Application of SWAP-WOFOST to evaluate the influence of water and oxygen stress on potato yield in a Dutch farm

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List of Important Acronyms

AMAXTB	maximum leaf CO_2 assimilation rate as a function of development stage of the crop
DM	dry matter
DVS	development stages
EF	model efficiency
FLTB	assimilates partitioning factors: fraction leaves
FM	fresh matter
FOTB	assimilates partitioning factors: fraction organs
FSTB	assimilates partitioning factors: fraction stems
OB	observation
SLATB	specific leaf area
SM	simulation
SPAN	life span of leaves
SSE	sum of squared errors
SWAP	Soil Water Atmosphere Plant
TSUM1	the temperature sum from emergence to anthesis
TSUM2	the temperature sum from anthesis to maturity
TSUMEM	temperature sum from sowing to emergence
TWSO	total dry weight of storage organs
UWW	under water tuber weight
WOFOST	WOrld FOod Studies
WSO	dry matter weight of storage organ
Ya	actual yield
Yn	nutrient-limited yield
Yp	potential yield
Yw	water-limited yield

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Abstract

Potato (*Solanum tuberosum L.*) is one of the most important food crops in the world and it is sensitive to water stress. The purpose of this study was to investigate the influence of drought and oxygen stress on potato yields in the south of the Netherlands and improve water management at farm level.

Yield gap analysis was done by using the integrated agro-hydrology and crop growth model SWAP-WOFOST. The model WOFOST was calibrated at the potential production level before integration with SWAP. The integrated model SWAP-WOFOST was not calibrated but applied using standard parameters, but sensitivity analysis were performed to assess uncertainty of estimated water-limited yields.

WOFOST was well calibrated with satisfactory validation results, with a model efficiency between 0.89-0.95 for (4 out of 5) fields in terms of fresh matter tuber yield simulation. Potential fresh yield of potato cultivar Fontane was determined at the farm with a range of 90-120 t/ha, depending on the growing period and weather (e.g. radiation, temperature). Simulated yield gap (FM) caused by water was 18.7 to 31.0 t/ha in 2013 and 0.6-10.7 t/ha in 2014. Yield gap caused by water in 2013 & 2014 was mainly due to water deficiency. Moreover, it was found that tuber yield largely reduced by the insufficient water supply at the tuber initiation and filling stages (MacKerron and Jefferies, 1986; Haverkort et al., 1990; Lynch et al., 1995; Yuan et al., 2003). Oxygen stress was also found at some fields with the insignificant impact on the yield. In 2013, drought stress was found strongly influenced by the precipitation, soil characteristics and also ground water levels in the model simulations. Therefore, precise precipitation data, soil inputs data and groundwater level data are both essential for robust model results. Furthermore, SWAP-WOFOST was served to qualitatively plan irrigation schedules to close water limited yield gaps. The complete and accurate data (rainfall, soil, groundwater) are required in order to implement the model for irrigation schedule.

However, actual tuber yield were found even larger than simulated potential yield at some fields in 2014. This can be attributed to the yield data selection during the calibration. This issue can be solved with experiments under potential production conditions. As for SWAP-WOFOST performance, the water limited yield simulations cannot be verified because no water limited production experiments were done at the farm. Yield gaps caused by drought and oxygen stress cannot be exactly determined, as improved calibration is needed, but is clear that a large part of yield gaps can be explained by water limitation during the growing season. Further experiments are required for SWAP-WOFOST calibration.

Contents

1. Introduction

1.1 Problem statement

1.1.1 Growing food demand

According to the UN (2013), a world population of 9.6 billion is expected in 2050. Thus, to satisfy increasing food demands there is a great challenge to global crop production in the coming decades. Generally (1) expanding agricultural land area and (2) increasing the yield are the two possible approaches to increase production (Licker et al., 2010). However, due to the shortage of productive land and growing demand of non-agricultural land uses, expanding agricultural area will not be the desirable option. Therefore, increasing the yield will be the key to satisfy the future requirements (Neumann et al., 2010). The Green Revolution that started in the middle of the 20^{th} century, has led to a high yield increase in many countries by introducing high-yielding crop varieties and artificial fertilizers and pesticides (Hedden, 2003). However, in developed countries like the Netherlands this led to environmental pollution, like nitrate leaching and biodiversity loss. And although yields in the Netherlands are close to the optimal level (Van Ittersum et al., 2013), there is still a large variability (spatial & temporal) and uncertainty among and within farms (http://www.vandenborneaardappelen.com/).

1.1.2 Yield gap analysis

Yield gap analysis is applied to identify and sequence the influence of possible factors (e.g. water, nutrient) on yield which can be the interpretive outcomes of the observed yield and it has been used widely in many countries (Prost and Jeuffroy, 2008). In order to have a clear overview of yield gap analysis, several basic concepts are introduced here. Potential yield (Yp) is defined as the yield of a crop cultivar obtained when the crop is optimally supplied with water and nutrients and is completely protected against growth-reducing factors. The potential yield is determined by the weather (i.e. temperature, CO_2, radiation) and crop properties (Van Ittersum and Rabbinge, 1997). Definition of water-limited (Yw) and nutrient-limited (Yn) yield is related to Yp, but crop growth is limited by water and nutrient supply respectively (Van Ittersum et al., 2013). Actual yield (Ya) is not only influenced by growth-defining and growth-limiting factors but also affected by pests and diseases and sub-optimal management (Fig. 1). The yield gap (Yg) is defined as the difference between benchmark yield (could be Yp, Yw or Yn) and actual yield (Ya).

Yield can be increased by closing the yield gap (Van Ittersum et al., 2013). In the Netherlands, potential yields are still linearly increasing due to genetic improvement of crops (Rijk et al., 2013). Yield gaps vary widely across the globe (Neumann et al., 2010), but also among and within farms, as mentioned above. In the Netherlands, the average yield gap is less than 20% (Van Ittersum et al., 2013), but for individual farms and fields, large gaps occur. Moreover, most yield gap analysis focus on the global and regional level. To better understand the impacts of farm characteristics, crop management and soil conditions, it is important to study variations between and within farms. However, yield gap analysis based on fields experiments are time consuming and expensive. Several processed based crop models, integrating system approaches and multiple disciplines, have been developed in the last decades which can assist yield gap analysis (Bhatia et al., 2008; Boote et al., 1996). In this study, the model SWAP-WOFOST was used. Detailed information of the model SWAP-WOFOST will be described in the methods section.

