Netherlands.* http://www.bodemdata.nl. October 2011

Batjes NH. 2005. *SOTER-based soil parameter estimates for Latin America and the Caribbean (ver. 1.0). Report 2005/02.* Wageningen: ISRIC – World Soil Information.

Bodlaender KBA. 1963. The influence of temperature, radiation and photoperiod on development and yield. In: Ivins JD, Milthorpe FL, eds. *Growth of the Potato*. London: Butterworths, 199–210.

Burstall L, Harris PM. 1986. The physiological basis for mixing varieties and seed 'ages'in potato crops. *Journal of Agricultural Science, Cambridge* **106**: 411-418.

Caldiz DO, Struik PC. 1999. Survey of potato production and possible yield constraints in Argentina. *Potato Research* **42**: 51-71.

Caldiz DO. 2000. *Survey Analysis of seed and ware potato production systems and yield constraints in Argentina*. PhD Thesis, Wageningen University, The Netherlands.

Caldiz DO, Gaspari FJ, Moreno Kiernan A, Struik PC. 2002. Agro-ecological zoning at the regional level: patio-temporal variation in potential yield of the potato crop in the Argentinian Patagonia. *Agriculture, Ecosystems and Environment* **88**: 3-10.

Clutterbuck BJ, Simpson K. 1978. The interactions of water and fertilizer nitrogen in effects on growth pattern and yield of potatoes. *Journal of Agricultural Science, Cambridge* **91**: 161-172.

Dan Y, Raz Z, Yaalon DH, Koyumdjisky H. 1975. *Soil map of Israel*, Israel: Ministry of Agriculture.

De Vos JA. 1997. *Water flow and nutrient transport in a layered silt loam soil.* PhD Thesis, Wageningen University, The Netherlands.

De Wit CT. 1968. Plant production. *Miscellaneous papers Landbouwhogeschool Wageningen* **3**: 25-50

Driver CM, Hawkes JG. 1943. Photoperiodism in the Potato. *Technical Communication of the Imperial Bureau of Plant Breeding and Genetics* **10**.

Dijkshoorn JA, Van Engelen VWP, Huting JRM. 2008. *Soil and landform properties for LADA partner countries (Argentina, China, Cuba, Senegal and The Gambia, South Africa and Tunisia). ISRIC report 2008/06 and GLADA report 2008/03*. Wageningen: ISRIC – World Soil Information and FAO.

Dwelle RB, Kleinkopf GE, Pavek JJ. 1981. Stomatal conductance and gross photosynthesis of potato (*Solanum tuberosum* L.) as influenced by irradiance, temperature, and growth stage. *Potato Research* **24**: 49-59.

Dyson PW, Watson DJ. 1971. An analysis of the effects of nutrient supply on the growth of potato crops. *Annals of Applied Biology* **69**: 47-63.

Fahem M, Haverkort AJ. 1988. Comparison of the growth of potato crops grown in autumn and spring in North Africa. *Potato Research* **31**: 557-568.

FAO-Unesco. 1988. *FAO/Unesco Soil Map of the World, Revised Legend. World Resources Report 60.* Rome: FAO.

FAO. 1998. *Topsoil characterization for sustainable land management.* Rome.

Ghida Daza C, Sánchez C. 2009. *Zonas Agroeconómicas Homogéneas: Córdoba, área de influencia de la EEA INTA MANFREDI*. Córdoba: INTA Manfredi.

Gregory LE. 1965. Physiology of tuberization in the potato plant (tubers and tuberous roots). In: Ruhland W, ed. *Encyclopedia of Plant Physiology vol. 15/1***.** Berlin: Springer-Verlag, 1328–1354.

Griffin TS, Johnson BS, Ritchie JT. 1993. A Simulation Model for Potato Growth and Development: SUBTOR-Potato Version 2.0. *IBSNAT Research Report Series* **02**.

Gunasena HPM, Harris PM. 1968. The effect of the time of application of nitrogen and potassium on the growth of the second early potato, variety Graig's Royal. *Journal of Agricultural Science, Cambridge* **71**: 283-296.

Gupta SC, Larson WE. 1979. Estimating Soil Water Retention Characteristics From Particle Size Distribution, Organic Matter Percent, and Bulk Density. *Water Resources Research* **15**: 1633-1635.

Goudriaan J, Monteith JL. 1990. A Mathematical Function for Crop Growth Based on Light Interception and Leaf Area Expansion. *Annals of Botany* **66:** 695-701.

Haverkort AJ. 1990. Ecology of potato cropping systems in relation to latitude and altitude. *Agricultural Systems* **32**: 251-272.

Hengsdijk H, Langeveld JWA. 2009. Yield trends and yield gap analysis of major crops in the world. *Werkdocumenten, Wettelijke Onderzoekstaken Natuur en Milieu* **170**.

Huber R. 2010. *Yield-Gap Analysis of Potato Yield in Poland*. MSc Thesis, Wageningen University, The Netherlands.

INTA. 2011. *Instituto Nacional de Tecnología Agropecuaria, Technical Office Villa Dolores*. http://www.inta.gov.ar/manfredi/info/boletines/extension/villadolores/villadolores_influencia.htm. March 2011.

IUSS Working Group WRB. 2006. *World reference base for soil resources 2006,* 2nd edition. Rome: FAO.

Jansen DM. 2002. *Handleiding voor het simuleren, calibreren, optimaliseren in TIPS-Z. Nota 161*. Wageningen: Plant Research International.

Janssen BH. 1970. *Soil fertility in the Great Konya Basin, Turkey.* PhD Thesis, Wageningen University The Netherlands.

Jeffries RA, Mackerron DKL. 1989. Radiation Interception and Growth of Irrigated and Droughted Potato (*Solanum tuberosum*). *Field Crops Research* **22**: 101-112.

Johnson KB, Conlon RL, Adams SS, Nelson DC, Rous DI, Teng PS. 1988. Validation of a simple potato growth model in the North Central United States. *American Journal of Potato Research* **65**: 27-44.

KNMI. 2011. *Various past weather data*. http://www.knmi.nl. September 2011.

Kooman P L, Haverkort AJ. 1995. Modelling development and growth of the potato crop influenced by temperature and day length: LINTUL-POTATO. In: Haverkort AJ, MacKerron DKL, eds. *Potato Ecology and Modelling of Crops under Conditions Limiting Growth.* Dordrecht: Kluwer Academic Publishers, 41-60.

Kooman PL, CJT Spitters. 1995. A coherent set of models to simulate potato growth. In: Kabat P, Marshall B, Van den Broek BJ, Vos J, Van Keulen H, eds. *Modelling and parameterisation of the soil-plant-atmosphere system, a comparison of potato growth models*. Wageningen: Wageningen Pers, 253-274.

Maas SJ. 1993. Parameterized Model of Gramineous Crop Growth: I. Leaf Area and Dry Mass Simulation, *Agronomy Journal* **85:** 348-353.

MacKerron DKL, Davies HV. 1986. Markers for maturity and senescence in the potato crop. *Potato Research* **29**: 427-436.

MAGyA. 2011. *Unidad Provincial del Sistema Integrado de Información Agropecuaria.* http://magya.cba.gov.ar/section.php?module=pagina&id=71. April 2011.

Markovskaya EF, Sysoyeva MI, Bezdenezhnykh VA. 1996. Thermoperiodicity of crop plants and strategies for climate control. *Journal of Agricultural Science, Cambridge* **127**: 452-431.

National Weather Service. 2011. *Precipitation data for caribou*. http://www.weather.gov/climate/local_data .php?wfo=car. June 2011.

NIVAP. 2007. *Netherlands catalogue of potato variaties.*http://www.aardappelpagina.nl/uk/nivap/downloads. June 2011.

Peel MC, Finlayson BL, McMahon TA. 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences Discussions* **4**: 439-473.

De Wit CT, Penning de Vries FWT. 1982. L'Analyse des systemes de production primaire. In: Penning de Vries FWT, Djiteye MA, eds. *La productivite des pdturages sahe'liens. Une etude des sols, des vegetations et de l'exploitation de cette ressource naturelle.* Agricultural Research Reports 918, Wageningen: PUDOC 20-37.

Penning de Vries FW, Rabbinge R. 1995. Models in research and education, planning and practice. In: Haverkort AJ, MacKerron DKL, eds. *Potato Ecology and Modelling of Crops under Conditions Limiting.* Dordrecht: Kluwer, 1-18.

Pirovano F. 2008. Argentina Potatoes Voluntary 2008*, Gain report, USDA* **AR8003**.

Porter JR. 1984. A model of canopy development in winter wheat. *Journal of Agricultural Science* **102**: 383-392.

Porter GA, Sisson JA. 1991. Response of Russet Burbank and Shepody potatoes to nitrogen fertilizer in two cropping systems. *American Journal of Potato Research* **68**: 425-443.

Science and Advice for Scottish Agriculture. 2011. *European Cultivated Potato Database*. http://www.europotato.org/display_description.php?variety_name=Shepody. June 2011.

Shah SFA , Mckenzie BA, Gaunt RE, Marshall JW, Frampton CM. 2004. Effect of production environments on radiation interception and radiation use efficiency of potato (*Solanum tuberosum*) grown in Canterbury, New Zealand. *New Zealand Journal of Crop and Horticultural Science* **32**: 113-119.

Spitters CJT. 1987. An analysis of variation in yield among potato cultivars in terms of light absorption, light utilization and dry matter partitioning. *Acta Horticulturae* **214**: 71-84

Spitters CJT. 1990. Crop growth models: their usefulness and limitations. *Acta Horticulurae* **267**: 349-368.

Spitters CJT, Schapendonk AHCM. 1990. Evaluation of breeding strategies for drought tolerance in potato by means of crop growth simulation. *Plant and Soil* **123**: 193-203.

Stolte J, Wesseling JG, Wösten JHM. 1996. Pedotransfer functions for hydraulic and thermal properties of soil and the tool HERCULES. *DLO Winand Staring Centre report* **126**.

US department of Energy. 2011. *National Solar Radiation Database.* http://rredc.nrel.gov/solar/ld_data/nsrdb/1961-1990/hourly. June 2011.

USDA. 2011. Aroostook County, North eastern part, Maine *Custom Soil Resource Report for Aroostook County*.

USNO. 2011. *Astronomical Applications of The United States Naval Observatory, part of the United States NAVY.* http://aa.usno.navy.mil/data/docs/RS_OneYear.html. March 2011.

Van Dam J, Kooman PL, Struik PC. 1996. Effects of temperature and photoperiod on early growth and final number of tubers in potato (*Solanum tuberosum* L.). *Potato Research* **39**: 51-62.

Van Delden A. 2001. *Yielding ability and weed suppression of potato and wheat under organic nitrogen management.* PhD Thesis, Wageningen University, The Netherlands.

Van Delden A, Schroeder JJ, Kropff MJ, Grashoff C, Booij R. 2001. Simulation of attainable potato yield under different organic nitrogen management strategies: model development and explorations. In: Van Delden A. *Yielding ability and weed suppression of potato and wheat under organic nitrogen management.* PhD Thesis. Wageningen University, The Netherlands: 97-128.

Veerman A. 2003. *Teelt van consumptieaardappelen.* Lelystad: Praktijkonderzoek Plant & Omgeving.

Vos J, Van der Putten PEL. 1998. Effect of nitrogen supply on leaf growth, leaf nitrogen economy and photosynthetic capacity in potato. *Field Crops Research* **59**: 63-72

Westermann DT, Kleinkopf GE. 1985. Nitrogen requirements of potatoes. *Agronomy Journal* **77**: 616-621.

Went FW. 1944. Plant growth under controlled conditions 2. Thermoperiodicity in growth and fruiting of the tomato. *American Journal of Botany* **31**: 135-150.

Winkler E. 1971. Kartoffelbau in Tirol 2. Photosynthesevermögen und Respiration von verschiedenen Kartoffelsorten. *Potato Research* **14**: 1-18.

Wunderground. 2011. *Weather data website*. http://www.wunderground.com. June 2011.

Wolf J. 2002. Comparison of two potato simulation models under climate change. I. Model calibration and sensitivity analyses. *Climate Research* **21**: 173-186.

APPENDIXES

Appendix 1 Report of adapting LINPAC and data collection

In this report the process building LINPACsa from LINPAC and the subsequent collection and formatting of data for calibration and validation is described. Also an indication of the time that was needed for these processes is given (Table 1).

Running LINPAC in TIPS_Z

For automated calibration LINPAC first needed to be embedded in the TIPS_Z modelling environment (Jansen, 2002) both models are written in FORTRAN. The modelling environment organises the simulation and performs the optimisation of model parameters, the core modules make up the actual crop growth model. Any crop growth model written in FORTRAN could in theory be adapted for use in TIPS_Z. To run TIPS_Z and LINPAC the licensed Compaq Visual Fortran 6.6 package was needed, which only runs in windows XP or earlier versions. It proved incompatible with windows 2010 after several attempts. For calibration the automatic sleep function which is default on WUR pc's needed to be shut down. After permission of the ICT department was received the software configurations were set to start running the models.

After arranging the software requirements the modules of the GECROS model had to be removed from the TIPS_Z version received. Then two (*UTILS* and *CROPRO*) out of four modules (others were *WFPROD* and *CROPSEAS*) of the LINPAC model were added to TIPS_Z. This was done because both LINPAC and TIPS_Z have modules that read in weather data and govern the simulation. The weather module of LINPAC was not added in TIPS_Z because it is designed to handle weather data per pixel and has a read procedure of weather data different from the weather data used for TIPS_Z. The simulation driver of the TIPS_Z environment was used because it is better suited for the automated calibration modules and cannot easily be replaced.

In the model text of the *CROPRO* module the statements that are used to make multiple runs and to define values per pixel were removed. This had to be done carefully to make sure information needed for the basic crop growth calculations was not removed. All statements for reading in parameters and data input in *CROPRO* were then changed into statements that corresponded with the read statements used in TIPS_Z. All write statements were also changed. Put statements were added for the simulation outputs that were needed in calibration. With these statements the outputs were put on a virtual blackboard that can be used by the calibration module for comparison with observed crop characteristics.

Statements from the *WFRPROD* and *CROPSEAS* modules that were used later on by *CROPRO* were transferred to *CROPRO*. For this transfer it was essential that the new statements were inserted in the right sections because the order in which statements are executed depends on their position in the model text. Often errors occurred because of a wrong order of statements. The causes of many errors were hard to track. The time needed to get LINPAC running correctly is estimated at 10 working weeks.

Adaptations for calibration of LINPACsa

The adaptations needed to convert LINPAC into LINPACsa and therefore making it applicable for potato are described in chapter 2.3. During these adaptations not many errors occurred, resulting in a relatively fast completion of the LINPACsa model. For calibration, however LINPACsa had to be adapted. A new parameter was introduced in the model to calibrate the day of emergence. It proved difficult to introduce this parameter

Cropstday in such a way that it could defined per year and experiment. This was necessary to be able to change parameter values into newly found values for every separate year and experiment after a calibration stage. The parameter was defined as an array defined by the management name (unique for every experiment and year) whilst most crop parameters were defined per cultivar. Also an on switch was added for calibration of *Cropstday* to be able to calibrate this parameter only experiments within a calibration of which the day of emergence is not known. LAI parameters *rm*, *tb* and *cm* were added as variable parameters, in LINPAC the values for these parameters were defined in the model text and could not be changed in calibration.

For available and total water content a mechanism was used comparable to the mechanism described for *Cropstday*. The values for these parameters were added as an array defined by the experimental location. This was done to be able to calibrate and change water contents for experiments of which the water contents are not certain. Problems occurred with names in the model of parameters not exactly corresponding with names in the model. Another problem was the maximum size an array could assume. It took a lot of time before it was found that this was the cause of error. The time involved in adapting LINPACsa for calibration is estimated at 3 working weeks.

Formatting data

Data from field experiments had to be converted into 6 types of files for automated calibration. In these files all treatments were included, also treatments not used in this report. An observations file (.ptt) for observations of yields, LAI and other crop characteristics including the date of observation. For many experiments units had to be converted. For the experiment names, crop season, location and weather file directory two types of files were needed (.pts and .ptx). The three file types mentioned were made per experimental year, 91 files in total for this report. For the management, amount of seed, nitrogen and water applied a separate file type was made (.jou), this file had to be made for every repetition with a unique name, in total 268 files were made for this report. Weather files were formatted in Microsoft Excel 2010 from (.csv) files after additional calculations were made. Then the (.xls) files were transferred into the (.txt) format with the a country code (e.g. ARG) and the last digits of the year as extension (e.g. .999 for 1999). In total 26 weather files were made for calibration and validation. Another 18 weather files were made to simulation. In the parameter listing file (cropdata*experimentabbreviationcultivarname*.dat) the available water contents and texture classes for experimental location were added. Because of different experimental locations and cultivars in total 9 files had to be made. The format and the content of the files proved very important as the model only reads correct files, errors occur as soon as one space, letter or name is incorrect. Including correcting files, time consumed by formatting data is estimated at 9 working weeks.

Table 1 Time spend on activities including simulation and calibration and validation, not mentioned in the text.

Activity	**Time needed**
Running LINPAC in TIPS_Z	10
Adaptations for calibration of LINPACsa	3
Formatting data	9
Calibration and validation	8
Simulation	3

Appendix 2 Report of internship week Farm Frites

To gain more insight in the production and quality aspects of potatoes for potato chip production, I got the chance to accompany the employees of Farm Frites during an internship week. In week 3 of 2011, from the 17th of January until the 20th of January I visited farmers with representatives of Farm Frites and did potato quality testing. With Cees van den Hoek, an agronomist for Farm Frites, I visited a couple of farmers with specific storage problems, with representatives Emiel Mol and Dirk Meulenberg I visited farmers in the east of Brabant and Zeeland respectively. Below a summary is given of what I have learned about the production chain that starts with seed tubers and ends with potato chip production at Farm Frites.

The production of potatoes for the Farm Frites factories starts with seed tubers. Farm Frites supplies these to the farmers that grow potatoes for the factory. The seed tubers come from companies that propagate and develop potato cultivars. Each of these propagation companies has their own cultivars. Cultivars are the licensed property of the company that developed them and these cultivars may be propagated only with permission of the propagation company.

One plant with the desired properties, the new cultivar, is derived after crossing parental lines. This one plant is propagated through tissue culture to make sure the seed tubers are free of viruses, fungi and bacteria. The tubers of the plants resulting from tissue culture, called mini tubers, are propagated by "normal" propagation by means of planting seed tubers. The number of available seed tubers is then multiplied by propagation via tubers for several generations. Every generation of tubers descending from the mother plant is considered of less quality compared to the previous generation. A system of quality control classes is applied to all tubers , beginning with mini tubers, then virus free tubers S (Super quality) trough SE (Super Elite), E (Elite), A, B and C. For every class there is a set of quality standard concerning the presence and amounts of viruses and fungi. The NAK (a Dutch control institute working for the Dutch ministry of agriculture) controls the quality of seed tubers.