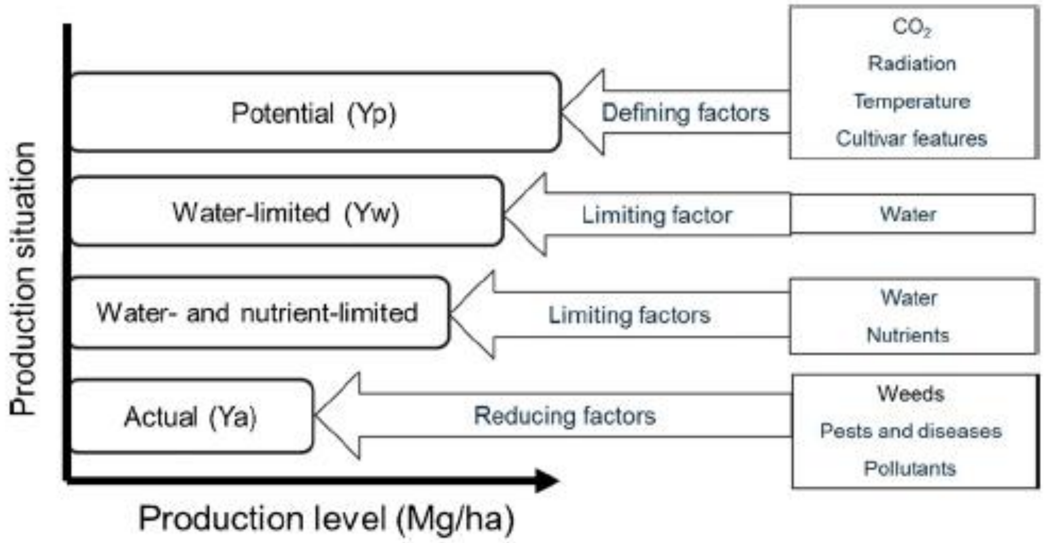

Fig. 1. Different production levels as determined by different factors respectively (Van Ittersum et al., 2013)

1.1.3 Yield gap analysis on a precision agriculture farm

Precision agriculture is a production system that promotes variable management practices within a field, according to site conditions. The system is based on the global positioning system (GPS), geographic information systems (GIS), yield monitoring devices, soil, plant and pest sensors, remote sensing and other technologies (Seelan et al., 2003). Van den Borne Aardappelen is a Dutch potato farm located at the border of the Netherlands and Belgium. In 2007, Van den Borne started to integrate precision agriculture into their business. By taking site specific conditions into account, the application efficiency of fertilizer, pesticide, water and fossil fuel can be achieved optimally and at the right time (http://precisielandbouw.eu/pplnl/Home.html). To improve the precision agriculture, Van den Borne Aardappelen started another program called “Making Sense” in 2010 with BLGG , TTW (agricultural consultancy company) and WUR (Wageningen University and Research Centre). The project Making Sense contributes to the development of a precision management decision module for soil fertility and fertilization of arable crops on the basis of soil and crop sensor data, climate data, a soil and a crop model (http://www.vandenborneaardappelen.com/.html). Within the farm Van den Borne Aardappelen yield gaps vary. In order to make better use of the data collected in the farm and improve farm management, a yield gap analysis is expected to be increase efficiency of inputs for the fields within this farm.

1.1.4 Drought stress

Water is important for plant growth. It is the fundamental molecule for plant physiological activities. Moreover potato has a high water content which accounts for approximately 85% of the composition in living plant tissues. 1 % of the water is needed for metabolic processes and 99% for transpiration. Water stress can cause severe physiological impacts, for instance on photosynthesis, transpiration and cell development (Van Loon, 1981).

The potato crop is sensitive to water deficiency. Water stress could lead to reducing leaf area and/or reducing photosynthesis efficiency at all stages of potato growth. Water shortage in the tuber filling period causes most significant yield loss compared to drought during other stages (Van Loon, 1981). Previous studies showed that drought during different potato growth periods result in shorter growing (1-4 weeks) and dormancy (2-8 weeks) periods (Karafyllidis et al., 1996) and decreases in tuber yield, the number of tubers per plant, tuber size and quality (MacKerron and Jefferies, 1986; Ojala et al., 1990; Yuan et al., 2003). Compared to barley and sugar beet, potato has a shallow and relatively weak root system, which is one of the factors causing the sensitivity of potato to water stress (Van Loon, 1981).

Simulations performed in Flevoland estimated water-limited yields to be 23% lower than potential yields (Reidsma et al. 2015). Water limitation is however larger on sandy soils like occurring in the south of Brabant. Provisional analysis of Van den Borne Aardappelen data suggest a large influence on yield differences between fields. Water-limited yields can be estimated based on the actual evapotranspiration compared to potential evapotranspiration. In the agro-hydrological model SWAP (Soil Water Atmosphere Plant), Richards' eq is employed to calculate waters flow for the unsaturated-saturated zone. SWAP solves Richards' eq numerically for specified boundary conditions with an implicit, backward, limited different scheme (upper boundary condition consists of daily precipitation, irrigation and potential evapotranspiration) and the bottom boundary is controlled by pressure head, flux or the relation between flux and pressure head. The water balance can be calculated by considering two boundary conditions: the top and bottom boundaries. The Penman-Monteith eq can be used to estimate evapotranspiration of uniform surfaces (wet and dry vegetation, bare soil). Potential transpiration T_p and potential evaporation E_p are calculated from leaf area index (LAI) and soil cover fraction (SC). Actual transpiration depends on the moisture and salinity situations in the root zone, weighted by the root density and crop characteristics. Actual evaporation depends on the capacity of the soil to transport water to the soil surface. Surface runoff will be calculated when the ponding reservoir exceeds a critical value. Field drainage can be simulated using the Hooghoudt and Ernst eqs in homogenous and heterogeneous soil profiles (Ines et al., 2001; Van Dam et al., 2008).

1.1.5 Oxygen stress

Oxygen is essential for plant performance especially in the root zone. In the condition of low oxygen, the plant hormone ethylene could be generated. Additionally, a low oxygen concentration will impede the transportation of water and nutrients to the upper parts of the plant due to the reducing root pressure. Furthermore, adventitious roots and aerenchyma could occur from hypoxia. As extra energy is required during the formation of aerenchyma or adventitious roots, less energy contributes to the yield. Further hypoxia in roots can result in closing of stomata, withered leaves, and reducing photosynthesis (Holtman et al., 2014). At the field scale, water logging and flooding disturb plant root functions frequently. Several studies have reported damage caused by low oxygen stress. Else et al (1995) reported a decrease of potential leaf water persisted for 8 hours in tomato plants at a flooding event. Ashraf and Mehmood (1990) investigated four *Brassica* species with waterlogging tolerance. They reported a noticeable reduction in chlorophyll content for all four species (up to 64.49% difference compared to the control).

2. Research Aim & Questions

2.1 Research Aim

The main purpose of this study is to investigate the potato yield gap (Yp to Yw) at a farm level. The model SWAP-WOFOST will be used to explain how and to what extent water and oxygen stress contributes to the yield gap in different fields. Meanwhile, this study serves as a test how well the SWAP-WOFOST model performs in explaining the influence of hydrological conditions on yields at farm level. Moreover, the outcome of the research should be applicable for instructions how to improve field water management.

2.2 Research Questions

The following questions will be explored in this study:

I. What is the potential yield of main potato cultivar in the south of the Netherlands?

II. Can the influence of drought and oxygen stress be simulated adequately with SWAP-WOFOST?

III. What is the influence of drought and oxygen stress in different potato fields within one farm?

IV. How can SWAP-WOFOST be used for precision agriculture regarding water management to reduce yield gaps?

3 Materials and Methods

3.1 Case Study and data

3.1.1 Van den Borne Aardappelen

The precision arable farm Van den Borne Aardappelen is located in the south of the Netherlands. It covered 139 (455.6 hectares) and 143 (511.82 hectares) potato fields in the years 2013 and 2014 respectively (Fig. 2). Average fresh tuber yields of 60 t/ha and 67 t/ha were achieved in year 2013 and 2014 respectively. The fields of the farm are distributed in both Dutch and Belgian territory, within an area of 800 km^2 approximately.