The propagation companies have growers that propagate the higher classes (e.g. S, SE and E) for them, usually producing A class seed tubers to be sown by farmers that produce for consumption. Farm Frites buys seed tubers (class A) of different cultivars from different growers, which are later on sold to supplying farmers. Different cultivars are needed because cultivars have different productivities and qualities depending on soil type and storage time. The seed potatoes are mainly produced in the north of the Netherlands. Because Farm Frites mainly has its supplying farmers in the south of Holland, part of the seed tubers is temporarily stored in refrigerated barns in the south of the country. This is done because farmers will simultaneously need seed tubers when the weather is favourable for planting and logistically it is not possible to transport seed tubers over such a large distance in a short notice.

Farmers that supply for Farm Frites can sign contracts on prices and quantities of seed potatoes they buy and ware potatoes they deliver. Also time of delivery to the factory is taken up in the contract, usually delivery times are given in a range of weeks. The planning of the supply for the factory is the reason for these delivery dates. To optimise the use of factory capacity a constant supply with the right cultivars is needed. For some farmers delivery time is long after harvest and they have to store the potatoes on their farm, sometimes up to 9 months. In storage, quantity and quality losses can occur, in case of losses Farm Frites will pay less because less is delivered and the quality is lower. However, for storing the farmer does get a bonus on the price he receives for the potatoes, based on the time he has to store potatoes.

The contracted growers have either fixed a price and quantity to be delivered or have the agreement to grant Farm Frites the first choice to buy their product at free market price. The rest of the potatoes needed for processing are bought from the free market. For farmers, the risk of producing for the free market is that prices can be low. However in years like 2011, when the prices are high due to a bad growing season and a bad, wet harvest, market prices are very profitable. A fixed contract price on the other hand, gives certainty but can be low compared to the market prices.

The farmer has to choose whether to accept storage loss risks and low fixed prices or to speculate on high prices at the end of the season. The role of the representatives of Farm Frites is to get the right supply of potatoes for the factory by contracting farmers. The representative has his own district in which he knows the farmers. The terms of the contract are set by Farm Frites, farmers have to comply to them. To ensure that farmers under contract choose to supply to Farm Frites in the following years, representatives try to guide and advise farmers the best they can. Problems having to do with crop growth, harvest or storage have to be solved by representatives in a way that is beneficial for Farm Frites but without unnecessary harming the interests of the farmer.

One of the biggest problems after the growing season is the storage of potatoes. Some farmers are obliged to store potatoes for Farm Frites because of their contract but are facing great losses in quality and quantity because of rot or sprouting. The farmer will lose a lot of income because of storage losses, but losses are also negative for Farm Frites because they depend on stored potatoes for supply of the factory . Therefore representatives of Farm Frites have to advice farmers on storage strategies. In some cases they have to arrange for batches to be taken to the factory before the supply date in the contract to prevent further losses. Taking in a batch of potatoes earlier means somewhere else potatoes have to be kept for longer and factory planning has to be rearranged. Therefore this decision is only made if the risk of further losses is urgent.

Sprouting is one of the problems that can occur when storing potatoes for potato chip production. Especially when sprouts have developed roots, the knives that cut the French fries in the factory can get clogged by the roots. An anti-sprouting agent called MH (maleïne hydrazide) can be applied on the crop canopy when the potatoes are almost ripened. MH stops sprouting by blocking cell division. In the barn of a farmer that tried out MH, part of the stored potatoes still formed sprouts. It was concluded that the moment of application is very important for the crop uptake of the agent. MH is an alternative for treating potatoes with anti-sprouting agents in powder form before storage. Treatment with powder has the negative effect of causing powder burn on some potato cultivars. During storage anti-sprouting agents are usually applied by frequent fogging.

This year during the potato harvest it was very rainy. Due to this tubers were stored with a lot of clay still attached. One problem associated with the clay attachment is sprouting of tubers in this clay layer. At the factory potatoes are washed, but the amount of clay that is attached to tubers in some batches is too great to wash off at the factory. The tubers will have to washed somewhere else for a long time to soak off the clay, this will be a great cost for the farmers. Maybe clay will fall off when tubers shrink because of long time storage. On lighter soils the wet harvest has smeared the soil to cover the whole tuber, blocking oxygen to the tuber which needs to respire. This leads to rotting, rotting potatoes infect the rest and only drying (heating intensely) can stop this. Heating costs, however will be a great expense to the farmer.

The quality of potatoes supplied to the potato chip factory is very important. First of all the dry matter content must be high enough for baking. If the dry matter content is not high enough, too much water is left in the chips which makes them wet and mushy. Dry matter content depends on the length of the growing season, nutrient supply and weather circumstances but it also varies per cultivar. Also baking colour is very important, if the tuber contains too much sugars it will colour brown during baking. Sugar content depends on storage and also varies among cultivars. The flesh colour of a potato is also a cultivar aspect which is important, yellow chips are preferred in the Netherlands and Germany, while other countries and fast food chains prefer white chips. Other quality aspects are the colour in frozen storage, presence of fall damage, size distribution and hollow tubers. Most quality requirements depend partly on cultivar, not all cultivars are suitable for potato chip production. Therefore Farm Frites regularly tests new cultivars on their suitability as potato chip cultivar.

Sampling is done regularly to assess quality aspects of potatoes in the field and later on in storage. Dry matter content is reflected in underwater weight, which is determined by weighing 5 kg potatoes under water. The underwater weight has to be at least 360g to be allowed for processing. Baking quality is determined by sampling 20 fries, each from a separate potato and baking them. The quality is then determined by visual assessment. If a batch of potatoes is not adequate for potato chip production, Farm Frites can try to sell it for another purpose or let the farmer sell the batch for example as fresh consumption potato.

Appendix 3 Parameter listing LINPAC

Abbreviation	Variable	Unit
Biom	Total crop biomass (dry weight)	kg/ha
Biom1	Translocatable biomass (dry weight)	kg/ha
BiomTrl	Rate of biomass translocated from Biom1 to yield	kg/ha
cBiom	Growth rate biomass	kg/ha/d
Chght	Crop height (depending on LAI) to determine Trpot	m
Chghtmx	Maximum crop height (to determine crop height)	m
chk1	Auxiliary variable for checking water balance	-
cLai	Growth rate LAI	m/m/d
cm	Parameter in expolinear function	˚Cd
croper	Parameter to determine if a crop is annual (1) or perennial (2)	-
CropFac	Crop factor for transpiration	-
cRtd	Growth rate of roots/rooted layer	m/d
cwsoil	Total of inflow and outflow rate layers 1 and 2	mm/d
cWsoil1	Rate of inflow or outflow of water in layer 1	mm/d
cWsoil2	Rate of inflow or outflow of water in layer 2	mm/d
cYield	Growth rate yield	kg/ha/d
dev	Deviation between cwsoil & all water flows in and out of layer (should be 0!)	mm/d
dLai	Death rate LAI due to severe water shortage	m/m/d
dLmax	Maximal death rate of leaves due to water shortage (0 if not possible)	m/m/d
Drain	Drainage from layer 2 out of the simulated system	mm/d
Drain1	Drainage from layer 1 to layer 2	mm/d
Draincu	Cumulative drainage from layer 2	mm
dslr	Number of days since last rain	d
Eact	Actual evaporation	mm/d
Epot	Potential evaporation	mm/d
ETa	Actual evapotranspiration	mm/d
Evapcu	Cumulative evaporation	mm
f1	Parameter to determine parameter tb	-
Fint	Fraction light intercepted	-
fLai3	Parameter of the fraction of the LAI at Tsm2 left when Tsm3 is reached	m/m
Flper	Flower period, fraction of Tsm1 (extra effect water shortage on seed set in this period)	-
fLue	Rate of decline of LUE	-
fLue3	Fraction of initial LUE left at Tsm3	-
frunoff	External runoff function using rain, rain intercept, texture class and slope class	-
HvI	Harvest	-
Iintc	Intercepted irrigation	mm
Ilev	Irrigation level 1=non-water limited 2=rain fed	-
Infil	Infiltration of water into the ground	mm/d
Irricu	Cumulative irrigation	mm

Irrig	Irrigation	mm/d
Kpar	Extinction coefficient (Lambert -beer)	-
Lai	LAI	m/m
Lai2	LAI at Tsm2	m/m
Laiem	LAI at emergence	m/m
Laimx	Maximal LAI a plant can reach	m/m
Lue	Light use efficiency	g/MJ
LueRed	Reduction of LUE due to temperature, ageing, and soil toxicity	-
newLAI	Auxiliary variable to calculate potential increase of LAI	m/m
newTsum	Temperature sum to calculate LAI	˚Cd
NoEmerg	Logical to define if emergence took place	-
Par	Photosynthetically active radiation	MJ/m2/d
Parcu	Cumulative of PAR intercepted	MJ/m2/d
Parint	PAR intercepted	MJ/m2/d
Parthr	PAR threshold for reduction of LUE due to high PAR	MJ/m2/d
Precipcu	Cumulative precipitation	mm
pval	Auxiliary variable to determine critical water content	-
r1	Parameter to determine tb	-
Raincu	Cumulative rainfall	mm
Rdepth	Maximum rooting depth	m
Rintc	Intercepted rain	mm/d
rm	Parameter in expolinear function	-
Rnoffcu	Cumulative runoff	mm
Rootr	Reduction of harvestable biomass (e.g. wood) by roots	-
Rtd	Root length/rooted layer	m
Rtdem	Root length at emergence	m
Runoff	Total runoff	mm/d
RunofI	Runoff for irrigation	mm/d
RunofR	Runoff for rain	mm/d
sdepth	Depth of rootable soil =rdepth	m
seedaf	Fraction of generative biomass to harvestable product	-
sinkcap	Reduction due to lower sink capacity caused by water limitation during flowering	-
Tac1	Auxiliary variable for determining sinkap	mm
Tac2	Auxiliary variable for determining sinkap	mm
Tacum	Cumulative actual transpiration	mm
tb	Parameter in expolinear function	-
Tintc	Transpiration of leaf-intercepted water	mm
tkl_dif	Growth of the thickness of top soil layer	m
tkl_old	Thickness of top soil layer one step of integration ago	m
tkl1	Top soil layer thickness	m
tkl2	Unrooted soil layer	m
tktop	Initial thickness of top soil layer	m
Tmbase	Base temperature	˚C

tmeff	Effective temperature	˚C
tmsum	Temperature sum accumulating from the start of simulation	˚Cd
Tpc1	Auxiliary variable for determining sinkcap	mm
Tpc2	Auxiliary variable for determining sinkcap	mm
Tpcum	Cumulative potential transpiration	mm
Tract	Actual transpiration	mm/d
Tracu	Cumulative transpiration	mm
TrCoef	Constant transpiration coefficient	L/kg
TrCrt	Parameter to determine critical water content, higher value means more drought tolerance.	mm/d
Trloc	The fraction of biomass produced in veg phase translocated to generative organs	-
Trpot	Potential transpiration	mm/d
TrRat	Transpiration ratio potential/actual affecting LAI, Biom and Yield	-
Tsm	Temperature sum accumulating from emergence	˚Cd
Tsm0	Temperature when maximal LAI is reached	˚Cd
Tsm1	Temperature sum ending LAI increase	˚Cd
Tsm2	Temperature sum ending constant LAI phase	˚Cd
Tsm3	Temperature sum at the end of LAI decline phase	˚Cd
tsmem	Temperature sum until emergence	˚Cd
Tsmrd	Temperature sum during which root growth takes place	˚Cd
Tsumold	Temperature sum needed for the development of LAI present one step of integration ago	˚Cd
Wdeficit	Amount of water required for non-water limited growth in case of water limitation	mm
Wintc	Tot intercepted water from irrigation and from rain	mm/d
Wsoil	Amount of water in both soil layers	mm
wsoil1	Amount of water in top layer	mm
wsoil2	Amount of water in unrooted layer	mm
wsoilav	Actual amount of water above pF air dry in top layer	mm
wsoilcr	Critical amount of water above pF wilting point without water limitation occurs in rooted layer	mm
Wsoilcu	Cumulative soil water content in both soil layers	mm
wsoilfc	Maximum amount of water between air dry and field capacity pFs in rooted layer	mm
Wsoilstart(1)	The initial soil water content in soil layer 1	mm
Wsoilstart(2)	The initial soil water content in soil layer2	mm
wsoiltr	Actual amount of water above wilting point rooted layer	mm
wsoilwp	Maximum amount of water in rooted layer between air dry and wilting point pFs	mm
wtransf	Soil water resulting from exploration going from the unrooted layer to the rooted layer	mm/d
xavailwatcont	Maximum plant available water content between wilting point and field capacity pFs	mm/m
xday	Day number of the year (366 for a leap year)	d
xLueToxRed	LAI growth rate reduction factor due to soil (toxic) conditions	-
xRain	Rain	mm/d
xRdd	Total irradiation	J/m2/d
xSlopeClass	Slope class of the soil	-
xTextureClass	Texture class of the soil	-
xtime	Days after start of simulation	d
xtotalwatcont	Maximum total water content between air dry and field capacity pFs	mm/m

Yield	Yieldable biomass (dry weight)	kg/ha

Appendix 4 Model text LINPACsa

```
*     For LINPAC more formal parameters were stated to transfer from one subroutine to the next
*     (e.g. weather and soil data from WFPROD and CROPSEAS subroutines) for LINPACsa however,
*     these variables are transferred via put and get statements.

      subroutine soilcrop (xNewTask,xModule,xLogFileUnit)

      implicit none
***************************************************************************************************************************
*---- FORMAL PARAMETERS---------------------------------------------------------------------------------------------------*
***************************************************************************************************************************

       integer xLogFileUnit
      character*(*)  xModule
      character*(*) :: xNewTask

***************************************************************************************************************************
*---- LOCAL PARAMETERS----------------------------------------------------------------------------------------------------*
***************************************************************************************************************************

*     In LINPAC formal parameters
      integer Year, xTime, xStTime, xday, ilev, etmeth
      integer xCropSeq, StartCrop, EndCrop
      real    xLatitude, xAltitude
      real    xRdd, xTmav, xRain, xvap, xwnd, xetr
      real    xSoildepth, xTotalWatCont,xAvailWatCont
      integer xSlopeClass, xTextureClass
      real    xLueToxRed
       real    Tmbase, WsoilStart(2), Sdepth

*     Weather variables added for LINPACsa
      real   xtmavd, xDL

*     Declarations model variables
      include 'tasks.inc'

*2011_06_22 added
      integer CropPlDay
       real    anga, angb

*     Plant variables
      real tmsum
```

```
*     Crop input tables
       integer ncmax, ngmax
      parameter (ncmax = 35)
       parameter (ngmax = 5)
       integer Crprtb(ncmax)
       real Laimtb(ncmax), Flaitb(ncmax), Dlaitb(ncmax), Kpartb(ncmax)
       real CHghtb(ncmax), Tmmxtb(ncmax), Tsmemtb(ncmax)
       real Tsm0tb(ncmax),Tsm1tb(ncmax),Tsm2tb(ncmax),Tsm3tb(ncmax)
       real Luetb(ncmax), Fluetb(ncmax), Parttb(ncmax), Flpertb(ncmax)
       real Tmt1tb(ncmax),Tmt2tb(ncmax),Tmt3tb(ncmax), Tmt4tb(ncmax)
       real Trcftb(ncmax),Hvitb(ncmax),Sdaftb(ncmax), Rtrtb(ncmax)
       real Trltb(ncmax), Rtdptb(ncmax), Trcrtb(ncmax)

       real Croper, Laimx,Flai3,dLmax,Kpar,CHghtmx, Tmmax,Tsmem,Tsm0,Tsm1,Tsm2
       real Tsm3,Lue,Flue3,Parthr, flper,Tmt1,Tmt2,Tmt3,Tmt4,Trcoef,Hvi
       real Seedaf,Rootr,Trloc,Rdepth, Trcrt

*     Added for LINPACsa
      integer IarrayN
       real alphayieldtb(ncmax),betayieldtb(ncmax)
       real AllocMNTB(ncmax), AllocMxTB(ncmax), AllocATB(ncmax)
      real AllocBTTB(ncmax), AllocBDLTB(ncmax),SOIniATB(ncmax)
       real SOIniBTTB(ncmax), SOIniBDLTB(ncmax),Tmbstb(ncmax)

      real alphaYield,betaYield
       real AllocMN, AllocMx, AllocA, AllocBT, AllocBDL
       real SOIniA, SOIniBT, SOIniBDL

*     States, rates and auxillary variables
       real tacum,tpcum,tac1,tac2,tpc1,tpc2, sinkcap
      real wsoil,wsoil1,wsoil2,cwsoil,cwsoil1,cwsoil2
      real tktop,tkl1,tkl2,tkl_dif,tkl_old,wtransf
      real wsoilcor,biom,cbiom,yield,cyield,lai,clai,dlai
      real chght,rtd,crtd
       real tmeff,tsm,tsmrd,biomtrl
       real trpot,tract,trrat,epot,eact,emax,eta,dslr
       real wintc,rintc,iintc,tintc
      real wsoilwp,wsoilfc,wsoiltr,wsoilcr,wsoilav,pval
       real tsumold,newtsum,tb,rm,cm,newlai,laiem,lai2,biom1,flue
       real fint,par,parint,krdd,rtdem
      real runofr,runofi,runoff,irrig,infil,wdeficit,drain1,drain
       real dev,chk1
```

```
*     Added for LINPACsa
       real alphaTrLoc, CalcTrLoc, CalcSOIni, CalcDayl
      real cBiomTrl, cBiom1, AllocNew, AlphaAlloc, FrYield,FrDMYield
       real DVRTI, DVSTI, xTsmLaiMx
       integer DayEmObs
      real wratat
      real rootdepth
      real wsoilavg_1,wsoilavg

*     Soil and crop output variables
      real evapcu,draincu,rnoffcu,raincu,wsoilcu
       real tracu,eactcu,irricu,precipcu,parcu

      real biomserie(2,ngmax),yieldserie(2,ngmax),parcuserie(2,ngmax)
      real transserie(2,ngmax),eactserie(2,ngmax)
      real irrigserie(2,ngmax),precipserie(2,ngmax)
       real evapserie(2),drainserie(2),runofserie(2),wsoilserie(2)
      real rainserie

*     Light Use Efficiency reduction
      integer    LUERedTbMxn,LUERedTbCnt
      parameter (LUERedTbMxn=12)
      real       LUERedTb(LUERedTbMxn)
      real       LUERed

*     Crop factor for transpiration
      integer    CropfacTbMxn,CropfacTbCnt
      parameter (CropfacTbMxn=10)
      real       CropfacTb(CropfacTbMxn)
      real       Cropfac

*     External functions
      real notnul,limit,Lint2,fRunoff
      integer getun

*     Miscellaneous variables
      integer ic, il, ig, ix
      integer Output
       real ncp,c1,c2, r1, f1
      character*1 q,c
      logical nocrop, noemerg

      save