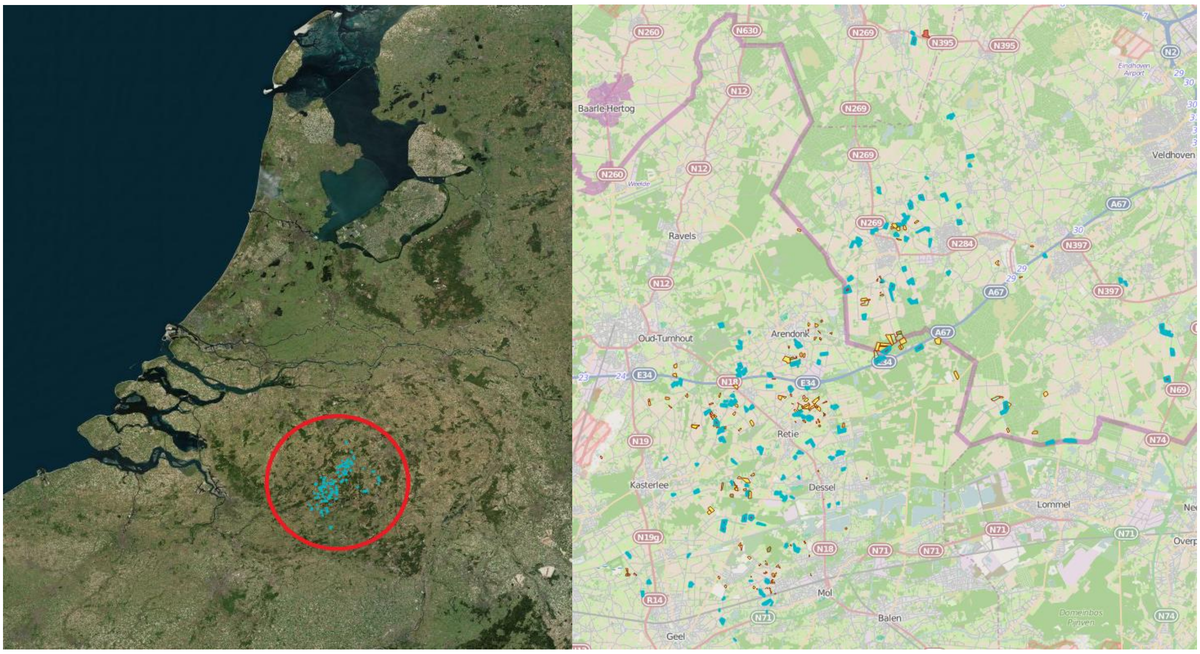

Fig. 2. Overview of the potato fields (blue dots) of farm Van den Borne Aardappelen in 2014.

3.1.2 Climate

Climate data in this study are taken from the Royal Dutch Meteorological Institute KNMI and agricultural consultant firm Dacom. KNMI is the national institute for weather, climate and seismology of the Netherlands (www.knmi.nl). KNMI has different meteorological stations distributed in Netherlands. As Eindhoven station has the shortest distance to farm van den Borne Aardappelen, this station was selected for the main meteorological inputs (Fig.3). Additionally, Dacom measured the rainfall of several different fields during the main growing season for the year 2013 and 2014 (Appendix I), but it is incomplete and insufficient for the model simulation requirements. In order to achieve most precise and representative simulations, and also because of the spatially variability of rainfall, when possible, precipitation data from Eindhoven were replaced with the available data from Dacom for the specific field simulations.

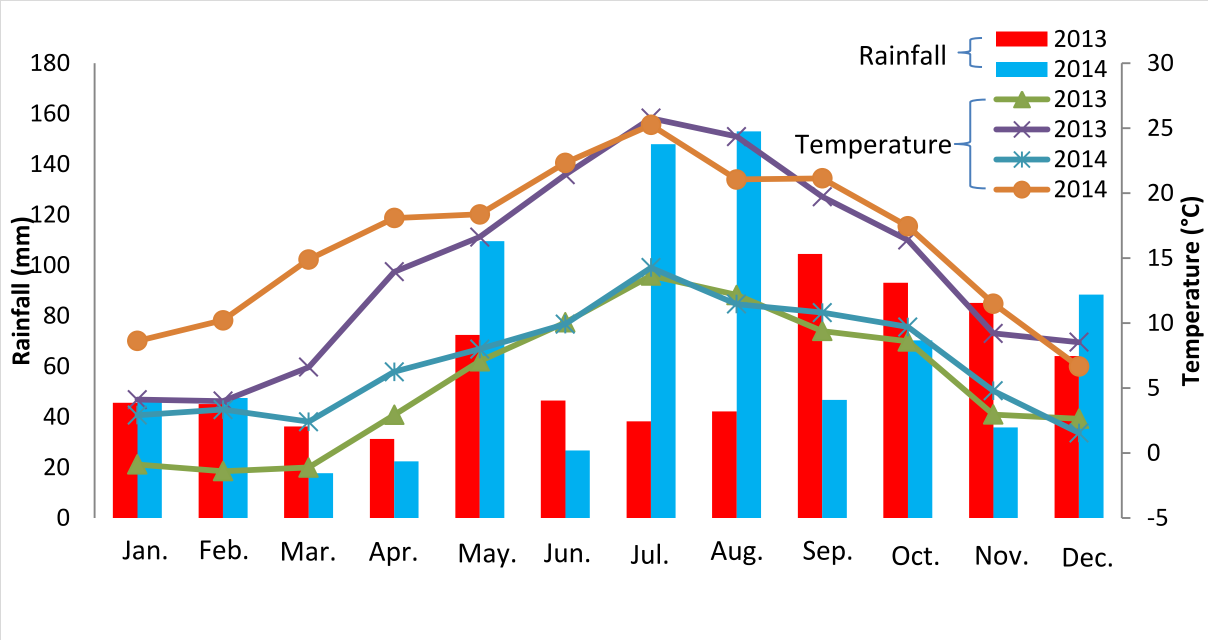

Fig. 3. Records of rainfall, mean monthly max. & min. temperature in year 2013 & 2014 (Station: Eindhoven).

In terms of weather data, the crop model that was used, WOFOST, requires solar radiation ($kJ \cdot m^{-2} \cdot d^{-1}$), minimum and maximum air temperature (°C), precipitation ($mm \cdot d^{-1}$), actual vapor pressure (kPa) and wind speed ($m \cdot s^{-1}$) data for the simulation. The CABO-format of weather file was employed in the simulation and the name of CABO file was defined as <location name><station number>.<last 3 numbers of the year>. All data from Eindhoven station could be imported into the model directly, except for actual vapor pressure which cannot be measured directly. Actual vapor pressure was derived from saturation vapor pressure at maximum and minimum daily temperature (Eq 1).

Eq 1

$$e°(T) = 0.6108\exp[\frac{17.27T}{T + 273.3}]$$

$$e_s = \frac{e°(T_{max}) + e°(T_{min})}{2}$$

$$e_a = e_s \frac{RH}{100}$$

'Where e°(T) is saturation vapour pressure at the air temperature T [kPa]; T is air temperature [°C]; e_s *is mean saturation vapour pressure [kPa]; RH is the relative humidity;* e_a *is actual vapor pressure [kPa]'*; (Ventura et al., 1999).

WOFOST climate data were used for potential yield calibration and validation.

Similarly, for the daily weather records, the hydrological model SWAP requires solar radiation, air temperature (min and max), air humidity, wind speed, precipitation and evapotranspiration data. When running SWAP, different weather files were used for different fields within one region to allow the differences in precipitation (Appendix I).

3.1.3 Soil information

Generally, the soil texture in this study area can be categorized as sandy. But due to the large area and scattered location of fields of the farm, soil properties differ per field (Fig. 4). Appendix (II) shows the full size of the soil map of Netherlands with legend.

Soil data of this study are taken from Wösten et al (2012). Vertical discretization data of soil profiles such as number of soil layers and layer depths were imported into SWAP. Moreover, soil hydraulic function parameters values were specified in SWAP including: ORES (residual water content, cm^3/cm^3), OSAT (saturated water content, cm^3/cm^3), ALFA (shape parameter alfa of main drying curve, cm^{-1}), NPAR (shape parameter n), KSAT (saturated vertical hydraulic conductivity, cm/d), LEXP (exponent in hydraulic conductivity function), ALFAW (alfa parameter of main wetting curve in case of hysteresis, cm^{-1}), H_ENPR (entry pressure head, cm). See Appendix III for the values used in this study.

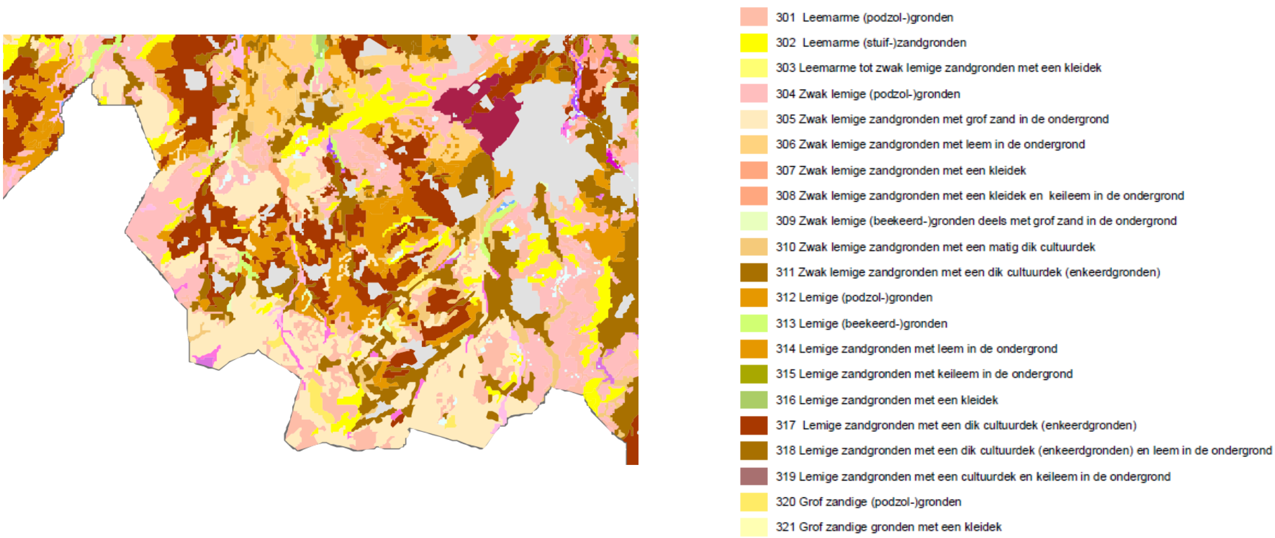

Fig. 4. Overview of the spatial soil profile variability of the studying area (Wösten et al., 2012).

3.2 Structure of WOFOST

The model WOFOST (WOrld FOod STudies) was used for crop simulation in this study. Most part of this section was from the WOFOST model manual (Boogaard et al., 2014). WOFOST is a carbon-driven crop growth simulation model with a time step of one day. WOFOST simulates the growth of an annual crop with a series of specific soil and weather data. The mechanism of the WOFOST simulation is generated from main eco-physiological processes including: phenological development, light interception, carbon dioxide assimilation, evapotranspiration, respiration, distribution of assimilates to organs, and dry matter formation (Fig. 5). In WOFOST potential production and limited production (nutrient & water) can be simulated. Weeds and pests are not taken into account (Boogaard et al., 2014).

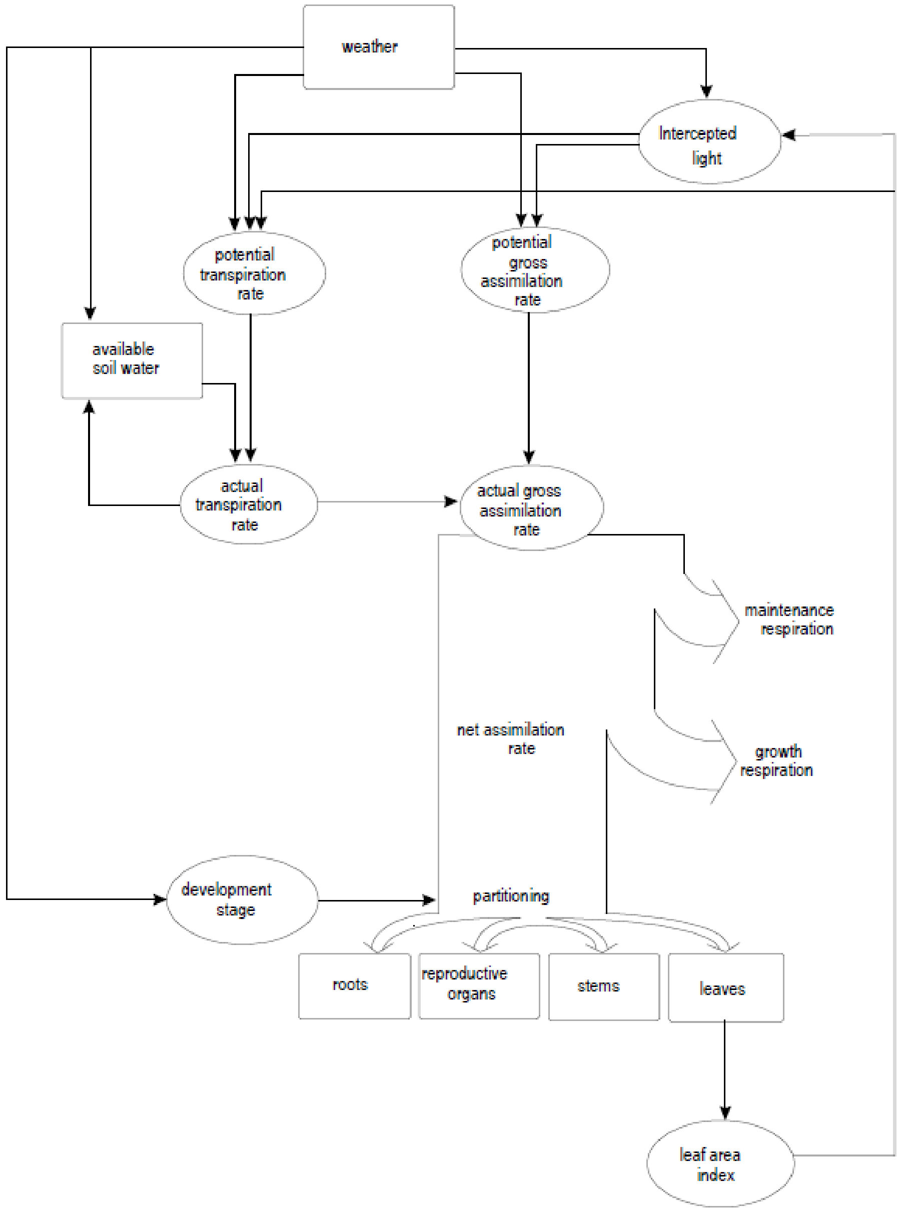

Fig. 5. Simplified structure of WOFOST (Boogaard et al., 2014).