```

```
            call getsi  (xModule, 'idoy'  ,xday)
            call getsi  (xModule, 'iyear', year)
            call getsi (xModule, 'CropPlDay', CropPlDay)

          if (xNewTask.eq.'initialize') then

*         Read crop data from cropdata'cultivarname'.dat
            call getaim  (xmodule,'Crprtb', Crprtb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Laimtb', Laimtb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Flaitb', Flaitb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Dlaitb', Dlaitb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Kpartb', Kpartb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'CHghtb', CHghtb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Tmbstb', Tmbstb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Tmmxtb', Tmmxtb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Tsmemtb',Tsmemtb,ncmax, IarrayN, -99)
            call getarpm (xmodule,'Tsm0tb', Tsm0tb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Tsm1tb', Tsm1tb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Tsm2tb', Tsm2tb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Tsm3tb', Tsm3tb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Luetb',  Luetb,  ncmax, IarrayN, -99)
            call getarpm (xmodule,'Fluetb', Fluetb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Flpertb',Flpertb,ncmax, IarrayN, -99)
            call getarpm (xmodule,'Parttb', Parttb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Tmt1tb', Tmt1tb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Tmt2tb', Tmt2tb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Tmt3tb', Tmt3tb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Tmt4tb', Tmt4tb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Trcftb', Trcftb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Trcrtb', Trcrtb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Hvitb',  Hvitb,  ncmax, IarrayN, -99)
            call getarpm (xmodule,'Sdaftb', Sdaftb, ncmax, IarrayN, -99)
            call getarpm (xmodule,'Rtrtb',  Rtrtb,  ncmax, IarrayN, -99)
            call getarpm (xmodule,'Trltb',  Trltb,  ncmax, IarrayN, -99)
            call getarpm (xmodule,'Rtdptb', Rtdptb, ncmax, IarrayN, -99)

*         Added for LINPACsa
            call getarpm (xmodule,'AllocMn', AllocMnTB, ncmax, IarrayN, -99)
            call getarpm (xmodule,'AllocMx', AllocMxTB, ncmax, IarrayN, -99)
            call getarpm (xmodule,'AllocA',  AllocATB,  ncmax, IarrayN, -99)
            call getarpm (xmodule,'AllocBT', AllocBTTB, ncmax, IarrayN, -99)
            call getarpm (xmodule,'AllocBDL',AllocBDLTB,ncmax, IarrayN, -99)
            call getarpm (xmodule,'SOIniA',  SOIniATB,  ncmax, IarrayN, -99)
            call getarpm (xmodule,'SOIniBT', SOIniBTTB, ncmax, IarrayN, -99)
```

```
      call getarpm (xmodule,'SOIniBDL',SOIniBDLTB,ncmax, IarrayN, -99)

       call getsi(xModule, 'CropStday', DayEmObs)
      call getsi (xmodule,'cropseq',xCropSeq)
      call getarpm  (xmodule,'alphaYieldtb',alphaYieldtb,ncmax,
     &   IarrayN,-99)
      call getarpm  (xmodule,'betaYieldtb',betaYieldtb,ncmax,
     &   IarrayN,-99)
      call getsi (xmodule,'startcrop',startcrop)
      call getsi (xmodule,'slopeclass',xslopeclass)
       call getsi (xmodule,'TextureClass',xTextureClass)
       call getsrp (xmodule,'LueToxRed',xLueToxRed)
      call getsi (xmodule, 'ilev',ilev)
       call getsi (xmodule,'etmeth',etmeth)
      call getsrp (xmodule,'lat',xLatitude)
      call getsrp (xmodule,'elev',xAltitude)
      call getsrp (xmodule,'soildepth',xsoildepth)
      call getsrp (xmodule,'AvailWatCont',xAvailWatCont)

*     Added for LINPACsa
      ic  = xCropSeq
       Rootdepth = rtdptb(ic)
       Sdepth = min(xsoildepth, rootdepth)
      xTotalWatCont = xAvailWatCont*Wratat(xtextureclass)
      tktop = min(sdepth,0.2)
      tkl1  = tktop
       tkl2  = sdepth - tkl1
       wsoil1   = wsoilstart(1)
       wsoil2   = wsoilstart(2)
       wsoil    = wsoil1 + wsoil2
      wsoilcor = 0.
       call angstrom (xlatitude,anga,angb)

*     Initialize local soil depth and water
      WsoilAvg_1 = 0.2    * xTotalWatCont
      WsoilAvg   = Sdepth * xTotalWatCont

      wsoilstart(1) = wsoilavg_1
      wsoilstart(2) = wsoilavg - wsoilavg_1

*      Setting soil output to zero
      Wsoilcu = 0.
      Evapcu  = 0.
      Draincu = 0.
```

```
        Rnoffcu = 0.
        Raincu  = 0.

*       Setting crop output to zero
        Biom     = 0.
        Yield    = 0.
         Parcu    = 0.
        Tracu    = 0.
         Eactcu   = 0.
         Irricu   = 0.
         Precipcu = 0.

*     Added for LINPACsa
        Allocnew = 0.
        FrYield  = 0.
         FrDMYield= 0.

*       Setting auxillary variables to zero
        TSM   = 0.
        Tmsum = 0.
         Biom1 = 0.
        Lai   = 0.
        Lai2  = 0.
        Rtd   = 0.
         Tacum = 0.
         Tpcum = 0.
        CHght = 0.
        Tac1  = 0.
        Tpc1  = 0.
        Tac2  = 0.
        Tpc2  = 0.

*       counters and flags
        Output  = 1

*       initialize situation without crop
        NoCrop = .true.

        if (.not. NoCrop) then
        call fatalerr ('geprod','not nocrops failure')
         end if

*       Assigning values to crop-specific input parameters
        Croper = Crprtb(ic)
```

```
          Laimx  = Laimtb(ic)
          Flai3  = Flaitb(ic)
          dLmax  = Dlaitb(ic)
          Kpar   = Kpartb(ic)
          CHghtmx= CHghtb(ic)
          Tmmax  = Tmmxtb (ic)
           Tsmem  = Tsmemtb(ic)
          Lue    = Luetb (ic)
          Flue3  = Fluetb(ic)
          Flper  = Flpertb(ic)
           Parthr = Parttb(ic)
          Tmt1   = Tmt1tb(ic)
          Tmt2   = Tmt2tb(ic)
          Tmt3   = Tmt3tb(ic)
          Tmt4   = Tmt4tb(ic)
          Trcoef = Trcftb(ic)
          Trcrt  = Trcrtb(ic)
          HvI    = Hvitb(ic)
          Seedaf = Sdaftb(ic)
          Rootr  = Rtrtb(ic)
          Trloc  = Trltb(ic)

*     Added for LINPACsa
          alphaYield = alphaYieldtb(ic)
           betaYield = betaYieldtb(ic)
           AllocMn  = AllocMnTB(ic)
          AllocMx  = AllocMxTB(ic)
          AllocA   = AllocATB(ic)
          AllocBT  = AllocBTTB(ic)
          AllocBDL = AllocBDLTB(ic)
          SOIniA   = SOIniATB(ic)
          SOIniBT  = SOIniBTTB(ic)
          SOIniBDL = SOIniBDLTB(ic)
          Tmbase = Tmbstb (ic)

          Tsm3   = Tsm3tb(ic)
          Tsm1   = Tsm1tb(ic)
          Tsm2   = Tsm2tb(ic)

*     Added a difference in temperature sum calculation between potato (croper=3) and determinate crops (croper=1)
          if (croper < 3) then
             Tsm1   = Tsm1tb(ic)
             Tsm0   = min(Tsm0tb(ic),tsm1)
             Tsmrd = 0.75 * tsm0
```

```
          else
              Tsm1 = 1.e6
             Tsm0 = Tsm0tb(ic)
             Tsmrd = 0.75 * tsm2
          end if

          if (tsm3 .lt. 0.) then
          call fatalerr ('cropro','negative tsm3')
           end if

*     Adjusting soil depth and rooting depth
          if (Rdepth .gt. xSoildepth) then
            Rdepth = xSoildepth
           end if

*     Additional calculations
          Krdd  = 0.75 * Kpar

*     Added a difference in calculation of LAI parameters between potato (croper=3) and determinate crops (croper=1)
          if (croper < 3) then
             r1 = (5./1050.)
              f1 = 0.47
             rm = 0.009
             xTsmLaiMx = tsm0
              tb = (r1 / (Laimx/xTsmLaiMx)) * f1 * xTsmLaiMx
              cm = Laimx * rm / (log(1. + exp(rm*(xTsmLaiMx-tb))))
          else
          call getsrp (xmodule, 'rm', rm)
           call getsrp (xmodule, 'tb', tb)
           call getsrp (xmodule, 'cm', cm)
          endif

           if (cm .lt. 0.) then
          call fatalerr('soilcrop', 'negative cm')
           end if

*         values at emergence
           Laiem = (cm/rm) * log(1. + exp(rm*(0. - tb)))
           if (Laiem .lt. 0.) then
          call fatalerr('soilcrop', 'negative Laiem')
           end if

*     Added rooting depth for potato (croper=3)
          if ((croper .eq. 1) .or. (croper.eq.3)) then
```

```
      Rtdem = 0.05
       else if (croper .eq. 2) then
      Rtdem = Rdepth
       else
      call fatalerr ('cropro','crop perennial indicator failure')
       endif

*     Put values into table for effect temperature on lue
      LUEredTb(1)  =-200.
      LUEredTb(2)  =   0.
      LUEredTb(3)  = Tmt1
      LUEredTb(4)  =   0.
      LUEredTb(5)  = Tmt2
      LUEredTb(6)  =   1.
      LUEredTb(7)  = Tmt3
      LUEredTb(8)  =   1.
      LUEredTb(9)  = Tmt4
      LUEredTb(10) =   0.
      LUEredTb(11) = 200.
      LUEredTb(12) =   0.
      LUEredTbCnt  =  12

*     Put values into table for effect lai on crop factor / transpiration
*     For now: crop factor is  species independent function of lai with maximum value of 1.2 at lai=5.0
      CropfacTb(1)  = 0.
      CropfacTb(2)  = 1.
      CropfacTb(3)  = 4.
      CropfacTb(4)  = 1.2
      CropfacTb(5)  = 8.
      CropfacTb(6)  = 1.4
      CropfacTb(7)  = 12.
      CropfacTb(8)  = 1.4
      CropfacTb(9)  = 20.
      CropfacTb(10) = 1.4
      CropfacTbCnt  = 10

*     Setting crop output to zero
      Biom     = 0.
      Yield    = 0.
       Parcu    = 0.
      Tracu    = 0.
       Eactcu   = 0.
       Irricu   = 0.
       Precipcu = 0.
```

```
*        Setting auxillary variables to zero
         Tmsum = 0.
          Biom1 = 0.
         Lai   = 0.
         Lai2  = 0.
         Rtd   = 0.
          Tacum = 0.
          Tpcum = 0.
         CHght = 0.
         Tac1  = 0.
         Tpc1  = 0.
         Tac2  = 0.
         Tpc2  = 0.
         tmeff    = 0.
         cLai     = 0.
         dLai     = 0.
          cBiom    = 0.
          cYield   = 0.
          cRtd     = 0.
          Parint   = 0.
          Tract    = 0.
          Wintc    = 0.
         Wdeficit = 0.
         Eact     = 0.
         Drain    = 0.
         Runoff   = 0.
         xRain    = 0.
         irrig    = 0.
         tract    = 0.
         wintc    = 0.
         cwsoil1  = 0.
         cwsoil2  = 0.

*      Added for LINPACsa
         cbiom1   = 0.
         dvrti    = 0.
         dvsti    = 0.

*        new crop situation
         NoCrop  = .false.
         NoEmerg = .true.

       elseif( xday < CropPlday) then
```

```
         return

       else if (xnewTask == 'do_rates') then

****************************************************************************************************************************
*--------RATES SECTION------------------------------------------------------------------------------------------------------*
****************************************************************************************************************************

*      Reading weather data, in LINPAC transferred from WFPROD, in LINPACsa called from TIPS_Z WHTAB subroutine
         call getsrt(xmodule,'rdd', xrdd)
         call getsrt(xmodule,'tmda' , xtmav)
         call getsrt(xmodule,'vp', xvap)
         call getsrt(xmodule,'wn',xwnd)
         call getsrt(xmodule,'rain', xrain)

*      Added average daytime temperature for calculation of LUE reduction
         call getsrt(xmodule,'tmdad' , xtmavd)
         xDl = CalcDayL (xDay, xlatitude)

         call ETref(ETmeth, xday, xlatitude, xaltitude, anga, angb, xrdd,
     &        xtmav, xvap, xwnd, xETr)

*      Initialization of cropping rate variables that are used during integration or in the soil water section
         tmeff    = 0.
         cLai     = 0.
         dLai     = 0.
          cBiom    = 0.
          cYield   = 0.
          cRtd     = 0.
          Parint   = 0.
          Tract    = 0.
          Wintc    = 0.
         Wdeficit = 0.

*      Added for LINPACsa
         cbiom1   = 0.
          dvrti    = 0.

        if (xday .eq. 206) then
           continue
         endif

*---------------------------------------------------------------------------------------------------------------------------
* -- Calculation of potential E and T                                                                                       *
```

```
* -----------------------------------------------------------------------------------------------------------------------

*     Needed here to provide soil and crop with 'water demands'. First step is to calculate amount of rain/irrigation
*     interception by the crop.For now: assumed that no irrigation water is intercepted (either no irrigation at all or
*     drip irrigation near the ground).

        Irrig = 0.
        if (Lai .gt. 1.e-5) then
          call Intercep (xRain,Irrig,Lai,Wintc,Rintc,Iintc)
         else
           Wintc = 0.
           Rintc = 0.
           Iintc = 0.
         end if

*     Second step is to determine Trpot and Epot
        CropFac = 0.
         if  (Lai .gt. 1.e-5) then
          CropFac = Lint2 ('CropfacTb',CropfacTb,CropfacTbCnt,Lai)
         end if

        call ETpot(ETmeth, xday, xLatitude, xAltitude,
     &              xRdd, xTmav, xVap, xWnd, xETr, CropFac,
     &              Lai, CHght, Krdd, Wintc, Tintc, Trpot, Epot)

*     If no crop is present, skip this crop part and continue with soil part below
        if (.not. nocrop) then
*------------------------------------------------------------------------------------------------------------------------
* -0- Effective temperature   (degrees Celsius)
*
* -----------------------------------------------------------------------------------------------------------------------

        Tmeff = max(0., (min(xtmav, Tmmax) - Tmbase))

*     Actual production and growth of biomass and lai only starts after emergence
        if (xDay >= DayEmObs) then

*     Temperature sum after emergence
        Tsm = tmsum - tsmem
*------------------------------------------------------------------------------------------------------------------------
* -1- Change in leaf area index (m/m)                                                                                         *
* -----------------------------------------------------------------------------------------------------------------------

*     Lai development is simulated via three phases: increasing, constant and decreasing lai.
```

```
*     Adapted for LINPACsa with a more flexible LAI development during three phases
        if (croper .ne. 3) then
          if (Tmeff .gt. 0.) then
             if ((Tsm .le. Tsm1) .and. (Lai .le. Laimx)) then
               Tsumold = 0.
                 if (Lai.gt.Laiem)
*     Calculation of previously accumulated temperature sum as function of actual lai ('inverse' of expolinear equation)
     &           Tsumold = tb + log(exp(Lai*rm/cm) - 1.)/rm
                 newTsum = Tsumold + Tmeff
*     Calculation of new lai as function of new tsum (expolinear equation)
                 newLai  = (cm/rm) * log(1. + exp(rm*(newTsum - tb)))
                 if (newLai .gt. Laimx) newLai = Laimx
*     Potential increase as function of difference between actual and new lai
                   cLai = newLai - Lai
*     Effect of soil (toxic) conditions
                 cLai = cLai * xLueToxRed
                 end if
             end if
*       Calculation of lai decrease during the 3rd phase (thus lai stays constant between tsm0 or tsm1 and tsm2)
             if (Tsm .gt. Tsm2) then
              cLai = -Lai2 * min(1., fLai3) * (Tmeff / (Tsm3-Tsm2))
             if ((Tsm+Tmeff) .gt. Tsm3)
     &            cLai = -max(0., ((Lai - Lai2* max(0., 1. - fLai3))))
             if (-cLai .gt. Lai)  cLai = -Lai
           end if
        else
*     For crops with indeterminate leaf growth (i.e. not stopped at flowering), e.g. potato (croper=3):
*     Assumptions:
*    1. leaf growth can go on till Tsm3
*    2. After Tsm0, leaf growth is gradually reduced, in fraction of possible growth
*    3. fraction of possible growth is related to the relative difference in actual tsum vs Tsm3
          if (Tmeff .gt. 0.) then
               Tsumold = 0.
                 if (Lai.gt.Laiem)
*     Calculation of previously accumulated temperature sum as function of actual lai ('inverse' of expolinear equation)
     &           Tsumold = tb + log(exp(Lai*rm/cm) - 1.)/rm
                  newTsum = Tsumold + Tmeff
*     Calculation of new lai as function of new tsum (expolinear equation)
                  newLai  = (cm/rm) * log(1. + exp(rm*(newTsum - tb)))
*     Potential increase as function of difference between actual and new lai
                 cLai = newLai - Lai
*     Effect of soil (toxic) conditions
                 cLai = cLai * xLueToxRed
                 if ((Tsm .gt. Tsm0)) then
```

```
*     Reduction of leaf area growth after Tsm0
                cLai = cLai * max(0., min(1., (Tsm3 - Tsm) /
     &                            max(1.e-6, (Tsm3 - Tsm0))))
                 end if
*     Calculation of lai decrease during the 3rd phase
                if (Tsm .gt. Tsm2) then
                   cLai = cLai - Lai2 * min(1., fLai3) * (Tsm - Tsm2) /
     &           (Tsm3-Tsm2)
                if ((Tsm+Tmeff) .gt. Tsm3)
     &              cLai = -max(0., ((Lai - Lai2* max(0., 1. - fLai3))))
                if (-cLai .gt. Lai)  cLai = -Lai
                 end if
          end if
        end if
*------------------------------------------------------------------------------------------------------------------------
* -2- Fraction intercepted radiation (50% PAR/RDD and 5% reflection assumed)                                            *
*------------------------------------------------------------------------------------------------------------------------

         Par = 0.5 * (xRdd/1.E6)
        Fint = (1. - 0.05)*(1. - exp(-Kpar * Lai))
*------------------------------------------------------------------------------------------------------------------------
* -3- Plant biomass production (kg dry matter per ha, per day)                                                          *
*------------------------------------------------------------------------------------------------------------------------

*     Reduction factor for light use efficiency based on development if Tsm > Tsm2 with minimum value of fLue3
        fLue = 1.
         if (Tsm .gt. Tsm2) then
           fLue = 1. + (Tsm-Tsm2) * ((fLue3-1.) / (Tsm3-Tsm2))
        if (fLue .lt. fLue3) fLue = fLue3
         end if

*     Overall reduction factor for lue based on temperature, development and a soil factor
        if (croper .ne. 3) then
          LueRed = Lint2 ('LueRedTb',LueRedTb,LueRedTbCnt,xTmav) * fLue
     &                   * xLueToxRed
*     Adapted temperature effect on LUE for LINPACsa, for potato average daytime temperature is used (xTmavd)
        else if (croper .ge. 3) then
          LueRed = Lint2 ('LueRedTb',LueRedTb,LueRedTbCnt,xTmavd) * fLue
     &                   * xLueToxRed
        end if

*     Possible reduction on LUE based on PAR intensity(based on Q.Jing, dec. 2008)
        if (Parthr .gt. 0.) then
           Luered = Luered * (Parthr / (Parthr + Par))
```

```
            end if

*     Total plant production and PAR interception (multiplied by 10 because of conversion from g/m2 to kg/ha)
        cBiom = LueRed * Lue * Fint * Par * 10.
        Parint = Fint * Par
*---------------------------------------------------------------------------------------------------------------------
* -4- Yield formation (kg dry matter per ha, per day)                                                                 *
*---------------------------------------------------------------------------------------------------------------------

*     If harvest index <0 dynamic calculation of yield is performed, if HvI > 0 yield is calculated in rates section.
        if (HvI .lt. 0.) then
*     Assumed that after tsm1 100% of production is allocated to reproductive organs (no increase vegetative biomass).
*     Of these reproductive organs a fraction (seedaf) is allocated to the seeds (e.g. grains). A fraction (Trloc) of
*     vegetative biomass (Biom1, accumulated before tsm 1) is translocated to the reproductive organs in the period
*     after tsm1
          if (Tsm .gt. Tsm1) then
            if (Croper .ne. 3) then
               BiomTrl = Trloc * Biom1 * (Tmeff / (Tsm3-Tsm1))
               cYield   = (cBiom + BiomTrl) * seedaf
            else
*     Adapted for LINPACsa, moment of initiation of tubers is made dependent on temperature and daylength.
               DVRTI = CalcSoIni(xTmAv, xDL, SOIniA, SoIniBT, SoIniBDL)

*     Adapted for LINPACsa, the translocation of assimilates from translocatable pool Biom1 and the distribution from
*     newly formed biomass from Tsm1 onward are governed by fraction Allocnew. This is fraction is dependent on
*     temperature and daylength.
                     alphaAlloc = CalcTrLoc (xTmAv, xDL, AllocMn, AllocMx,