3.2.1 Phenological development

In WOFOST, phenological development is described by the order and the rate of vegetative and reproductive organs appearances. The order is independent of crop characteristics and the rate depends on crop characteristics in addition to temperature and photoperiod. In WOFOST development stage (DVS) is the descriptive variable for phenology. DVS is fixed at 0 for emergence, 1 at anthesis and 2 at maturity. WOFOST uses temperature sum to illustrate the effect of temperature on development rate. Several thermal time concepts applied here included: T_e (daily effective temperature after emergence) ; T (daily average temperature); T_{base} (base temperature). Besides, T_e remains constant when the temperature is above a certain maximum effective value (T_{max-e}), Between $T_{max,e}$ and T_{base}, the daily thermal time increase is calculated by linear interpolation (Fig. 6). The development rate (DVR) is obtained by the formula $= T_e/T_{req}$, where T_{req} is the thermal time required to enter the next development stage. The DVR of potato is also influenced by photoperiod (P) as calculated by the eq 2:

$F_{pr}=(P-P_c)/(P_o-P_c)$; $0\leq F_{pr}\leq 1$

$$DVR=F_{pr}\,(T_e/T_{req}) \qquad \text{Eq 2}$$

'where F_{pr} is the photoperiod reduction factor for the development rate until flowering, P_o is optimum photoperiod and P_c is critical photoperiod'(Boogaard et al., 2014).

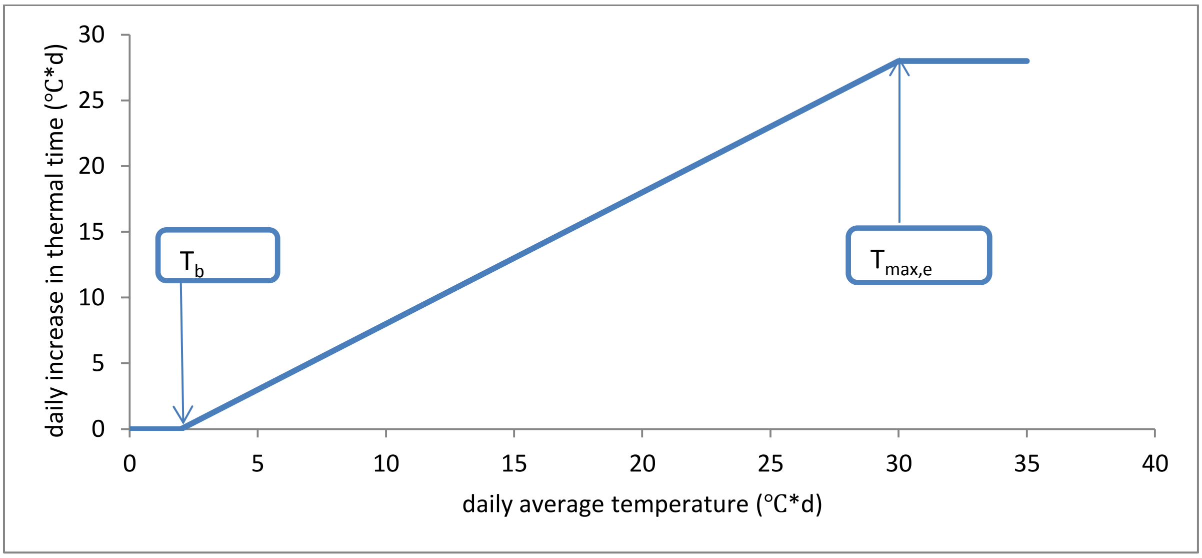

Fig. 6. Relation between daily average temperature (°C) and daily increase in the thermal time [°C*d], for the calculation of the development stage of a potato crop (T_{base} = 2 °C, $T_{max,e}$ = 28 °C) (modified from Boogaard et al., 2014).

3.2.2 Light interception and assimilation

WOFOST uses absorbed radiation (I_a) and the photosynthesis-light response curve of individual leaves to calculate daily CO2-assimilation rate. Temperature and leaf age determine the response curve. Total incoming radiation and the leaf area determine the absorbed radiation. There are two factors influencing photosynthesis response to light intensity. The first factor relates to the different levels of lights received in the canopy along the vertical plane. To calculate this, the canopy is divided into different layers. At each leaf layer, intercepted light is derived from the radiation flux at the top of the canopy and the transmission by overlying layers. The other factor is temporal, caused by the daily cycle of sun. WOFOST uses the eq 3 to simulate the mentioned two factors:

$I_0 = I \sin\beta$

$I_{aL} = dI_L/dL = (1-\rho) I_0 e^{-kLAI_L}$ Eq 3

'where I_0 is the radiation level at the top of the canopy on a clear day; β is sine of the angle between the sun and the earth's surface; I_{aL} is the adsorbed radiation by leaf layer L; I_L is the net radiation flux at depth L; k is the extinction coefficient; ρ is a reflection coefficient which is a function of solar elevation, leaf angle distribution, and reflection and transmission properties of the leaves; LAI_L is the cumulative leaf area index at depth L ([m^2 (leaf) m^{-2} (ground)]. (Boogaard et al., 2014).' After the light interception is settled, the instantaneous assimilation rate of a leaf layer can be calculated by the eq 4:

$A_L = (1 - e^{-\varepsilon(I_{aL}/Am)})$ Eq 4

'Where A_L is the gross assimilation rate [kg (CO_2) m^{-2} (leaf) s^{-1}]; A_m is the maximum gross assimilation rate; ε is the initial light use efficiency [kg (CO_2) J^{-1}'(Spitters et al., 1989);

By integrating the assimilation rates over layers and time, daily gross CO_2 assimilation is obtained. In this procedure, it is assumed that incoming radiation over the day is a sinusoidal course and a three-point Gaussian integration method (Goudriaan, 1986) is performed. Part of the assimilates are used for maintenance respiration, which is estimated based on the dry weight of different organs and their chemical composition. Assimilates are distributed to different organs and the assimilate partitioning is determined by the development stage (Fig. 7) (Penning de Vries, 1975; Penning de Vries et al., 1989).

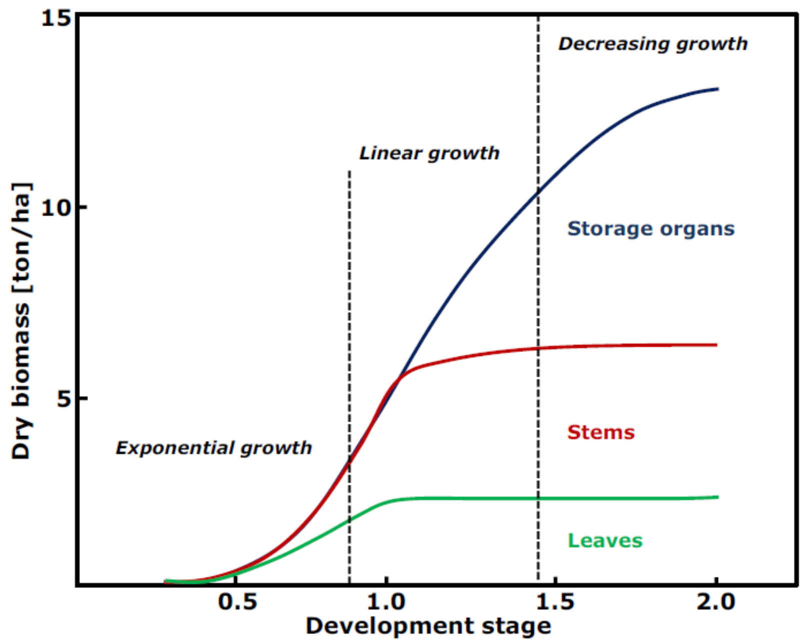

Fig. 7. An example of assimilates distribution by different development stages (Boogaard et al., 2014).

3.3 Structure of SWAP

The model SWAP (Soil Water Atmosphere Plant) was used for the hydrological simulation in this study. Most part of this section was from the SWAP manual (Van Dam et al., 2008). SWAP is an agro-hydrological model (Fig. 8). SWAP simulates transport of water, heat and solute in the vadose zone in interaction with vegetation development (Van Dam et al., 2008). SWAP is designed to simulate the transport process at field level during the growing season and it is a one-dimensional, vertically directed model. SWAP can be applied to plan irrigation, including timing criteria and depth criteria. SWAP requires inputs such as meteorological data, crop growth and drainage (Van Dam et al., 2008).

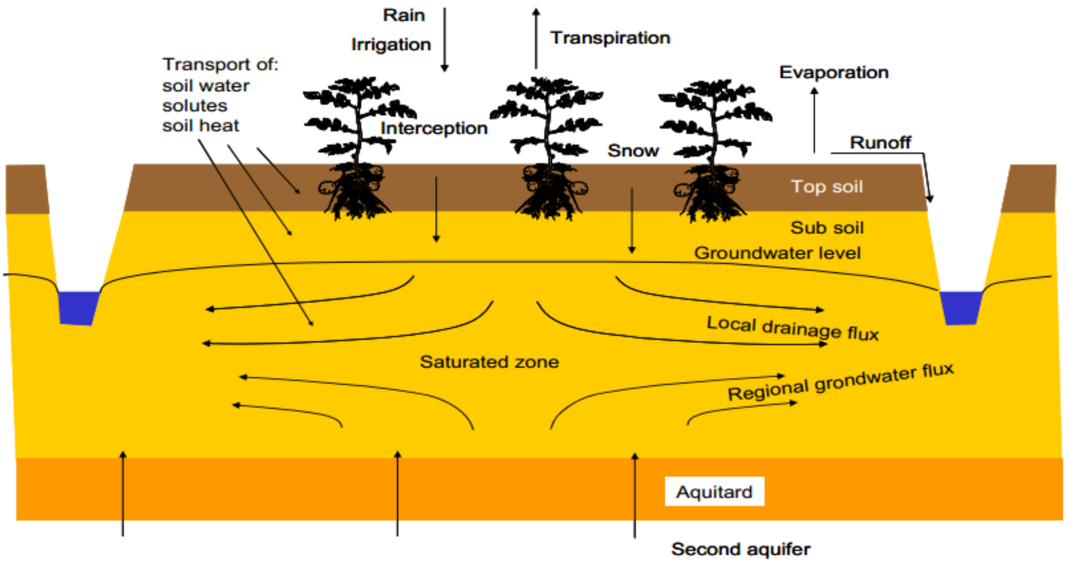

Fig. 8. SWAP model domain and transport process (Van Dam et al., 2008)

3.3.1 Soil water flow and bottom boundary condition

SWAP uses Darcy's eq to quantify vertical soil water fluxes (eq 5):

$$q = -K(h)\frac{\partial(h+z)}{\partial z} \qquad \textit{Eq 5}$$

'where q is soil water flux density (positive upward) (cm d^{-1}), K(h) is hydraulic conductivity (cm d^{-1}), h is soil water pressure head (cm) and z is the vertical coordinate (cm), taken positively upward (Van Dam et al., 2008)*'*.

By considering soil volume as infinitely small, the continuity eq for soil water is obtained (eq 6):

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q}{\partial z} - S_a(h) - S_d(h) - S_m(h) \qquad \textit{Eq 6}$$

'where ϑ is volumetric water content (cm^3 cm^{-3}), t is time (d), $S_a(h)$ is soil water extraction rate by plant roots (cm^3 cm^{-3} d^{-1}), $S_d(h)$ is the extraction rate by drain discharge in the saturated zone (d^{-1}) and $S_m(h)$ is the exchange rate with macro pores (d^{-1})' (Van Dam et al., 2008).

By combing the eq (5) and eq (6), general soil water flow was generated as Richard's eq (7):

$$\frac{\partial\theta}{\partial t} = -\frac{\partial[K(h)(\frac{\partial h}{\partial z}+1)]}{\partial z} - S_a(h) - S_d(h) - S_m(h) \qquad \text{Eq 7}$$

SWAP solves Richards's eq numerically with the known relation between θ, h and K. Richard's eq is applied in SWAP integrally for the unsaturated-saturated zone. More detail information can be found in the SWAP manual.

As for bottom boundary conditions, one of the options is to prescribe groundwater levels. A field-averaged ground water level (ϕ_{avg}) is given as a function of time. SWAP linearly interpolates between the dates and times at which the groundwater levels are specified.

3.3.2 Rainfall interception and evapotranspiration

SWAP simulates intercepted precipitation by the eq proposed by Von Hoyningen-Hüne (1983) and Braden (1985) (eq 8):

$$P_i = a \cdot LAI(1 - \frac{1}{1+\frac{b \cdot P_{gross}}{a \cdot LAI}}) \qquad \text{Eq 8}$$

'where Pi is intercepted precipitation (cm d^{-1}), LAI is leaf area index, P_{gross} is gross precipitation (cm d^{-1}), a is an empirical coefficient (cm d^{-1}) and b is the soil cover fraction (-)' (Van Dam et al., 2008). According to eq 8 intercepted precipitation can asymptotically reach to the saturation amount (a·LAI) by increasing precipitation amounts. In principle, coefficient *a* must be determined by experiment and specified in the input file. For the ordinary agriculture crops, *a* is assumed as 0.025 cm d^{-1}. Coefficient b is estimated by eq 9:

$$b = 1 - e^{-K_{gr}LAI} \qquad \text{Eq 9}$$

'where b is the soil cover fraction and K_{gr} is the extinction coefficient for solar radiation'(Van Dam et al., 2008)

As for evapotranspiration, it refers to transpiration of plants and evaporation from the soil or ponding on the soil surface. It is assumed that root water extraction is equal to plant transpiration, because the water fluxes trough the canopy are larger than what is stored. The Penman-Monteith eq has become an international standard of potential evapotranspiration, due to its best performance in all kinds of climate conditions. Therefore, in SWAP the Penman-Monteith eq is used to calculate evapotranspiration (eq. 10):

$$ET_P = \frac{\frac{\Delta_v}{\lambda_w}(R_n - G) + \frac{p_1 \rho_{air} C_{air}}{\lambda_w}\frac{e_{sat} - e_a}{r_{air}}}{\Delta_v + \Upsilon(1 + \frac{r_{crop}}{r_{air}})} \qquad \text{Eq 10}$$