     &                    AllocA, AllocBT, AllocBDL)
               AllocNew = max(0., min(1., 1. - exp(max(-25., min(25.,
     &                   -alphaAlloc * (Tsm - Tsm1))))))
               cBiomTrl = Biom1 * AllocNew
               cYield = (cBiom * AllocNew + cBiomTrl) * seedaf
               cbiom1 = (1. - AllocNew) * cBiom * TrLoc - cBiomTrl
             end if
          elseif (Croper .ge. 3) then
            cBiom1 = cBiom * Trloc
             end if
        end if
*---------------------------------------------------------------------------------------------------------------------
* -5- Rooting depth development                                                                                       *
*---------------------------------------------------------------------------------------------------------------------

*     Roots grow as a function of effective temperature until either a certain temperature sum is reached or maximal
*     rooting depth is reached
```

```
          if (Tsm .le. Tsmrd) then
            cRtd = (Tmeff / Tsmrd) * Rdepth
             if (cRtd .gt. (Rdepth-Rtd)) cRtd = Rdepth - Rtd
          end if
*-------------------------------------------------------------------------------------------------------------------
* -6- Effects of water on cLai, cBiom and cYield                                                                    *
*-------------------------------------------------------------------------------------------------------------------

*     First calculation of potential transpiration (= demand) with two options:
*     a) constant transpiration coefficient (TrCoef > 0) or
*     b) transpiration directly calculated as function of weather characteristics, lai and crop factor
          if (TrCoef .gt. 0.) then
            TrPot = cBiom * TrCoef / 10000.
          end if

*     Calculation of actual transpiration by comparing demand with soil water availability.
*     -xtotalwc = maximum available water for transpiration and evaporation from ad to fc (in mm per m)
*     -xavailwc = maximum available water for transpiration from wp to fc (in mm per m)
*     -wsoilwp = maximum amount of water between ad and wp in rootable/rooted layer (mm)
*     -wsoilfc = maximum amount of water between ad and fc in rootabel/rooted layer(mm)
*     -wsoilav = actual amount of water above ad in rooted layer (mm)
*     -wsoiltr = actual amount of water above wp in rooted layer, thus available for transpiration (mm)
*     -wsoilcr = critical amount of water above wp in rooted layer above which TrAct = TrPot
          Wsoilwp = rtd * (xtotalwatcont - xavailwatcont)
          Wsoilfc = rtd * xtotalwatcont
           Wsoilav = Wsoil1 * min(rtd,tktop)/tktop
          Wsoiltr = max (0., (min(Wsoilav,Wsoilfc) - Wsoilwp))

          pval    = TrCrt / (TrCrt + TrPot)
          Wsoilcr = (Wsoilfc - Wsoilwp) * (1. - pval)

*     Preventing that TrAct > wsoiltr+wdeficit when il = 1 (potential production situation)
           if (Wsoilcr .lt. 0.1*(Wsoilfc - Wsoilwp))
     &      Wsoilcr = 0.1*(Wsoilfc - Wsoilwp)
           if (Wsoilcr .lt. TrPot) Wsoilcr = 1.001*TrPot

*     Wdeficit is calculated only for the potential production situation to determine the irrigation demand needed to
*     enable a production situation without water stress (Tract = TrPot). Actual transpiration for the water limited
*     situation  is calculated as ratio of plant available water over critical water amount.
          if (ilev .eq. 1) then
            TrAct = TrPot
            if (TrPot .gt. 0.) Wdeficit = max (0., (Wsoilcr - Wsoiltr))
          else if (ilev .eq. 2 ) then
            Tract = min(1., (Wsoiltr / Wsoilcr)) * TrPot
```

```
        else
          call fatalerr('soilcrop', 'wrong prod. level')
        end if

*       Finally, effects of water stress on rates of change via ratio actual and potential transpiration
        TrRat = 1.
        if (TrPot .gt. 0.) TrRat = Tract / Trpot

        if (cLai .gt. 0.) cLai = cLai * TrRat
        if (Trrat .lt. 0.7) then
          dLai = dLmax * Lai * ((-TrRat / 0.7) + 1.)
           if ((Lai + cLai - dLai) .lt. 0.) dLai = Lai + cLai
         end if
         cBiom  = cBiom  * min(sinkcap,TrRat)
        cYield = cYield * min(sinkcap,TrRat)

        end if ! crop production phase
       end if ! nocrop
*-----------------------------------------------------------------------------------------------------------------------
* -7- Soil water changes (infiltration, evaporation and drainage) and calculation of runoff                            *
*
*-----------------------------------------------------------------------------------------------------------------------

*       Runoff calculated for rain and irrigation
        Irrig  = 0.
         RunofI = 0.

         if (xAvailWatCont .gt. 0.) then
          RunofR = frunoff (xTextureClass,xSlopeClass,(xRain-Rintc))

*     Gross irrigation is not known, but Wdeficit based on necessary increase in soil water for potential production
*     has been determined above. Below possible loss of irrigation water is determined by calculating runoff
*     of irrigation water. As the gross irrigation application is unknown, an iteration loop (3 times) is used to
*     estimate the gross irrigation.
          if (Wdeficit .gt. 0.) then
             do ix = 1, 3
               Irrig = Wdeficit + RunofI
              RunofI = frunoff (xTextureClass,xSlopeClass,Irrig)
             end do
             Irrig = Wdeficit + RunofI
           end if
         else
*     Situation without water storage
           RunofR = xRain-Rintc
```

```
         end if
*     The irrigation application calculated here should have been applied one day earlier to bring the soil water of this day
*     at the adequate level of wsoilcr and thus to prevent water stress in the calculations of today.
*     For reasons of simplicitly in the sequence of model calculations, it comes now one day later.

*     Total runoff and infiltration (based on net inflows), turned off for LINPACsa potato because of ridges and
*     predomimant flatland cultivation
        if (croper .ne. 3) then
         Runoff = RunofR + RunofI
        else if (croper .ge. 3) then
        Runoff = 0
         end if

         Infil  = xRain + Irrig - Wintc - Runoff

*     Calculation of actual evaporation from top soil layer, based on potential evaporation. 'days since last rain'
*     (dslr) method is not used here. Eact is determined as a  function of Epot and wetness of the top soil layer.
        if ((infil .gt. Epot)) then
            dslr = 0.
           Eact = Epot
         else
           dslr = dslr + 1.
           Eact = 0.6 * Epot * (sqrt(dslr+1.) - sqrt(dslr)) + Infil
           if ((tkl1*xtotalwatcont) .gt. 0.) then
           Eact = Epot * min(1., (wsoil1 / (0.85*tkl1*xtotalwatcont))**2)
            else
           Eact = 0.
            endif
         end if

*     Check on calculated value and prevent wsoil1 becoming negative (but in a very small sense: -1 E-4)
        Emax = 0.999*(wsoil1 + Infil - TrAct)
        Eact = min(Eact, Emax, Epot)
        ETa  = Eact + TrAct

*     Drainage at the bottom of the soil compartment 1 (0 - 20 cm or rtd, if rtd > 20 cm)
        Drain1  = max((Wsoil1+Infil-ETa)-(tkl1*xtotalWatCont),0.)
         cWsoil1 = Infil - ETa - Drain1

*     Drainage at the bottom of the soil compartment 2 (20 cm or rtd - root depth)
        Drain = max((Wsoil2+Drain1)-(tkl2*xtotalWatCont),0.)
         cWsoil2 = Drain1 - Drain

*     Special case: texture = 0 => water (lake, river, swamp). Not applicable for LINPACsa
```

```
          if (xtextureclass .eq. 0) then
             Eact    = Epot
            Runoff  = xRain - Eact              ! negative runoff = runon
             cWsoil1 = 0.
             cWsoil2 = 0.
             Drain   = 0.
           end if
**********************************************************************************************************************
*------OUTPUT SECTION------------------------------------------------------------------------------------------------*
**********************************************************************************************************************

*     Added for LINPACsa, putting variables on the blackboard for calibration
        call putsrt (xModule, 'Tsm',      Tsm)
        call putsrt (xModule, 'Biomtrl',  Biomtrl)
        call putsrt (xModule, 'Parcu',    Parcu)
        call putsrt (xModule, 'Wdeficit', Wdeficit)
        call putsrt (xModule, 'Parint',   Parint)
        call putsrt (xModule, 'Lai',      Lai)
        call putsrt (xModule, 'Biom',     Biom)
        call putsrt (xModule, 'Yield',    Yield)
*     For LINPACsa potato, calculation of fresh yield based on dry matter yield
        if (yield .gt. 0) then
          FrDMYield = alphaYield * log(Yield) + betaYield
          FrYield = yield / FrDMYield
        end if
         call putsrt (xModule, 'FrYield', FrYield)
        call putsrt (xModule, 'FrDMYield', FrDMYield)
        call putsrt (xModule, 'Tracum',   Tracu)
        call putsrt (xModule, 'Irricu',   Irricu)
        call putsrt (xModule, 'Trratio',  Trrat)
        call putsrt (xModule, 'DayEmObs' , 1.* DayEmObs)


      else if (xNewTask == 'output') then
*
        call outdat (2, 0, 'Year',     1.* year)
        call outdat (2, 0, 'Day',      1.* xday)
*     Putting output Rdd in Kj/m2/d for readabillity
        call outdat (2, 0, 'Rdd',      xrdd/1000)
        call outdat (2, 0, 'Tmav',     xTmav)
        call outdat (2, 0, 'Vap',      xvap)
        call outdat (2, 0, 'Wind',     xwnd)
        call outdat (2, 0, 'Rain',     xrain)
        call outdat (2, 0, 'Irrig',    1.* irrig)
```

```
         call outdat (2, 0, 'Latitude', xLatitude)
         call outdat (2, 0, 'Cropnr',   1.* xcropseq)
         call outdat (2, 0, 'Ilevel',   1.* ilev)
         call outdat (2, 0, 'Lai',      lai)
         call outdat (2, 0, 'Rtd',      rtd)
         call outdat (2, 0, 'Sdepth',   Sdepth)
         call outdat (2, 0, 'Parcu',    Parcu)
         call outdat (2, 0, 'Biom',     Biom)
         call outdat (2, 0, 'Biom1',    Biom1)
         call outdat (2, 0, 'Yield',    yield)
         call outdat (2, 0, 'FrYield',   FrYield)
          call outdat (2, 0, 'FrDMYield', FrDMYield)
          call outdat (2, 0, 'alphaYield', alphaYield)
         call outdat (2, 0, 'Wsoil',    wsoil)
         call outdat (2, 0, 'Evapcu',   evapcu)
         call outdat (2, 0, 'Tracum',   tracu)
         call outdat (2, 0, 'Irricu',   irricu)
         call outdat (2, 0, 'Draincu',  draincu)
         call outdat (2, 0, 'Rnoffcu',  rnoffcu)
         call outdat (2, 0, 'Drain',    drain)
         call outdat (2, 0, 'Runoff',   runoff)
         call outdat (2, 0, 'ETref',    xETr)
         call outdat (2, 0, 'totalwatcont', xtotalwatcont)
          call outdat (2, 0, 'availwatcont', xavailwatcont)
         call outdat (2, 0, 'Epot',     Epot)
         call outdat (2, 0, 'Trpot',    Trpot)
         call outdat (2, 0, 'Eact',     Eact)
         call outdat (2, 0, 'Tract',    Tract)
         call outdat (2, 0, 'Trratio',  Trrat)
         call outdat (2, 0, 'LueToxRed',1.* xLueToxRed)
         call outdat (2, 0, 'Biomtrl',  Biomtrl)
         call outdat (2, 0, 'Tsm',      Tsm)
         call outdat (2, 0, 'Allocnew', Allocnew)
          call outdat (2, 0, 'DVSTI',    DVSTI)
          call outdat (2, 0, 'xDL',      xDL)
************************************************************************************************************************
*------STATES SECTION--------------------------------------------------------------------------------------------------*
************************************************************************************************************************

      else if (xNewTask == 'do_states') then
*     In this section a time step of 1 (day) has been assumed implicitly!

*     Soil water state variables:
*     Wsoil1 is the amount of water in the soil top layer above air dry
```

```
*     Wsoil2 is the amount of water in the soil bottom layer above air dry
         Wsoil1  = Wsoil1 + cWsoil1
         Wsoil2  = Wsoil2 + cWsoil2
         Wsoil   = Wsoil1 + Wsoil2
        Wsoilcu = Wsoil - (WsoilStart(1) + WsoilStart(2) - Wsoilcor)

*     Check values
        if (wsoil1 .lt. 0.0) then
          if (wsoil1 .gt. -1.e-3) then
           wsoil1 = 0.
          else
            call fatalerr ('Cropro','soil water negative')
          end if
        end if

         if (wsoil2 .lt. 0.0) then
          if (wsoil2 .gt. -1.e-3) then
           wsoil2 = 0.
          else
            call fatalerr ('Cropro','soil water negative')
          end if
        end if

*     Cumulative soil water flows
        Evapcu   = Evapcu + Eact
        Draincu  = Draincu + Drain
        Rnoffcu  = Rnoffcu + Runoff
        Raincu   = Raincu  + xRain

       if (.not. nocrop) then
*     Plant state variables
           Tmsum = Tmsum + Tmeff
           Lai   = Lai + cLai - dLai
           Rtd   = Rtd + cRtd
           Biom  = Biom + cBiom
           Yield = Yield + cYield
*     Added for potato in LINPACsa the development stage until tuber initiation
            if (croper .eq. 3) then
               DVSTI = DVSTI + DVRTI
               if ((DVSTI >= 0.999999) .and. (Tsm1 > 0.5e6)) then
                   Tsm1 = Tsm
               end if
            end if
```

```
*     Calculation of yield in case a positive harvest index is given in the input file
          if (HvI .ge. 0.) then
            Yield = HvI * Biom * (1. - Rootr)
           end if

*     Cumulative plant interception, transpiration and irrigation
          Parcu    = Parcu + Parint
          Tracu    = Tracu + Tract + Wintc
          Eactcu   = Eactcu + Eact
           Irricu   = Irricu  + Irrig
          Precipcu = Precipcu + xRain

*     Extra effect of water shortage on seed set around flowering (between (1-flper)*Tsm1 and (1+flper)*Tsm1)
           Tacum = Tacum + Tract
           Tpcum = Tpcum + Trpot

          sinkcap = 1.
           if (Croper .ne. 3) then
            if (flper .gt. 0.) then
               if ((Tmsum-tsmem) .le. ((1. - flper)*Tsm1)) then
                 Tac1 = Tacum
                 Tpc1 = Tpcum
               end if
               if ((Tmsum-tsmem) .le. ((1. + flper)*Tsm1)) then
                 Tac2 = Tacum
                 Tpc2 = Tpcum
               else
                  if (tpc2 .gt. tpc1) then
*     Cumulative transpiration ratio
                     sinkcap = (tac2 - tac1) / (tpc2 - tpc1)  !
                    else
                     sinkcap = tac2 / tpc2
                    end if
*     Threshold of 0.8 for reduction
                   sinkcap = min(1., (sinkcap/0.8))
               end if
             end if
           end if

*     State calculations for lai and biom just before Tmsum-Tsmem exceeds Tsm1 resp. Tsm2
*     Adapted for potato in LINPACsa Biom1 is a reallocatable pool and can grow also after Tsm1 has been reached
          if (Croper .ne. 3) then
              if ((Tmsum-tsmem) .le. Tsm1) then
                Biom1 = Biom
```

```
            end if
         else
           Biom1 = Biom1 + cBiom1
         end if
        if ((Tmsum-tsmem) .le. Tsm2) then
          Lai2   = Lai
         end if

*     Inititalization at emergence, DayEmObs comes from TIPS_Z and is thus an adaptation for LINPACsa
        if ((xDay >= DayEmObs) .and. (NoEmerg))
     &      then
           Lai = Laiem
*     Setting tsmem as tsum at emergence (and not using fixed parameter setting)
              tsmem = tmsum
           Rtd = max(Rtdem, min(1.,((Tmsum-Tsmem)/Tsmrd))*Rdepth)
           NoEmerg = .false.
        end if

*     Determination of layer thicknesses of the two soil layers depending on rtd
        tkl_old = tkl1
        tkl1    = max(rtd, tktop)
        tkl2    = sdepth - tkl1

*     In case roots grow deeper (beyond 20 cm), soil layer 1 increases at the expense of soil layer 2
*     An amount of water (wtransf) is reassigned from layer 2 towards layer 1
        wtransf = 0.
         tkl_dif = 0.
         if (rtd .gt. tktop) tkl_dif = tkl1 - tkl_old
        if (tkl_dif .gt. 0.) then
          wtransf = (tkl_dif / (sdepth - tkl_old)) * wsoil2
           wsoil1 = wsoil1 + wtransf
           wsoil2 = wsoil2 - wtransf
         end if

*     Check values again
        if (wsoil1 .lt. 0.0) then
           if (wsoil1 .gt. -1.e-3) then
             wsoil1 = 0.
           else
             call fatalerr ('Cropro','soil water negative')
           end if
         end if
        if (wsoil2 .lt. 0.0) then
           if (wsoil2 .gt. -1.e-3) then
```

```
              wsoil2 = 0.
            else
              call fatalerr ('Cropro','soil water negative')
            end if
          end if

*     Check values
          if (Lai .lt. 0.0) then
            call fatalerr ('Cropro','leaf area negative')
          end if
        end if

*     Calculate crop height for determining Trpot (in m), not being used.
          CHght = Lai * (CHghtmx / Laimx)

*     Check on water balance
        cwsoil = cwsoil1 + cwsoil2
        dev = cwsoil - (xrain + irrig
     &                - runoff - eact - tract - wintc - drain)

        if (cwsoil .gt. 0.1) then
          chk1 = dev / cwsoil
        else
          chk1 = dev
        end if
        if (abs(chk1) .gt. 1.e-3) then
          pause
        end if
      end if
      return
      end

************************************************************************************************************************
*--------FUNCTIONS-----------------------------------------------------------------------------------------------------*
************************************************************************************************************************

*-----------------------------------------------------------------------------------------------------------------------
* --  Function CalcTrloc calculating the slope of the allocation formula for tuber growth                               *
*
*-----------------------------------------------------------------------------------------------------------------------

*     Function to calculate the slope of the allocation formula for tuber growth, based on day length and temperature
      real function CalcTrLoc(xTmAv, xDL, AllocMn, AllocMx,
     &                      AllocA, AllocBT, AllocBDL)
```

```
      real xtemp
       xtemp = min(25., max(-25., AllocA * (xTmAv - AllocBT) *
     &              (xDL + AllocBDL)))

      CalcTrLoc = min (AllocMx, AllocMn + (AllocMx-AllocMn) /
     &              (1. + exp(xtemp)))
      return
       end

*----------------------------------------------------------------------------------------------------------------------
* --  Function CalcSOIni calculating the rate to tuber initiation                                                     *
*
*----------------------------------------------------------------------------------------------------------------------

       real function CalcSoIni(xTmAv, xDL, SOIniA, SoIniBT, SoIniBDL)
      CalcSoIni = xtMav * (1. + SoIniBT * xTmAv) *
     &                   (1. + SoIniBDL * xDL) / SoIniA
       return
       end

*----------------------------------------------------------------------------------------------------------------------
* --  Function CalcDayL to calculate day length                                                                       *
*
*----------------------------------------------------------------------------------------------------------------------

*     Function to calculate day length
      real function CalcDayL (IDOY, LAT)

      IMPLICIT NONE

*     Formal parameters
      INTEGER IDOY
      REAL LAT
*     Local parameters
      REAL SOLCON, DAYL, DSINB, SINLD, COSLD, AOB
      REAL PI, DEGTRAD, DOY, DEC, ZZCOS, ZZA
      SAVE

*     PI and conversion factor from degrees to radians
      PARAMETER (PI=3.1415927, DEGTRAD=0.017453292)

*     Error check and conversion of day number
      IF (ABS (LAT).GT.90.) CALL FATALERR
```

```
     &   ('CalcDayl','LAT > 90 or LAT < -90')
      DOY = REAL (IDOY)

*     Declination of the sun as a function of daynumber,
*     calculation of daylength from intermediate variables
*     SINLD, COSLD and AOB

      DEC   = -ASIN (SIN (23.45*DEGTRAD)*COS (2.*PI*(DOY+10.)/365.))
      SINLD = SIN (DEGTRAD*LAT)*SIN (DEC)
      COSLD = COS (DEGTRAD*LAT)*COS (DEC)
      AOB   = SINLD/COSLD

      IF (AOB.LT.-1.) THEN
c         WRITE (*,'(2A)') ' WARNING from SASTRO: ',
c     &          'latitude above polar circle, daylength=0 hours'
         CalcDAYL  = 0.
      ELSE IF (AOB.GT.1.) THEN
         CalcDAYL  = 24.
      ELSE
         CalcDAYL  = 12.*(1.+2.*ASIN (AOB)/PI)
      END IF


      RETURN
      END
```

Appendix 5 LUE reduction by sub- and supraoptimal temperatures

After calibration of LAI for Bintje and Eersteling in calibration stage 1, whole plant biomass calibrated in calibration stage 2 was lagging behind observed values for Bintje and Eersteling in the Droevendaal experiment (the only experiment with whole plant biomass observations). As LAI was already fitted by calibration, other parameters that influence biomass production should be adjusted to get a better fit. A reducing effect on LUE caused by temperature might be causig (part of) the discrepancy between observed and calculated plant biomass.

Sub and supra optimal temperatures cause a reduction of LUE, this effect is already included in LINPACsa. Light use efficiency is dependent on photosynthesis, respiration and efficiency of dry matter production. For these processes there are optimal temperatures and therefore reduction at sub or supraoptimal temperatures is feasible. However, the way temperatures and reduction of LUE are expressed in the model could be adapted to have more realistic (higher) whole plant biomass calculations compared to observed values.

In the model the average 24 hour temperature is calculated from the minimum and maximum temperature and if this is lower or higher than the optimum temperature range for LUE (between 18 and 24°C(Kooman & Haverkort, 1995)), a reduction factor for LUE is used. However, it might make more sense to distinguish between the effects of day and night temperature on the different processes that make up the LUE. For some crops it is assumed that for optimal dry matter growth the optimal night temperature (respiration) is lower than the day temperature (photosynthesis), this phenomena is called thermoperiodicity (Went, 1944). There has been much debate about the existence of thermoperiodicity in different crops (Markovskaya et al. 1996). For potato gross photosyntesis rates are optimal for temperatures between 24 and 30°C (Dwelle et al., 1981) while net photosynthesis (including maintenance respiration and dark respiration) has an optimal range of 16-20°C (Winkler, 1971). Because the latter temperature range is an average of the higher gross photosynthesis optimum and the lower optimum for respiration, the optimum range for respiration will ben lower than 16-20°C. With a low optimum for respiration and a high optimum for photosynthesis, temperatures will tend to be sub-optimal for photosynthesis rather than for respiration. This is especially applicable to temperate climates where temperatures tend to be too low rather than too high for photosynthesis. Therefore it can be argued that in this case for LUE reduction the optimum range for photosynthesis can be used as the limiting factor. As photosynthesis takes place during the day, using the day time temperature to determine whether LUE is temperature limited would make sense. A calculation for the average daytime temperature was found in the weather module of TIPS_Z (Jansen, 2002), (Eq. 1).

Equation.1 $$tmavd = tmmax - 0.25 * (tmmax - tmmin)$$

Using the optimum temperature range by Dwelle et al. (1981) and the *tmavd* (Eq 1), the number of optimal days in a weather file from the Droevendaal experiment was less than the number of optimal days using the temperature range from Kooman & Haverkort (1995) and the 24 average temperature. This might indicate that using the average daytime temperatures underestimates the reduction of LUE when combining them with the temperature range from Kooman & Haverkort (1995). This contradicts the theory explained above, however the optimum ranges mentioned in literature are large and there is a great deal of uncertainty in these ranges.

Nevertheless, for Bintje the overall fit was better compared to the model in which the temperature reduction effect on LUE was excluded. The values for whole plant biomass calculated with the model version using daytime average temperature for LUE were higher compared to the values calculated with the original model for both Bintje and Eersteling. The adapted temperature for the reduction effect of sub and supra optimal temperatures for LUE will be used in further calibration.

Appendix 6 Selection of treatments or experimental years for validation

A list of all field experiments and treatments selected for calibration and validation. In the column validation treatments excluded from calibration for sake of validation are mentioned.

Exp. location	Year	Treatments selected for calibration	Validation
Lovinkhoeve	1961	7=180N, 8=210N, 16=180N	
Lovinkhoeve	1962	6=200N, 7=240N, 8=280N, 14=200N, 15=240N, 16=280N, 23=200N 24=240N	
Lovinkhoeve	1963	6=200N, 7=240N, 8=280N, 14=200N, 15=240N, 16=280N, 22=200N, 23=240N, 24=280N, 30=200N, 31=240N, 32=280N	
Lovinkhoeve	1964	6=200N, 7=240N, 8=280N	
Lovinkhoeve	1965	6=200N, 7=240N, 8=280N, 15=200N, 16=240N, 23=180, 24=210N, 30=200N, 31=240N, 32=280N	
Lovinkhoeve	1966	6=200N, 7=240N, 8=280N, 14=200N, 15=240N, 16=280N, 22=200N, 23=240N, 4=280N, 30=200N, 31=240N, 32=280N	
Lovinkhoeve	1967	6=200N, 7=240N, 8=280N, 14=200N, 15=240N, 16=280N, 22=200N, 23=240N, 24=280N	
Lovinkhoeve	1969	6=200N, 7=240N, 8=280N, 15=180, 16=210N, 23=180, 24=210N, 31=180, 32=210N	All
Lovinkhoeve	1970	6=200N, 7=240N, 8=280N, 14=200N, 15=240N, 16=280N, 22=200N, 23=240N, 4=280N, 30=200N, 31=240N, 32=280N	
Lovinkhoeve	1971	6=200N, 7=240N, 8=280N, 14=200N, 15=240N, 16=280N, 22=200N, 23=240N, 4=280N, 30=200N, 31=240N, 32=280N	All
Lovinkhoeve	1973	6=200N, 7=240N, 8=280N, 15=180, 16=210N, 23=180, 24=210N, 31=180, 32=210N	
Lovinkhoeve	1974	6=200N, 7=240N, 8=280N, 15=200N, 16=240N, 23=200N, 24=240N, 31=200N, 32=240N	
Lovinkhoeve	1975	6=200N, 7=240N, 8=280N, 14=200N, 15=240N, 16=280N, 22=200N, 23=240N, 24=280N, 30=200N, 31=240N, 32=280N	
Lovinkhoeve	1977	5=180N, 6=220N, 7=260N, 8=300N, 14=180N, 15=210N, 16=240N, 22=180N, 23=210N, 24=240N, 30=180N, 31=210N, 32=240N	
Lovinkhoeve	1978	5=180N, 6=220N, 7=260N, 8=300N, 13=180N, 14=220N, 15=260N, 16=300N, 21=180N, 22=220N, 23=260N, 24=300N, 29=180N, 30=220N, 31=260N, 32=300N	
Lovinkhoeve	1982H	10=180N, 11=180N, 12=180N, 13=235N, 14=235N, 15=235N, 16=290N, 17=290N, 18=290N, 19=345N, 20=345N, 21=345N, 22=400N, 23=400N, 24=400N	
Lovinkhoeve	1982O	4=180N, 5=235N, 6=290N, 7=345N, 8=400N	
Lovinkhoeve	1983H	10=180N, 11=180N, 12=180N, 13=235N, 14=235N, 15=235N, 16=290N, 17=290N, 18=290N, 19=345N, 20=345N, 21=345N, 22=400N, 23=400N, 24=400N	
Lovinkhoeve	1983O	4=180N, 5=235N, 6=290N, 7=345N, 8=400N	
Lovinkhoeve	1985H	10=180N, 11=180N, 12=180N, 13=235N, 14=235N, 15=235N, 16=290N, 17=290N, 18=290N, 19=345N, 20=345N, 21=345N, 22=400N, 23=400N, 24=400N	
Lovinkhoeve	1985O	4=180N, 5=235N, 6=290N, 7=345N, 8=400N	
Lovinkhoeve	1986H	10=180N, 11=180N, 12=180N, 13=235N, 14=235N, 15=235N, 16=290N, 17=290N, 18=290N, 19=345N, 20=345N, 21=345N, 22=400N, 23=400N, 24=400N	
Lovinkhoeve	1986O	4=180N, 5=235N, 6=290N, 7=345N, 8=400N	
Lovinkhoeve	1987H	10=180N, 11=180N, 12=180N, 13=235N, 14=235N, 15=235N, 16=290N, 17=290N, 18=290N, 19=345N, 20=345N, 21=345N, 22=400N, 23=400N, 24=400N	
Lovinkhoeve	1987O	4=180N, 5=235N, 6=290N, 7=345N, 8=400N	
Lovinkhoeve	1989H	10=180N, 11=180N, 12=180N, 13=235N, 14=235N, 15=235N, 16=290N, 17=290N, 18=290N, 19=345N, 20=345N, 21=345N, 22=400N, 23=400N, 24=400N	
Lovinkhoeve	1989O	4=180N, 5=235N, 6=290N, 7=345N, 8=400N	
Lovinkhoeve	1990H	10=180N, 11=180N, 12=180N, 13=235N, 14=235N, 15=235N, 16=290N, 17=290N, 18=290N, 19=345N, 20=345N, 21=345N, 22=400N, 23=400N, 24=400N	
Lovinkhoeve	1990O	4=180N, 5=235N, 6=290N, 7=345N, 8=400N	
Droevendaal	1996	3=Bint200N, 6=Eerstel200N	
Droevendaal	1997	3=Bint200N, 4=Bint300N, 7=Eerstel200N, 8=Eerstel300N, 11=Bint100N+, 12=Bint100N+	
Droevendaal	1998	4=P1N4, 7= P2N1T1A3, 10= P2N1T2A3, 13=P2N2T1A3, 16=P2N2T2A3, 20=P3T1N4, 24=P3T2N4	
Droevendaal	1999	4=P1N4, 7=P2T1A3, 10=P2T2A3, 14=P3T1N4, 18=P3T2N4	
Droevendaal	2000	4=P1PO1N4, 8=P1PO2N4, 11=P2PO1T1N3, 14=P2PO1T2N3, 17=P2PO2T1N3, 20=P2PO2T2N3	
Aroostook	1986	6=Rusafg225N, 7=Rusafg270N	7
Aroostook	1987	6=Rusafg225N, 7=Rusafg270N, 13=Shepafg225N, 14=Shepafg270N, 20=Rusafc225N, 26=Shepafc225N	13
Aroostook	1988	6=Rusafg225N, 7=Rusafg270N, 13=Shepafg225N, 14=Shepafg270N, 20=Rusafc225N, 26=Shepafc225N	7
Aroostook	1989	5=Rusafg270N, 11=Shepafg225N, 17=Shepafc225N	5
Kollumerw.	2008	1,2,3	2

Kollumerw.	2009	1,2,3	1
Kollumerw.	2010	1,2,3	2
K Zeelim	2009	1,2,3	1
K Zeelim	2010	1,2,3	1
Simancas	2009	1,2,3	2
Simancas	2010	1,2,3	3

Appendix 7 Determining soil properties for Villa Dolores based on GLADA and SOTERLAC.

Soil types in Villa Dolores were identified based on the GLADA soil map (Dijkshoorn et al., 2008) (Fig. 1). Because of lack of data, the underlying soil parameters for the soil types were based on the database with soil parameter estimates belonging to the SOTERLAC soil map (Batjes, 2005; JA Dijkshoorn, Wageningen University, the Netherlands, pers. comm). The distribution of soil types in the GLADA and SOTERLAC maps do not match exactly, partly due to deviations in geo -referencing (JA Dijkshoorn, Wageningen University, the Netherlands, pers. comm) (Figs 1 and 2).

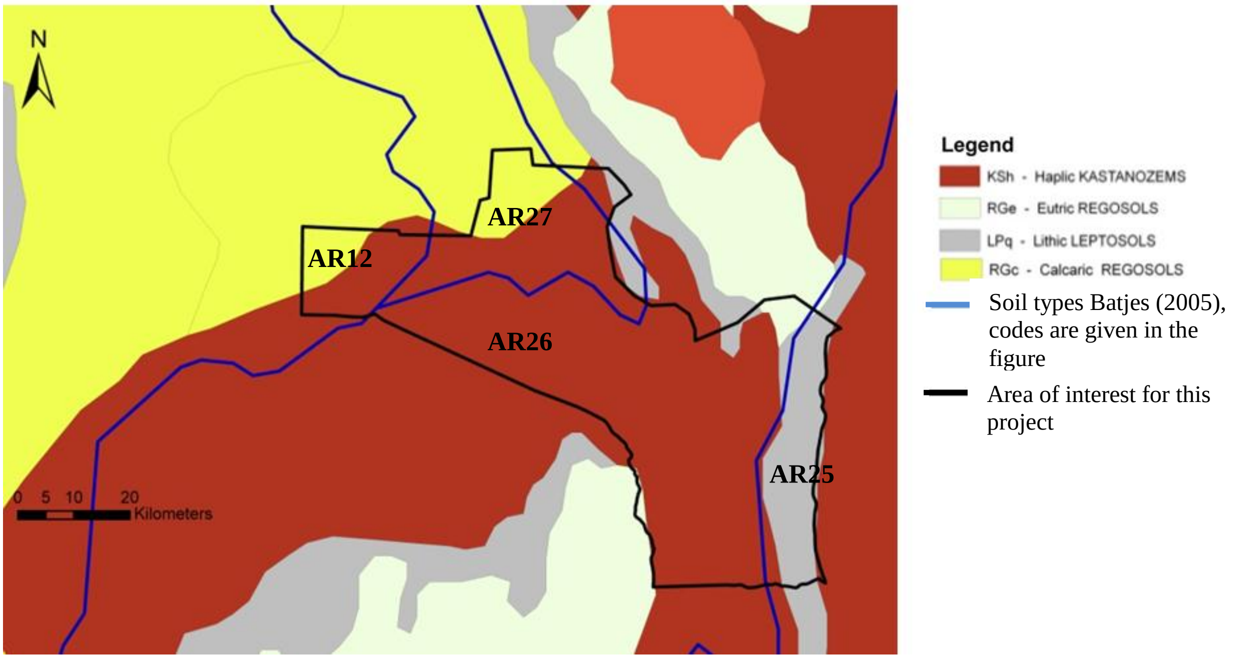


Fig. 1 Soil types as given in GLADA (Dijkshoorn et al., 2008) are displayed here in colour, the identification codes of the soil types from SOTERLAC (Batjes, 2005) are given in the map and delimited by blue lines.

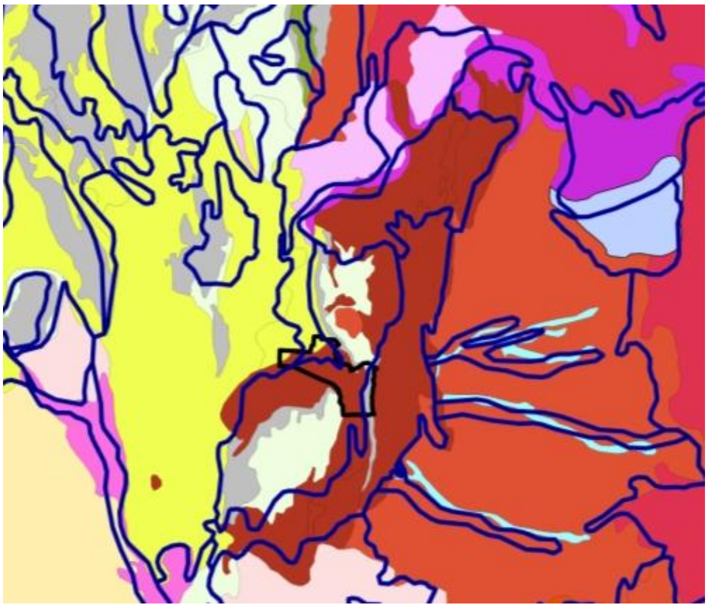


Fig. 2 Overview of the pattern of soil types as displayed in the GLADA map (Dijkshoorn et al., 2008), given in colours, and the SOTERLAC map (Batjes, 2005), delimited by blue lines.

In the SOTER methodology used for both soil maps, a soil type is attributed to a terrain component (the actual polygons displayed on the soil map) and displayed on the map based on the soil types of soil components within the terrain component. The soil type of a soil component is based on one soil profile, however the soil component is not made spatially explicit. For the abundance of soil components within a terrain component estimates are made, the soil type of the soil component that is estimated to be most abundant will be the soil type of the terrain component.