'where ET_p is the potential transpiration rate of the canopy (mm d^{-1}), Δv is the slope of the vapour pressure curve (kPa °C^{-1}), λ_w is the latent heat of vaporization (J kg^{-1}), Rn is the net radiation flux at the canopy surface (J m^{-2} d^{-1}), G is the soil heat flux (J m^{-2} d^{-1}), p1 accounts for unit conversion (=86400 s d^{-1}), ρ_{air} is the air density (kg m^{-3}), C_{air} is the heat capacity of moist air (J kg^{-1} °C^{-1}), e_{sat} is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), γ_{air} is the psychrometric constant (kPa °C^{-1}), r_{crop} is the crop resistance (s m^{-1}) and r_{air} is the aerodynamic resistance (s m^{-1})' (Van Dam et al., 2008).

The estimation of potential and actual evapotranspiration is possible with the Penman-Monteith eq, but this approach requires canopy and air resistance which is not available for many crops. Therefore, SWAP uses two steps to calculate actual evapotranspiration. The first step is the calculation of potential evapotranspiration with the minimum value of canopy resistance and the actual air resistance. Detailed information on this step can be found in the SWAP manual. The second step is to calculate actual evapotranspiration by taking into account of root water uptake due to water and/or salinity stress. The potential root water uptake is calculated in SWAP as follows:

$$S_p(z) = \frac{\iota_{root}(z)}{\int_{-D_{root}}^{0} \iota_{root}(z)dz} T_p \qquad \text{Eq 11}$$

'where Sp(z) is the potential root water extraction rate at a certain depth, $l_{root}(z)$ is ,D_{root} is the root layer thickness, T_p is potential evapotranspiration'(Van Dam et al., 2008).

$S_p(z)$ can be reduced by stress of dry or wet conditions, which is explained in the next section.

3.3.3 Water stress and oxygen stress

In SWAP, water stress is described by the function proposed by Feddes et al. (1978), which is interpreted in Fig. 9. In the range of $h_3<h<h_2$, water uptake is optimal. Below h_3 water uptake linearly decreases due to drought stress until point h_4 (wilting point). Above h_2 water uptake linearly decreases due to insufficient aeration until 0 at h_1. The critical pressure head h3 increases for higher potential transpiration Tp (Fig. 9).

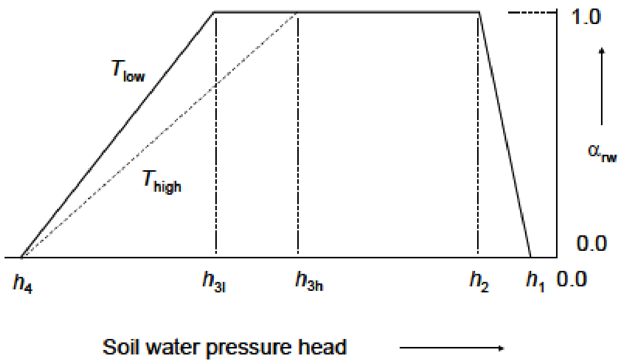

Fig. 9. Reduction coefficient for root water uptake, α_{rw}, as function of soil water pressure head h and potential transpiration rate Tp (Feddes et al., 1978).

In this study, salinity is not taken into account, so the actual root water flux Sa(z) (d^{-1}) is calculated as:

$$S_a(z) = \alpha_{rw} S_p \qquad \text{Eq 12}$$

'where a_{rw} is dimensionless water stress coefficient' (Van Dam et al., 2008)

Besides, in SWAP the maximum evaporation rate that the top soil can sustain is calculated by Darcy's law:

$$E_{\max} = K_{\frac{1}{2}}\left(\frac{h_{atm}-h_1-Z_1}{z_1}\right) \qquad \text{Eq 13}$$

'where $K_{½}$ is the average hydraulic conductivity (cm d^{-1}) between the soil surface and the first node, h_{atm} is the soil water pressure head (cm) in equilibrium with the air relative humidity, h_1 is the soil water pressure head (cm) of the first node, and z_1 is the soil depth (cm) at the first node'(Van Dam et al., 2008).

The function of Feddes et al. (1978) is also generally used for oxygen stress assessment. But the Feddes-function does not combine plant physiological and soil physical processes to predict the reduction of root water uptake at insufficient soil aeration (Bartholomeus et al., 2008). Thus, Bartholomeus et al. (2008) proposed a plant physiological and soil physical process-based model to determine the minimum gas filled porosity of the soil (ϕgas_min) when oxygen stress occurs. In this model, they calculated the minimum oxygen concentration in the soil to just sustain roots respiration (micro-scale) and calculated ϕgas_min diffusion from the atmosphere through the soil (macro-scale) which relates to the minimum oxygen concentration (Fig. 10). Also, in the model they included soil type, temperature, organic matter content, soil depth and plant characteristics. They compared the result with the Feddes-function and drew a conclusion that this model based method is better because the Feddes-function might lead to large errors in the prediction of transpiration reduction and growth reduction through oxygen stress. Furthermore, they implemented the model into SWAP to improve the simulation root water uptake and root growth.

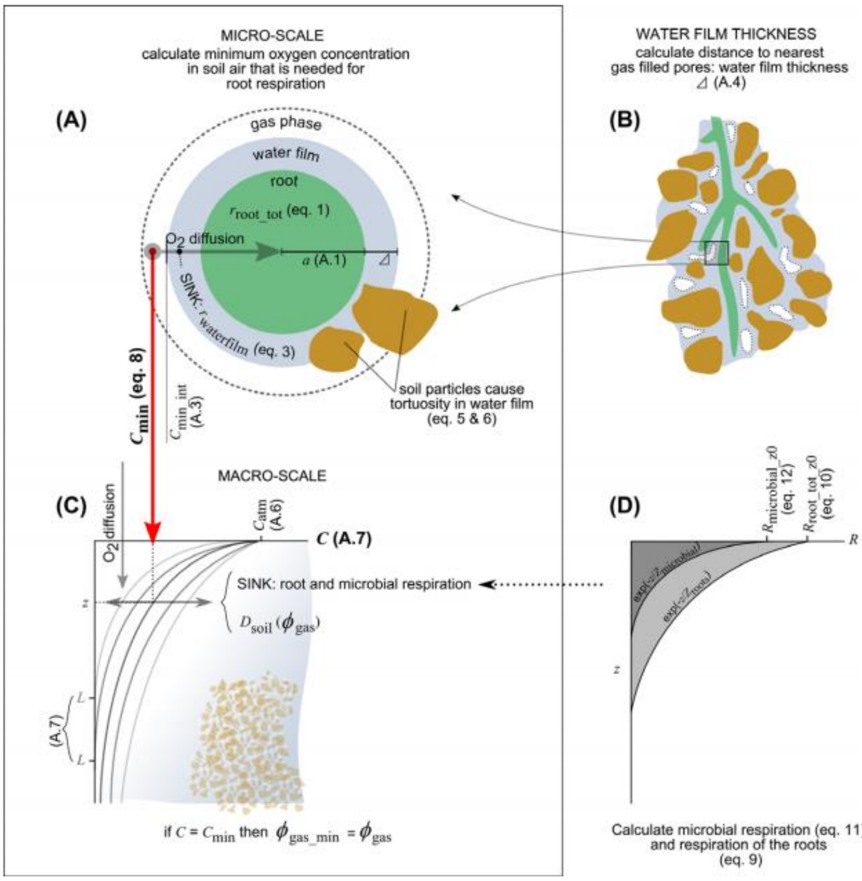

Fig. 10. Scheme for the calculation of critical values for oxygen stress, based on both physiological and physical processes (Bartholomeus et al., 2008).