The terrain components in both maps were matched based on their shape, geographical position and soil components. In Table 1 the match between the codes for the terrain components of the two maps is displayed. Also the underlying soil types (belonging to soil components) are mentioned, the ones most abundant are in bold. One exception was made for the Lithic Leptosol. This is not the most abundant soil type in the SOTERLAC terrain component but will be treated as such. This was done because of the discrepancy between the area described by the corresponding GLADA and SOTERLAC terrain components. The Lithic Leptosol, though only found on a small area, typically belongs to the shallow rocky soil in the east of the area of interest.

Table 1 Terrain components of the SOTERLAC map linked to the terrain components of the GLADA map. Also the underlying soil components are given. In this project the soil types as mentioned in the GLADA map are used. The soil parameter estimates of the matching soil types of the SOTERLAC map are used for simulation. Per terrain component 1 main soil type is given in bold.

Terrain component GLADA	Soil types of soil components GLADA	Terrain component SOTERLAC	Soil types of soil components SOTERLAC
AR190 (Brown in fig. 1)	**60 % Haplic Kastanozem** 20% Eutric Cambisol 10% Haplic Arenosol 10% Haplic Solonetz	AR26	**50% Haplic Phaeozem** 30% Dystric Cambisol 20% Luvic Phaeozem
AR195 (Yellow in fig. 1)	**40% Calcaric Regosol** 40% Eutric Cambisol 20% Haplic Solonetz	AR12	**50% Calcaric Regosol** 30% Dystric Fluvisol 20% Dystric Regosol
AR194 (Grey in fig. 1)	**50% Lithic Leptosol** 30% Eutric Regosol 20% Eutric Cambisol	AR25	60% Eutric Regosol 20% Mollic Leptosol **20% Lithic Leptosol**

The estimated soil parameters belonging to all soil components from the SOTERLAC soil map were mostly given per 20cm up to a depth of 100cm (Batjes, 2005). However, for the scope of this project a homogenous rootable zone is assumed so the values were averaged (Table 2). For simulating with LINPACsa the texture (class) of the soil, the available water content (between permanent wilting point and field capacity), the soil depth and possible toxicity of the soil are important. Texture classes in LINPACsa were divided in fine (class 3; >35% clay) medium (class 2; <65% sand, <35% clay) and coarse (class 1; >65% sand, <18% clay) (JG Conijn, Plant Research International, the Netherlands, pers. comm). The rootable depth of each soil type was taken as the maximal depth of the class mentioned in the GLADA soil properties database. The slope class used in

LINPACsa was assumed to be 1 (<8% slope) in all cases because for steeper slopes runoff and erosion risk will have to be considered, this is beyond the scope of this report.

Table 2 The soil parameters according to the soil components of the SOTERLAC map. The soil texture and the available water content are based on the parameter estimates in the SOTERLAC database (Batjes, 2005). Texture class was derived from the texture distribution according to the classification needed for the LINPAC model (JG Conijn, Plant Research International, the Netherlands, pers. comm). Rooting depth is derived from the database of the GLADA map (Dijkshoorn et al., 2008).

Terrain component SOTERLAC	**Soil types of soil components SOTERLAC**	Sand %	Silt %	Clay %	Texture class	Rooting depth (m)	Available water content (mm/m)
AR26	**50% Haplic Phaeozem**	56	37	7	2	1.0	126.0
	30% Dystric Cambisol	33	54	13	2	0.5	130.0
	20% Luvic Phaeozem	50	44	6	2	0.5	110.0
AR12	**50% Calcaric Regosol**	91	5	4	1	1.0	88.0
	30% Dystric Fluvisol	5	54	41	3	0.25	102.6
	20% Dystric Regosol	86	11	3	1	0.5	114.0
AR25	60% Eutric Regosol	75	18	7	1	0.5	42.2
	20% Mollic Leptosol	65	35	0	1	0.5	160.0
	20% Lithic Leptosol	43	29	28	2	0.5	150.0

The area in the east of Villa Dolores is not used for potato (section 2.1). Therefore the soil types corresponding to the grey colour in Fig. 1 (Terrain component AR25 in SOTERLAC) were not used in simulations. For simulation, the assumption is made that rootable depth is 1 meter for all soil types, therefore the potato crop can always grow until maximum rootable depth.

Appendix 8 Statistics model fits calibration and validation

Table 1 95% confidence intervals for regression coefficients LAI observations and calculations Droevendaal experiment.

Gegevens voor de regressie	
Meervoudige correlatiecoëfficiënt R	0.967
R-kwadraat	0.934
Aangepaste kleinste kwadraat	0.933
Standaardfout	0.506
Waarnemingen	38

Variantie-analyse

	Vrijheidsgraden	*Kwadratensom*	*Gemiddelde kwadraten*	*F*	*Significantie F*
Regressie	1	131.419	131.419	512.669	0.000
Storing	36	9.228	0.256		
Totaal	37	140.647			

	Coëfficiënten	*Standaardfout*	*T- statistische gegevens*	*P-waarde*	*Laagste 95%*	*Hoogste 95%*
Snijpunt	0.369	0.132	2.794	0.008	0.101	0.636
Variabele X 1	0.868	0.038	22.642	0.000	0.790	0.946

Table 2 95% confidence intervals for regression coefficients whole plant biomass observations and calculations Droevendaal experiment.

Gegevens voor de regressie	
Meervoudige correlatiecoëfficiënt R	0.973
R-kwadraat	0.946
Aangepaste kleinste kwadraat	0.943
Standaardfout	1283.651
Waarnemingen	20

Variantie-analyse

	Vrijheidsgraden	*Kwadratensom*	*Gemiddelde kwadraten*	*F*	*Significantie F*
Regressie	1	520522306.799	520522306.799	315.897	0.000
Storing	18	29659693.018	1647760.723		
Totaal	19	550181999.817			

	Coëfficiënten	*Standaardfout*	*T- statistische gegevens*	*P-waarde*	*Laagste 95%*	*Hoogste 95%*
Snijpunt	-59.029	488.308	-0.121	0.905	-1084.926	966.867
Variabele X 1	0.936	0.053	17.773	0.000	0.825	1.047

Table 3 95% confidence intervals for regression coefficients fresh tuber yield observations and calculations Lovinkhoeve experiment.

Gegevens voor de regressie	
Meervoudige correlatiecoëfficiënt R	0.265
R-kwadraat	0.070
Aangepaste kleinste kwadraat	0.024
Standaardfout	4012.103
Waarnemingen	22

Variantie-analyse

	Vrijheidsgraden	*Kwadratensom*	*Gemiddelde kwadraten*	*F*	*Significantie F*
Regressie	1	24289340.611	24289340.611	1.509	0.234
Storing	20	321939399.714	16096969.986		
Totaal	21	346228740.325			

	Coëfficiënten	*Standaardfout*	*T- statistische gegevens*	*P-waarde*	*Laagste 95%*	*Hoogste 95%*
Snijpunt	46719.278	5949.764	7.852	0.000	34308.288	59130.267
Variabele X 1	0.143	0.116	1.228	0.234	-0.099	0.385

Table 4 95% confidence intervals for regression coefficients fresh tuber yield observations and calculations Droevendaal experiment.

Gegevens voor de regressie	
Meervoudige correlatiecoëfficiënt R	0.973
R-kwadraat	0.947
Aangepaste kleinste kwadraat	0.946
Standaardfout	5581.338
Waarnemingen	40

Variantie-analyse

	Vrijheidsgraden	*Kwadratensom*	*Gemiddelde kwadraten*	*F*	*Significantie F*
Regressie	1	21339629433.452	21339629433.452	685.031	0.000
Storing	38	1183750704.205	31151334.321		
Totaal	39	22523380137.657			

	Coëfficiënten	*Standaardfout*	*T- statistische gegevens*	*P-waarde*	*Laagste 95%*	*Hoogste 95%*
Snijpunt	353.236	1258.020	0.281	0.780	-2193.493	2899.964
Variabele X 1	0.889	0.034	26.173	0.000	0.820	0.957

Table 5 95% confidence intervals for regression coefficients fresh tuber yield observations and calculations Innovator experiments.

Gegevens voor de regressie	
Meervoudige correlatiecoëfficiënt R	0.812
R-kwadraat	0.659
Aangepaste kleinste kwadraat	0.591
Standaardfout	5784.434
Waarnemingen	7

Variantie-analyse

	Vrijheidsgraden	*Kwadratensom*	*Gemiddelde kwadraten*	*F*	*Significantie F*
Regressie	1	323424987.630	323424987.630	9.666	0.027
Storing	5	167298361.571	33459672.314		
Totaal	6	490723349.201			

	Coëfficiënten	*Standaardfout*	*T- statistische gegevens*	*P-waarde*	*Laagste 95%*	*Hoogste 95%*
Snijpunt	10650.771	10258.610	1.038	0.347	-15719.824	37021.367
Variabele X 1	0.676	0.217	3.109	0.027	0.117	1.235

Table 6 95% confidence intervals for regression coefficients fresh tuber yield observations and calculations Aroostook experiment.

Gegevens voor de regressive	
Meervoudige correlatiecoëfficiënt R	0.645
R-kwadraat	0.416
Aangepaste kleinste kwadraat	0.343
Standaardfout	4429.187
Waarnemingen	10

Variantie-analyse

	Vrijheidsgraden	*Kwadratensom*	*Gemiddelde kwadraten*	*F*	*Significantie F*
Regressie	1	111626325.606	111626325.606	5.690	0.044
Storing	8	156941614.651	19617701.831		
Totaal	9	268567940.257			

	Coëfficiënten	*Standaardfout*	*T- statistische gegevens*	*P-waarde*	*Laagste 95%*	*Hoogste 95%*
Snijpunt	11369.339	10913.350	1.042	0.328	-13796.891	36535.568
Variabele X 1	0.681	0.285	2.385	0.044	0.023	1.339

Table 7 95% confidence intervals for regression coefficients fresh tuber yield observations and calculations for validation of Innovator treatments experiment.

Gegevens voor de regressie	
Meervoudige correlatiecoëfficiënt R	0.872
R-kwadraat	0.761
Aangepaste kleinste kwadraat	0.713
Standaardfout	4849.290
Waarnemingen	7

Variantie-analyse

	Vrijheidsgraden	*Kwadratensom*	*Gemiddelde kwadraten*	*F*	*Significantie F*
Regressie	1	374673628.026	374673628.026	15.933	0.010
Storing	5	117578058.049	23515611.610		
Totaal	6	492251686.074			

	Coëfficiënten	*Standaardfout*	*T- statistische gegevens*	*P-waarde*	*Laagste 95%*	*Hoogste 95%*
Snijpunt	13740.463	7029.528	1.955	0.108	-4329.514	31810.440
Variabele X 1	0.609	0.153	3.992	0.010	0.217	1.002

Table 8 95% confidence intervals for regression coefficients fresh tuber yield observations and calculations for validation of treatments Aroostook experiment.

Gegevens voor de regressie	
Meervoudige correlatiecoëfficiënt R	0.452
R-kwadraat	0.205
Aangepaste kleinste kwadraat	-0.193
Standaardfout	7299.843
Waarnemingen	4

Variantie-analyse

	Vrijheidsgraden	*Kwadratensom*	*Gemiddelde kwadraten*	*F*	*Significantie F*
Regressie	1	27412228.935	27412228.935	0.514	0.548
Storing	2	106575421.670	53287710.835		
Totaal	3	133987650.606			

	Coëfficiënten	*Standaardfout*	*T- statistische gegevens*	*P-waarde*	*Laagste 95%*	*Hoogste 95%*
Snijpunt	16911.935	29269.807	0.578	0.622	-109025.880	142849.750
Variabele X 1	0.553	0.770	0.717	0.548	-2.762	3.867

Appendix 9 Model fits calibration and validation

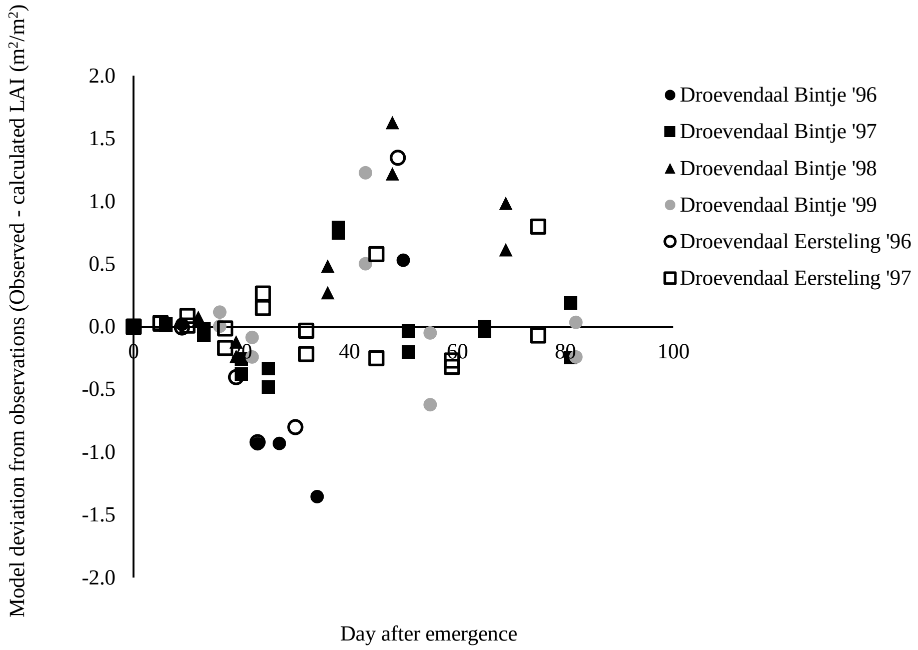


Fig. 1 Deviations of values calculated with the non- water limited model from observations (observed- calculated) for LAI in the Droevendaal experiment.

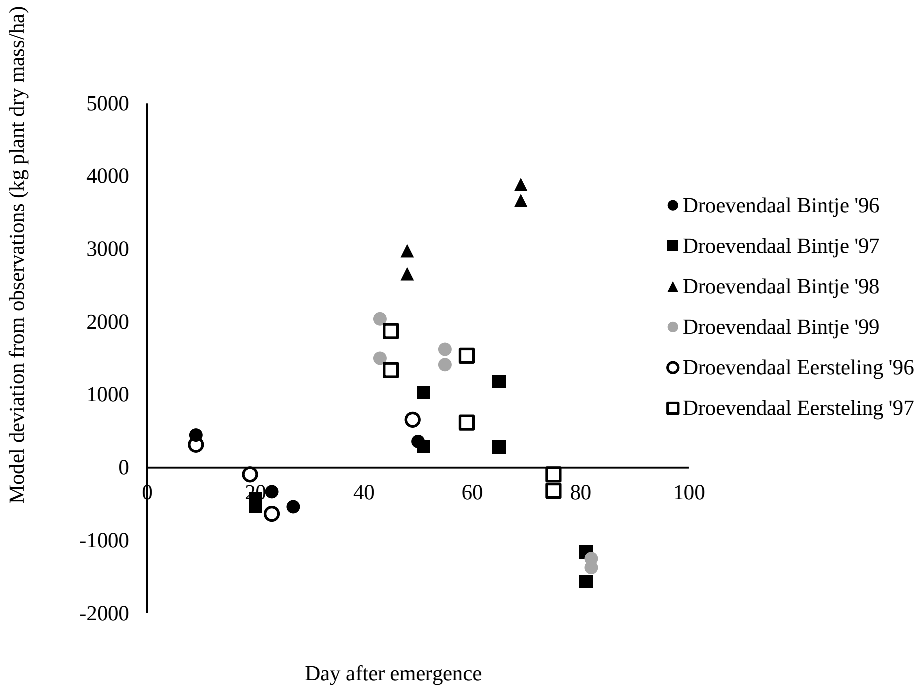


Fig. 2 Deviations of values calculated with the non- water limited model from observations (observed- calculated) for whole plant biomass in the Droevendaal experiment.

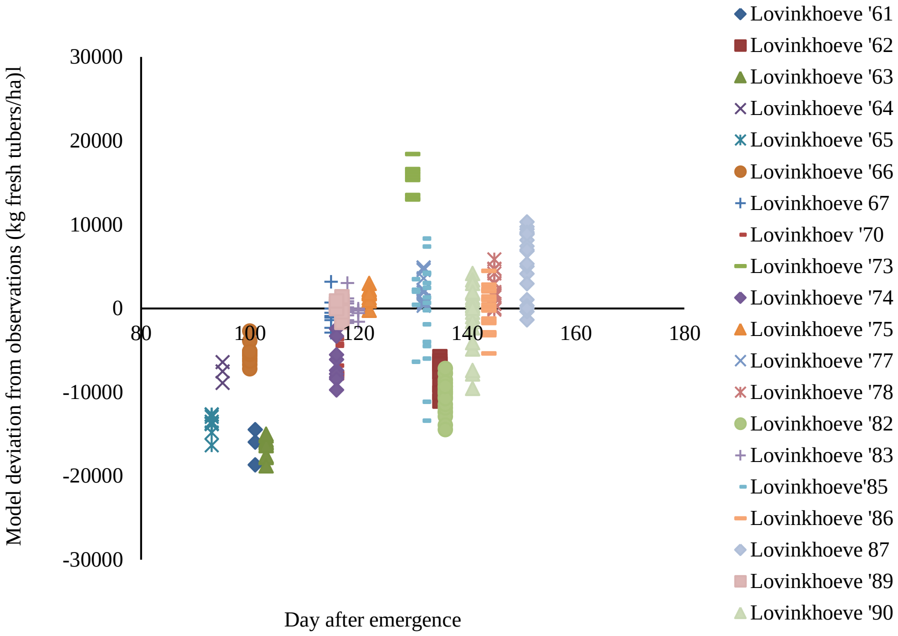


Fig. 3 Deviations of values calculated with the rain fed limited model from observations (observed- calculated) for fresh tuber yield in the Lovinkhoeve experiment.

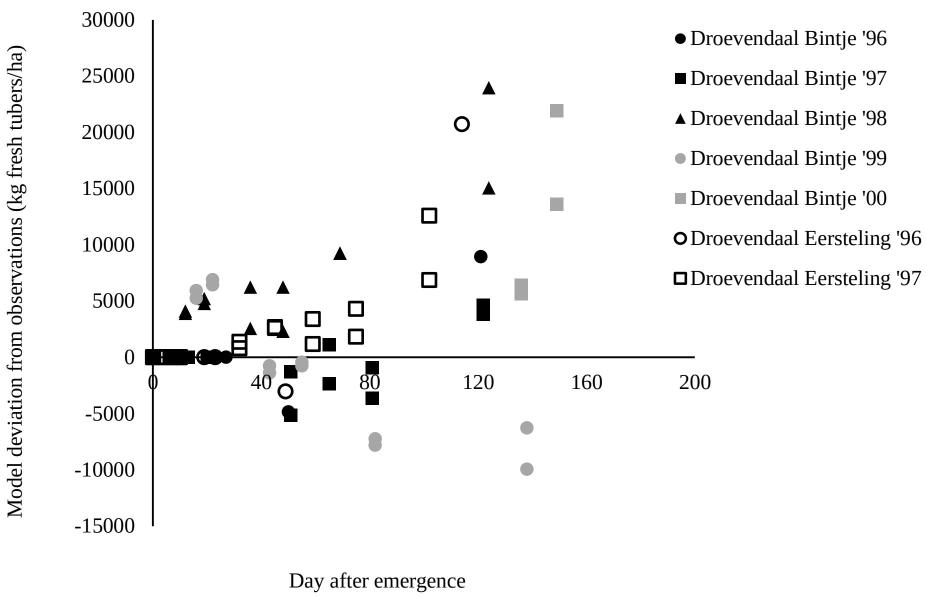


Fig. 4 Deviations of values calculated with the non- water limited model from observations (observed- calculated) for fresh tuber yield in the Droevendaal experiment.

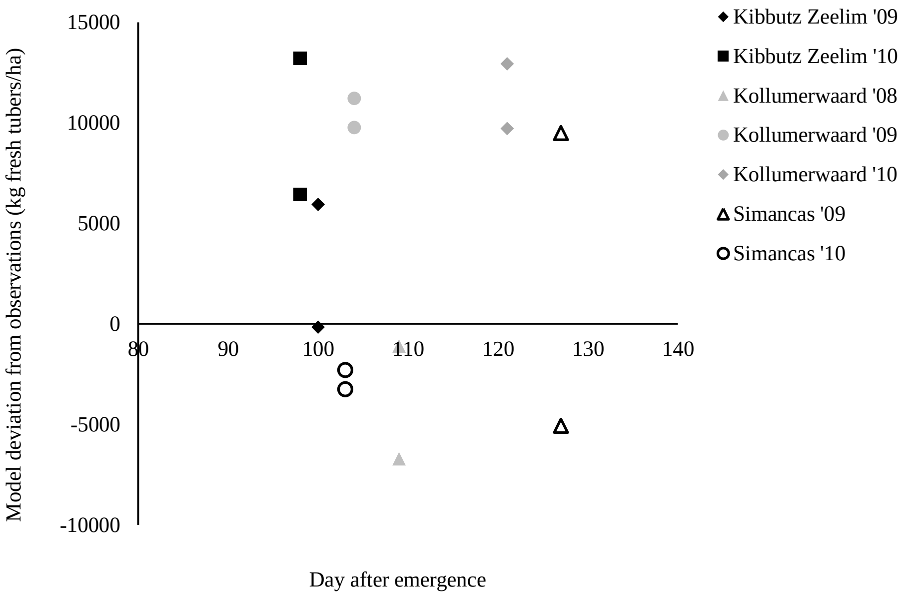


Fig. 5 Deviations of values calculated with the rain fed model from observations (observed- calculated) for fresh tuber yield in the Innovator experiments.

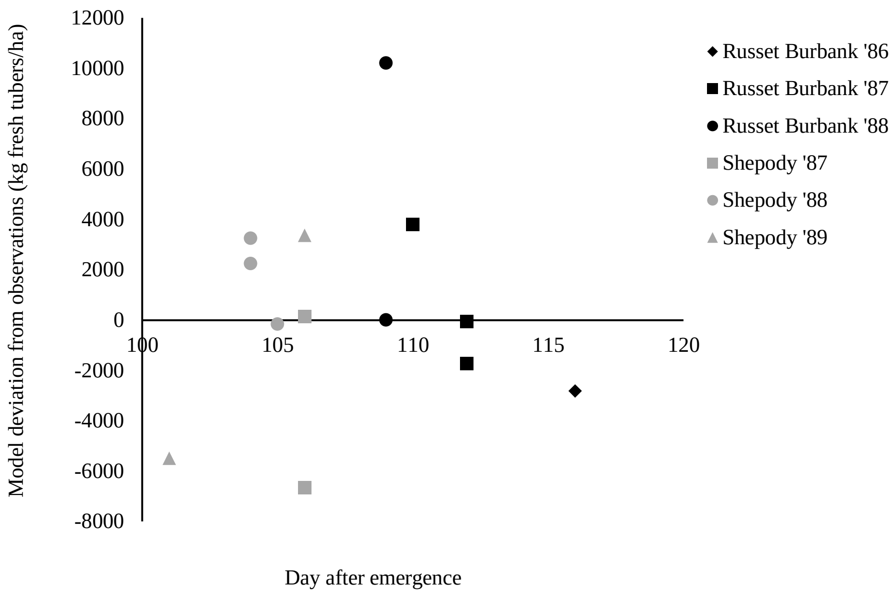


Fig. 6 Deviations of values calculated with the rain fed model from observations (observed- calculated) for fresh tuber yield in the Aroostook experiment.

Appendix 10 Calibrated parameter values

The parameter values from the automated calibration of the LINPACsa model are listed per cultivar (Table. 1).

Table 1 The parameter values for 5 cultivars optimised for LINPACsa by automated calibration.

Parameter	**Cultivar**				
	Eersteling	**Bintje**	**Innovator**	**Shepody**	**Russet Burbank**
tb	103.4	126.5	118.5	125.1	140.8
cm	0.018	0.018	0.013	0.014	0.014
rm	0.039	0.040	0.034	0.040	0.039
Tsm0	1.87	0.13	0.28	0.14	0.12
Tsm2	340.0	244.2	379.4	261.8	286.6
Tsm3	2840.8	2777.6	2454.1	2814.0	2343.1
Flai	0.59	0.63	0.42	1.00	0.47
SoIniA	124.7	162.2	39.2	155.0	163.0
SoIniBT	-0.032	-0.030	-0.031	-0.029	-0.029
SoIniBDL	-0.025	-0.020	-0.018	-0.021	-0.020
AllocMn	-2.36	-2.48	-2.48	-2.36	-2.60
AllocMx	2.68	2.72	2.67	2.84	2.72
AllocA	0.00024	0.00023	0.00024	0.00022	0.00023
AllocBT	18.85	3.78	0.73	7.45	3.48
AllocBDL	2.72	2.73	0.97	0.27	5.44
Dlai	0.0153	0.0003	0.0043	0.0017	0.0002
Trcrt	5.47	8.00	6.64	7.30	7.83

Emergence days were determined by automated calibration, the time from planting to emergence was averaged per cultivar (Table 2).

Table 2 Time between planting day and emergence in days averaged per cultivar. Obtained by calibration of emergence day.

Cultivar	**Emergence time (days)**
Eersteling	29
Bintje	24
Innovator	12
Shepody	14
Russet Burbank	15

The available water contents were adjusted by calibration, for Droevendaal no available water content is displayed because the available water content was not calibrated (Table 3). Also relative total water content was determined by calibration, this is the available water content expressed as a fraction of the total water content.

Table 3 Available and relative total water content (available water content as a fraction of total water content) for four experimental sites obtained by calibration.

Parameter	**Experimental site**			
	Aroostook	**Kollumerwaard**	**Kibbutz Zeelim**	**Simancas**
Available water content	325.88	228.25	214.79	218.56
Relative total water content	0.889	0.889	0.889	0.890

Appendix 11 SPSS output non-water limited simulation runs

Case Processing Summary

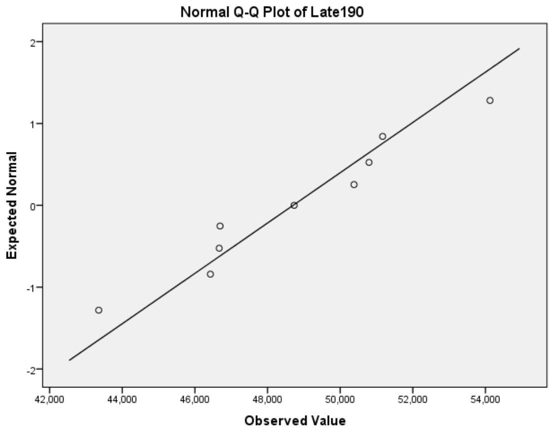
	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Late190	9	100.0%	0	.0%	9	100.0%
Mede190	9	100.0%	0	.0%	9	100.0%
Late910	9	100.0%	0	.0%	9	100.0%
Mede910	9	100.0%	0	.0%	9	100.0%

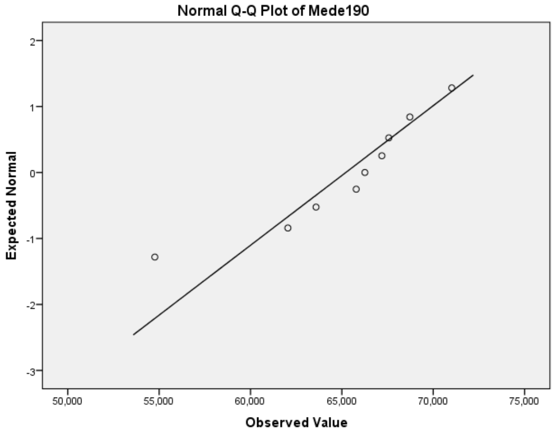
Tests of Normality

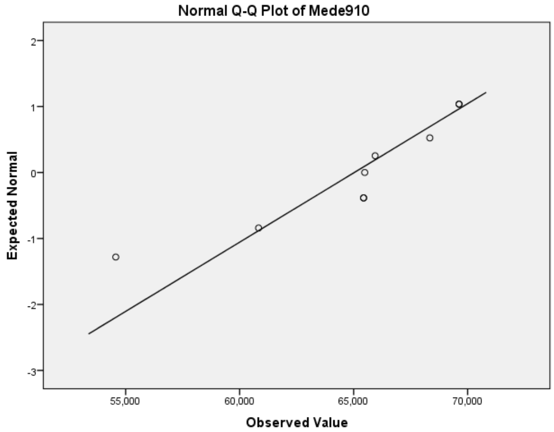
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Late190	.176	9	.200*	.967	9	.867
Mede190	.215	9	.200*	.896	9	.229
Late910	.234	9	.166	.881	9	.162
Mede910	.312	9	.012	.838	9	.055

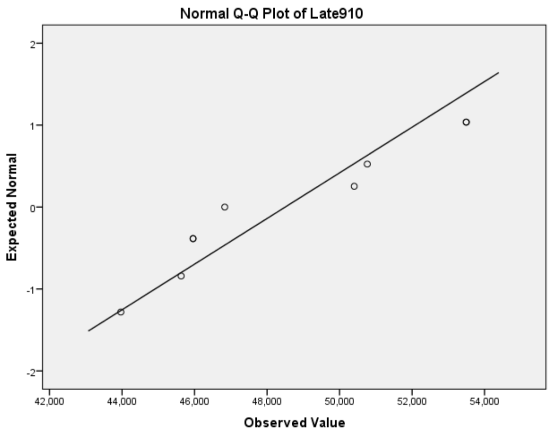
a. Lilliefors Significance Correction

*. This is a lower bound of the true significance.









One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Late190	9	48704.33	3253.341	1084.447
Late910	9	48499.78	3590.105	1196.702

One-Sample Test

	Test Value = 47000					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Late190	1.572	8	.155	1704.333	-796.41	4205.07
Late910	1.253	8	.245	1499.778	-1259.82	4259.38

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Mede190	9	65214.33	4726.321	1575.440
Mede910	9	65030.89	4765.022	1588.341

One-Sample Test

	Test Value = 55000					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Mede190	6.483	8	.000	10214.333	6581.36	13847.31
Mede910	6.315	8	.000	10030.889	6368.17	13693.61

Appendix 12 SPSS output fresh tuber yields 5 cultivars at 85% irrigation level

Case Processing Summary

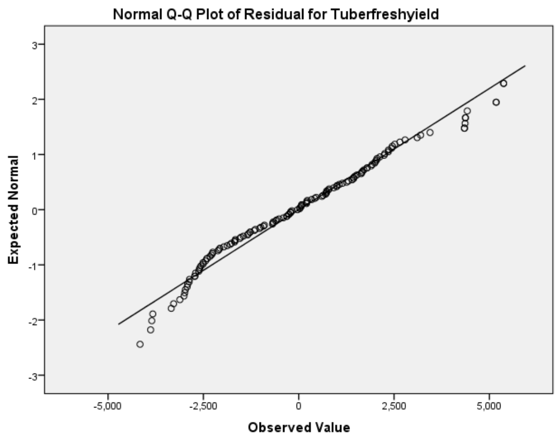
	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Residual for Tuberfreshyield	135	100.0%	0	.0%	135	100.0%

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Residual for Tuberfreshyield	.064	135	.200*	.971	135	.006

a. Lilliefors Significance Correction

*. This is a lower bound of the true significance.



Levene's Test of Equality of Error Variancesa

Dependent Variable:Tuber fresh yield

F	df1	df2	Sig.
1.668	14	120	.071

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Positionconditions + Cultivar + Positionconditions * Cultivar

Tests of Between-Subjects Effects

Dependent Variable:Tuber fresh yield

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4.912E9	14	3.509E8	60.669	.000
Intercept	1.752E11	1	1.752E11	30292.335	.000
Positionconditions	2789665.200	2	1394832.600	.241	.786
Cultivar	4.906E9	4	1.227E9	212.099	.000
Positionconditions * Cultivar	2859276.133	8	357409.517	.062	1.000
Error	6.940E8	120	5783015.337		
Total	1.808E11	135			
Corrected Total	5.606E9	134			

a. R Squared = .876 (Adjusted R Squared = .862)

Estimated Marginal Means

1. Position conditions

Dependent Variable:Tuber fresh yield

Position conditions	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Calcaric regosol	36223.133	358.485	35513.358	36932.909
Haplic Phaeozem	35892.933	358.485	35183.158	36602.709
Haplic Phaeozem910	35952.133	358.485	35242.358	36661.909

2. Cultivar

Dependent Variable:Tuber fresh yield

Cultivar	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Bintje	39514.074	462.802	38597.758	40430.390
Eersteling	36566.778	462.802	35650.462	37483.094
Innovator	44847.222	462.802	43930.906	45763.538
Russet Burbank	27510.852	462.802	26594.536	28427.168
Shepody	31674.741	462.802	30758.425	32591.057

3. Position conditions * Cultivar

Dependent Variable:Tuber fresh yield

Position conditions	Cultivar	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Calcaric regosol	Bintje	39802.222	801.597	38215.117	41389.328
	Eersteling	36870.667	801.597	35283.561	38457.772
	Innovator	45071.556	801.597	43484.450	46658.661
	Russet Burbank	27449.222	801.597	25862.117	29036.328
	Shepody	31922.000	801.597	30334.894	33509.106
Haplic Phaeozem	Bintje	39261.000	801.597	37673.894	40848.106
	Eersteling	36620.444	801.597	35033.339	38207.550
	Innovator	44533.222	801.597	42946.117	46120.328
	Russet Burbank	27515.667	801.597	25928.561	29102.772
	Shepody	31534.333	801.597	29947.228	33121.439
Haplic Phaeozem910	Bintje	39479.000	801.597	37891.894	41066.106
	Eersteling	36209.222	801.597	34622.117	37796.328
	Innovator	44936.889	801.597	43349.783	46523.995
	Russet Burbank	27567.667	801.597	25980.561	29154.772
	Shepody	31567.889	801.597	29980.783	33154.995

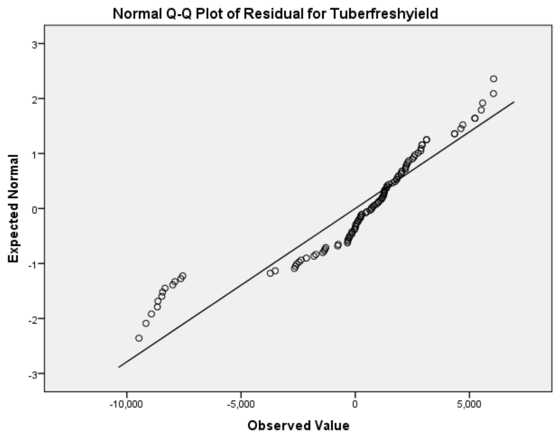
Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Residual for Tuberfreshyield	108	100.0%	0	.0%	108	100.0%

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Residual for Tuberfreshyield	.203	108	.000	.870	108	.000

a. Lilliefors Significance Correction



Levene's Test of Equality of Error Variances[a]

Dependent Variable:Tuber fresh yield

F	df1	df2	Sig.
.083	11	96	1.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Positionconditions + Cultivar + Positionconditions * Cultivar

Tests of Between-Subjects Effects

Dependent Variable:Tuber fresh yield

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4.838E9	11	4.398E8	30.678	.000
Intercept	3.035E11	1	3.035E11	21169.498	.000
Positionconditions	25070096.907	2	12535048.454	.874	.420
Cultivar	4.805E9	3	1.602E9	111.714	.000
Positionconditions * Cultivar	8090031.833	6	1348338.639	.094	.997
Error	1.376E9	96	14337594.093		
Total	3.097E11	108			
Corrected Total	6.215E9	107			

a. R Squared = .779 (Adjusted R Squared = .753)

Estimated Marginal Means

1. Position conditions

Dependent Variable:Tuber fresh yield

Position conditions	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Calcaric regosol	53665.028	631.084	52412.337	54917.719
Haplic Phaeozem	52857.833	631.084	51605.142	54110.524
Haplic Phaeozem910	52515.833	631.084	51263.142	53768.524

2. Cultivar

Dependent Variable:Tuber fresh yield

Cultivar	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Bintje	57540.926	728.713	56094.443	58987.409
Eersteling	53759.481	728.713	52312.998	55205.964
Innovator	58831.259	728.713	57384.776	60277.742
Shepody	41919.926	728.713	40473.443	43366.409

3. Position conditions * Cultivar

Dependent Variable:Tuber fresh yield

Position conditions	Cultivar	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Calcaric regosol	Bintje	58686.889	1262.167	56181.507	61192.271
	Eersteling	54294.333	1262.167	51788.951	56799.715
	Innovator	58974.889	1262.167	56469.507	61480.271
	Shepody	42704.000	1262.167	40198.618	45209.382
Haplic Phaeozem	Bintje	57058.222	1262.167	54552.840	59563.604
	Eersteling	53674.667	1262.167	51169.285	56180.049
	Innovator	58823.222	1262.167	56317.840	61328.604
	Shepody	41875.222	1262.167	39369.840	44380.604
Haplic Phaeozem910	Bintje	56877.667	1262.167	54372.285	59383.049
	Eersteling	53309.444	1262.167	50804.062	55814.827
	Innovator	58695.667	1262.167	56190.285	61201.049
	Shepody	41180.556	1262.167	38675.173	43685.938

Appendix 13 SPSS output fresh tuber yields for different plant- harvest day combinations at 85% irrigation level

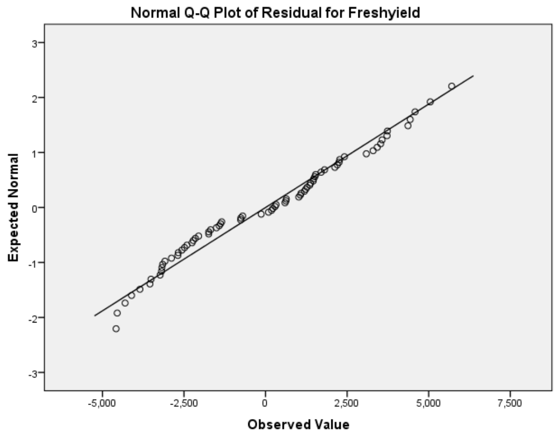
Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Residual for Freshyield	72	100.0%	0	.0%	72	100.0%

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Residual for Freshyield	.096	72	.096	.967	72	.058

a. Lilliefors Significance Correction



Levene's Test of Equality of Error Variances[a]

Dependent Variable:Fresh yield

F	df1	df2	Sig.
1.240	7	64	.295

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Soiltype + PlaHa + Soiltype * PlaHa

Tests of Between-Subjects Effects

Dependent Variable:Fresh yield

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2.796E8	7	39940951.460	5.091	.000
Intercept	1.434E11	1	1.434E11	18277.910	.000
Soiltype	4291473.389	1	4291473.389	.547	.462
PlaHa	2.751E8	3	91694475.000	11.688	.000
Soiltype * PlaHa	211761.833	3	70587.278	.009	.999
Error	5.021E8	64	7845034.622		
Total	1.442E11	72			
Corrected Total	7.817E8	71			

a. R Squared = .358 (Adjusted R Squared = .287)

Estimated Marginal Means

1. Soil type

Dependent Variable:Fresh yield

Soil type	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Calcaric regosol	44382.528	466.816	43449.955	45315.101
Haplic Phaeozem	44870.806	466.816	43938.232	45803.379

2. PlaHa

Dependent Variable:Fresh yield

PlaHa	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
41/181	47009.000	660.178	45690.142	48327.858
48/181	45700.167	660.178	44381.309	47019.024
55/181	44013.000	660.178	42694.142	45331.858
62/181	41784.500	660.178	40465.642	43103.358

3. Soil type * PlaHa

Dependent Variable:Fresh yield

Soil type	PlaHa	Mean	Std. Error	95% Confidence Interval Lower Bound	Upper Bound
Calcaric regosol	41/181	46800.556	933.633	44935.409	48665.702
	48/181	45525.778	933.633	43660.632	47390.924
	55/181	43721.889	933.633	41856.743	45587.035
	62/181	41481.889	933.633	39616.743	43347.035
Haplic Phaeozem	41/181	47217.444	933.633	45352.298	49082.591
	48/181	45874.556	933.633	44009.409	47739.702
	55/181	44304.111	933.633	42438.965	46169.257
	62/181	42087.111	933.633	40221.965	43952.257

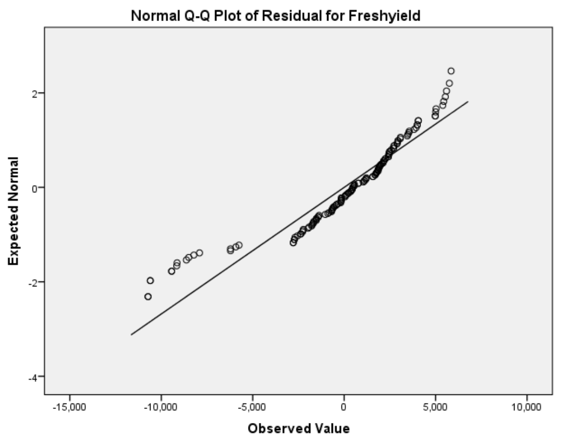
Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Residual for Freshyield	144	100.0%	0	.0%	144	100.0%

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Residual for Freshyield	.128	144	.000	.892	144	.000

a. Lilliefors Significance Correction



Levene's Test of Equality of Error Variances[a]

Dependent Variable:Fresh yield

F	df1	df2	Sig.
.092	15	128	1.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Soiltype + PlaHa + Soiltype * PlaHa

Tests of Between-Subjects Effects

Dependent Variable:Fresh yield

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.035E8	15	6899625.598	.444	.963
Intercept	4.855E11	1	4.855E11	31223.877	.000
Soiltype	461720.250	1	461720.250	.030	.863
PlaHa	1.023E8	7	14611329.806	.940	.478
Soiltype * PlaHa	753355.083	7	107622.155	.007	1.000
Error	1.990E9	128	15549021.630		
Total	4.876E11	144			
Corrected Total	2.094E9	143			

a. R Squared = .049 (Adjusted R Squared = -.062)

Estimated Marginal Means

1. Soil type

Dependent Variable:Fresh yield

Soil type	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Calcaric regosol	58121.528	464.713	57202.013	59041.043
Haplic Phaeozem	58008.278	464.713	57088.763	58927.793

2. PlaHa

Dependent Variable:Fresh yield

PlaHa	Mean	Std. Error	95% Confidence Interval

			Lower Bound	Upper Bound
196/305	57680.556	929.427	55841.525	59519.586
196/359	57680.556	929.427	55841.525	59519.586
203/305	58428.222	929.427	56589.192	60267.252
203/359	58438.556	929.427	56599.525	60277.586
210/305	58278.444	929.427	56439.414	60117.475
210/359	58777.000	929.427	56937.970	60616.030
217/305	56175.222	929.427	54336.192	58014.252
217/359	59060.667	929.427	57221.637	60899.697

3. Soil type * PlaHa

Dependent Variable:Fresh yield

				95% Confidence Interval	
Soil type	PlaHa	Mean	Std. Error	Lower Bound	Upper Bound
Calcaric regosol	196/305	57787.667	1314.408	55186.885	60388.448
	196/359	57787.667	1314.408	55186.885	60388.448
	203/305	58526.111	1314.408	55925.330	61126.892
	203/359	58546.778	1314.408	55945.996	61147.559
	210/305	58273.444	1314.408	55672.663	60874.226
	210/359	58862.556	1314.408	56261.774	61463.337
	217/305	56065.333	1314.408	53464.552	58666.115
	217/359	59122.667	1314.408	56521.885	61723.448
Haplic Phaeozem	196/305	57573.444	1314.408	54972.663	60174.226
	196/359	57573.444	1314.408	54972.663	60174.226
	203/305	58330.333	1314.408	55729.552	60931.115
	203/359	58330.333	1314.408	55729.552	60931.115
	210/305	58283.444	1314.408	55682.663	60884.226
	210/359	58691.444	1314.408	56090.663	61292.226
	217/305	56285.111	1314.408	53684.330	58885.892
	217/359	58998.667	1314.408	56397.885	61599.448

Appendix 14 SPSS output IUE 5 cultivars at 85% irrigation level

Case Processing Summary

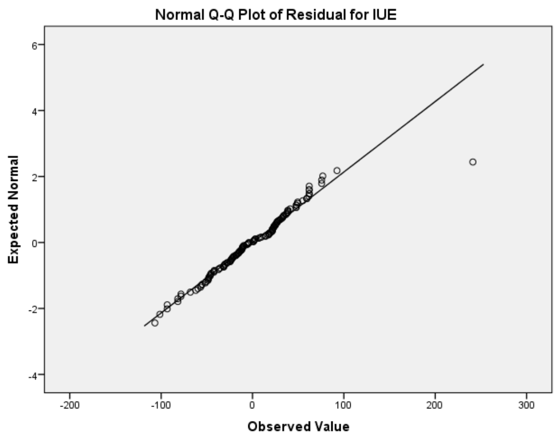
	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Residual for IUE	135	100.0%	0	.0%	135	100.0%

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Residual for IUE	.057	135	.200*	.947	135	.000

a. Lilliefors Significance Correction

*. This is a lower bound of the true significance.



Levene's Test of Equality of Error Variances[a]

Dependent Variable:IUE

F	df1	df2	Sig.
7.519	14	120	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Cultivar + Positionconditions + Cultivar * Positionconditions

Tests of Between-Subjects Effects

Dependent Variable:IUE

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	134482.821[a]	14	9605.916	3.925	.000
Intercept	1988469.959	1	1988469.959	812.412	.000
Cultivar	55692.466	4	13923.116	5.688	.000
Positionconditions	44685.565	2	22342.783	9.128	.000
Cultivar * Positionconditions	34104.790	8	4263.099	1.742	.096
Error	293713.538	120	2447.613		
Total	2416666.319	135			
Corrected Total	428196.360	134			

a. R Squared = .314 (Adjusted R Squared = .234)

Estimated Marginal Means

1. Cultivar

Dependent Variable:IUE

Cultivar	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Bintje	102.640	9.521	83.789	121.491
Eersteling	114.959	9.521	96.108	133.811
Innovator	137.712	9.521	118.860	156.563
Russet Burbank	99.630	9.521	80.778	118.481
Shepody	151.884	9.521	133.032	170.735

2. Position conditions

Dependent Variable:IUE

Position conditions	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Calcaric regosol	96.347	7.375	81.745	110.949
Haplic Phaeozem	128.669	7.375	114.067	143.271
Haplic Phaeozem910	139.079	7.375	124.477	153.681

Case Processing Summary

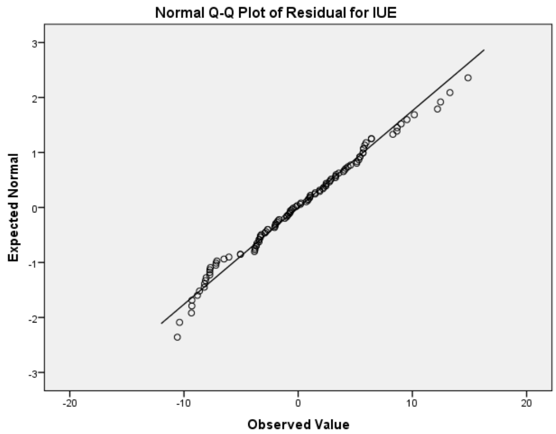
	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Residual for IUE	108	100.0%	0	.0%	108	100.0%

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Residual for IUE	.062	108	.200*	.982	108	.150

a. Lilliefors Significance Correction

*. This is a lower bound of the true significance.



Levene's Test of Equality of Error Variances[a]

Dependent Variable:IUE

F	df1	df2	Sig.
.450	11	96	.929

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Positionconditions + Cultivar + Positionconditions * Cultivar

Tests of Between-Subjects Effects

Dependent Variable:IUE

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	649.251[a]	11	59.023	1.640	.100
Intercept	321514.238	1	321514.238	8934.194	.000
Positionconditions	317.242	2	158.621	4.408	.015
Cultivar	323.897	3	107.966	3.000	.034
Positionconditions * Cultivar	8.111	6	1.352	.038	1.000
Error	3454.745	96	35.987		
Total	325618.234	108			
Corrected Total	4103.996	107			

a. R Squared = .158 (Adjusted R Squared = .062)

Estimated Marginal Means

1. Position conditions

Dependent Variable:IUE

Position conditions	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Calcaric regosol	52.473	1.000	50.488	54.458
Haplic Phaeozem	54.541	1.000	52.556	56.526
Haplic Phaeozem910	56.671	1.000	54.686	58.656

2. Cultivar

Dependent Variable:IUE

Cultivar	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Bintje	52.210	1.154	49.918	54.501
Eersteling	53.651	1.154	51.359	55.943
Innovator	56.588	1.154	54.296	58.879
Shepody	55.799	1.154	53.507	58.090

3. Position conditions * Cultivar

Dependent Variable:IUE

Position conditions	Cultivar	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Calcaric regosol	Bintje	50.611	2.000	46.642	54.581
	Eersteling	51.663	2.000	47.694	55.632
	Innovator	54.446	2.000	50.477	58.416
	Shepody	53.171	2.000	49.202	57.141
Haplic Phaeozem	Bintje	52.098	2.000	48.129	56.068
	Eersteling	53.446	2.000	49.477	57.416
	Innovator	56.601	2.000	52.631	60.570
	Shepody	56.019	2.000	52.050	59.988
Haplic Phaeozem910	Bintje	53.919	2.000	49.950	57.888
	Eersteling	55.844	2.000	51.875	59.813
	Innovator	58.715	2.000	54.746	62.685
	Shepody	58.206	2.000	54.237	62.176

Appendix 15 SPSS output IUE for different plant- harvest day combinations at 85% irrigation level

Case Processing Summary

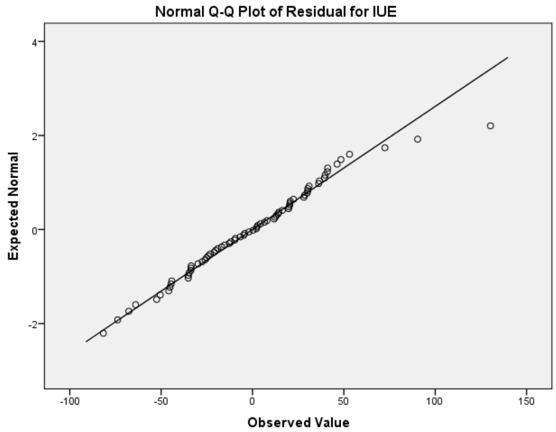
	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Residual for IUE	72	100.0%	0	.0%	72	100.0%

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Residual for IUE	.057	72	.200*	.979	72	.272

a. Lilliefors Significance Correction

*. This is a lower bound of the true significance.



Levene's Test of Equality of Error Variances[a]

Dependent Variable:IUE

F	df1	df2	Sig.
3.447	7	64	.003

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Soiltype + PlaHa + Soiltype * PlaHa

Tests of Between-Subjects Effects

Dependent Variable:IUE

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	30865.626[a]	7	4409.375	2.725	.015
Intercept	1207488.449	1	1207488.449	746.241	.000
Soiltype	18375.236	1	18375.236	11.356	.001
PlaHa	11776.198	3	3925.399	2.426	.074
Soiltype * PlaHa	714.192	3	238.064	.147	.931
Error	103558.055	64	1618.095		
Total	1341912.130	72			
Corrected Total	134423.681	71			

a. R Squared = .230 (Adjusted R Squared = .145)

Estimated Marginal Means

1. Soil type

Dependent Variable:IUE

Soil type	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Calcaric regosol	113.526	6.704	100.133	126.920
Haplic Phaeozem	145.477	6.704	132.084	158.870

2. PlaHa

Dependent Variable:IUE

PlaHa	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
41/181	141.928	9.481	122.987	160.869
48/181	140.783	9.481	121.842	159.724
55/181	124.412	9.481	105.471	143.353
62/181	110.883	9.481	91.942	129.824

3. Soil type * PlaHa

Dependent Variable:IUE

Soil type	PlaHa	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Calcaric regosol	41/181	122.271	13.409	95.485	149.058
	48/181	122.832	13.409	96.045	149.618
	55/181	109.502	13.409	82.716	136.289
	62/181	99.500	13.409	72.713	126.286
Haplic Phaeozem	41/181	161.584	13.409	134.798	188.371
	48/181	158.735	13.409	131.948	185.522
	55/181	139.322	13.409	112.536	166.109
	62/181	122.267	13.409	95.480	149.053

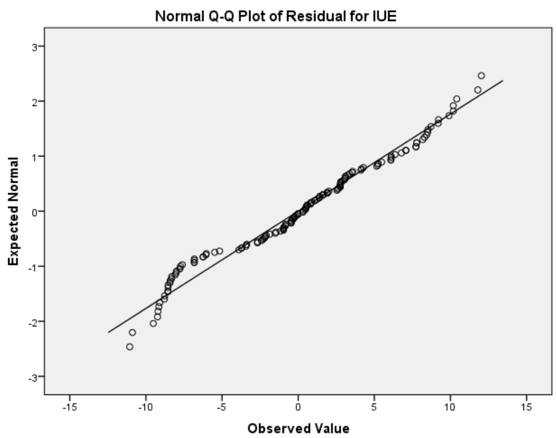
Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Residual for IUE	144	100.0%	0	.0%	144	100.0%

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Residual for IUE	.080	144	.024	.970	144	.003

a. Lilliefors Significance Correction



Levene's Test of Equality of Error Variances[a]

Dependent Variable:IUE

F	df1	df2	Sig.
.393	15	128	.979

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Soiltype + PlaHa + Soiltype * PlaHa

Tests of Between-Subjects Effects

Dependent Variable:IUE

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	313.678[a]	15	20.912	.584	.883
Intercept	452341.809	1	452341.809	12627.396	.000
Soiltype	165.523	1	165.523	4.621	.033
PlaHa	142.554	7	20.365	.568	.780
Soiltype * PlaHa	5.600	7	.800	.022	1.000
Error	4585.249	128	35.822		
Total	457240.735	144			
Corrected Total	4898.927	143			

a. R Squared = .064 (Adjusted R Squared = -.046)

Estimated Marginal Means

1. Soil type

Dependent Variable:IUE

Soil type	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Calcaric regosol	54.975	.705	53.579	56.371
Haplic Phaeozem	57.119	.705	55.723	58.515

2. PlaHa

Dependent Variable:IUE

PlaHa	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
196/305	57.432	1.411	54.641	60.223
196/359	57.432	1.411	54.641	60.223
203/305	56.363	1.411	53.572	59.155
203/359	56.376	1.411	53.584	59.167
210/305	55.254	1.411	52.463	58.045
210/359	55.478	1.411	52.686	58.269
217/305	54.382	1.411	51.591	57.174
217/359	55.659	1.411	52.867	58.450

3. Soil type * PlaHa

Dependent Variable:IUE

Soil type	PlaHa	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Calcaric regosol	196/305	56.129	1.995	52.181	60.076
	196/359	56.129	1.995	52.181	60.076
	203/305	55.197	1.995	51.249	59.144
	203/359	55.221	1.995	51.273	59.168
	210/305	54.257	1.995	50.309	58.204
	210/359	54.382	1.995	50.435	58.330
	217/305	53.674	1.995	49.727	57.622
	217/359	54.810	1.995	50.862	58.757
Haplic Phaeozem	196/305	58.735	1.995	54.788	62.683
	196/359	58.735	1.995	54.788	62.683
	203/305	57.530	1.995	53.583	61.478
	203/359	57.530	1.995	53.583	61.478
	210/305	56.251	1.995	52.304	60.199
	210/359	56.573	1.995	52.625	60.520
	217/305	55.090	1.995	51.143	59.038
	217/359	56.508	1.995	52.560	60.455

Appendix 16 SPSS output Relation N application and LUE

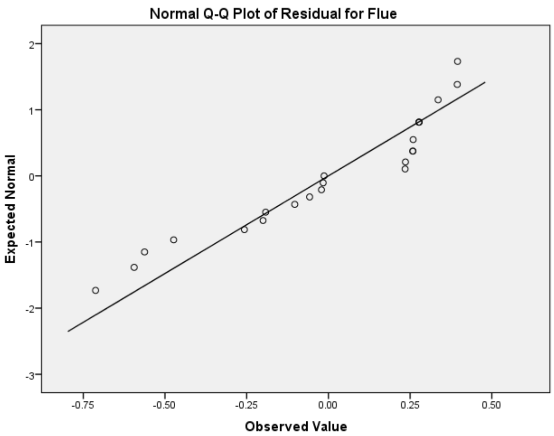
Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Residual for Flue	23	100.0%	0	.0%	23	100.0%

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Residual for Flue	.234	23	.002	.887	23	.014

a. Lilliefors Significance Correction



Levene's Test of Equality of Error Variances[a]

Dependent Variable:Flue

F	df1	df2	Sig.
.978	3	19	.424

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + NApplication

Tests of Between-Subjects Effects

Dependent Variable:Flue

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.087[a]	3	.029	.219	.882
Intercept	11.463	1	11.463	86.260	.000
NApplication	.087	3	.029	.219	.882
Error	2.525	19	.133		
Total	14.068	23			
Corrected Total	2.612	22			

a. R Squared = .033 (Adjusted R Squared = -.119)

Estimated Marginal Means

N Application

Dependent Variable:Flue

N Application	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
0	.605	.149	.293	.916
100	.723	.149	.411	1.034
200	.741	.149	.429	1.052
300	.764	.163	.423	1.105