3.4 WOFOST Calibration for Potential Yield

Before using SWAP-WOFOST to investigate the impact of water and oxygen limitation on potato yields, the crop growth model WOFOST needs to be calibrated. This is because default model parameters are based on experiments from more than 20 years ago (Boons-Prins et al. 1993, Boogaard et al. 2014), and currently observed yields are higher than the simulated potential.

3.4.1 Fields and Data

For WOFOST calibration, the cultivar Fontane was selected because it was widely planted in the years 2013 and 2014, and yields were higher compared to other cultivars. The data of the year 2014 were used for calibration while data from the year 2013 was used for validation. Nine fields were selected with a yield range of 87-105 t/ha. Because of data noise, among these 9 fields, 3 fields were selected: “geudens windmolens”, “wauters achter stal” and “fabrie arendonk”. Tuber yield was measured five times during the growing season (Fig. 11). The sowing date and date of harvest the nine different fields varied, with a range of 22 and 29 days respectively. The measurement dates were similar (one to three days difference) for the same measurement in different fields. However, the records of the second and third measurement dates were incomplete. It was assumed that the missing date is around the date of nearby fields based on other records at the farm level. Moreover, the fourth measurement date differed up to 30 days (Fig. 12).

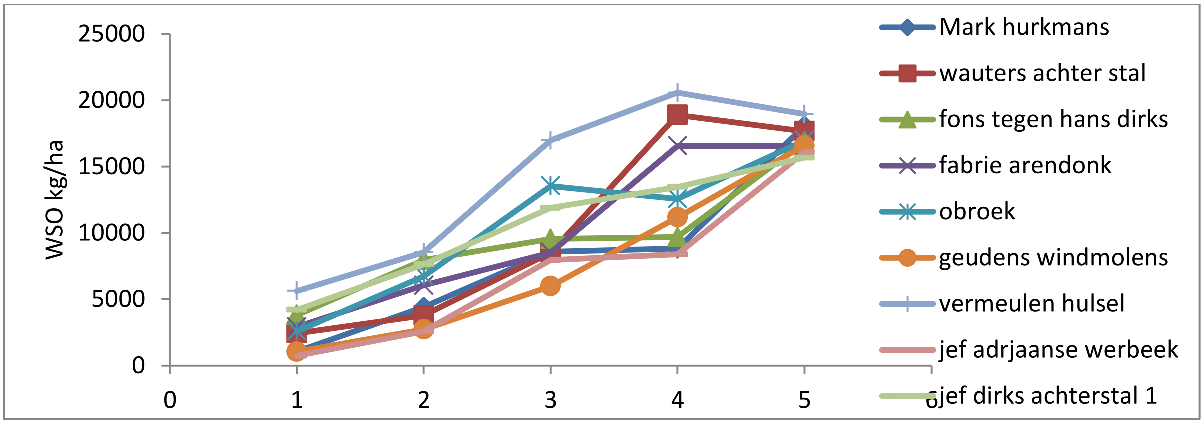

Fig. 11. Observed WSO (dry matter weight of storage organs) of different fields by different measurement times (some measurement days are unavailable) for calibration.

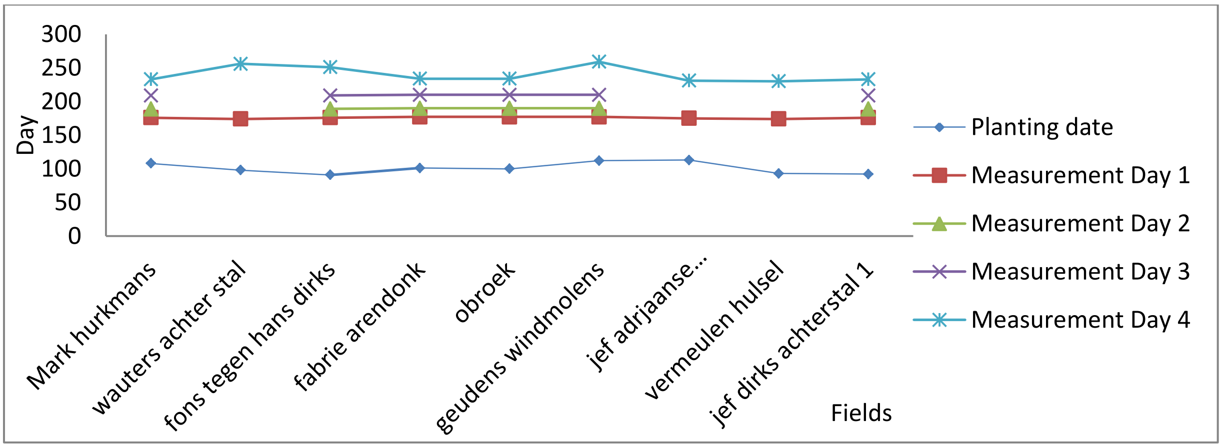

Fig. 12. Different planting and yield measurement days of the nine fields (some measurement days are unavailable).

No experiment was done for potential production circumstances, so it was assumed that highest yields were close to the potential. In order to make a representative and reliable model calibration, several fields were selected. The criterion of fields selection for potential yield calibration was based on the achieved highest yield. As for the data for calibration, fresh tuber yield was measured five times for all the fields during the whole growing period in year 2014. Also under water tuber weight (UWW) of most fields were available which can be used for dry matter content calculation. In this study dry matter content of tuber was calculated as UWW/18 (De Wilde et al., 2006). Data of tuber yield was the key input for calibration. Additionally, phenology such as emergence and maturity were observed for some fields which can be used for phenological calibration. Pictures were made during the growing season in several fields, which allowed to determine emergence and flowing. However, these fields were not the same as the 9 fields selected.

3.4.2 Potential yield without calibration

As a starting point, potential yield was simulated in WOFOST control center (version 2.1.2) with the crop file "Potato 701". The simulation periods correspond to the fields selected for calibration. After simulating the potential yield with default model parameters in 2014, model performance was evaluated by model efficiency.

3.4.3 Model Parameters

Parameters were selected according to the WOFOST calibration manual (Wolf, 2003) as follows: TSUMEM (temperature sum from sowing to emergence), TSUM1 (the temperature sum from emergence to anthesis), TSUM2 (the temperature sum from anthesis to maturity), AMAXTB (maximum leaf CO_2 assimilation rate as a function of development stage of the crop), SPAN (life span of leaves), SLATB (specific leaf area) and assimilates partitioning factors: FSTB (fraction stems), FOTB (fraction organs) and FLTB (fraction leaves). LAI (leaf area index), was not selected due to the limited data availability.

Wolf (2003) gave the procedure for WOFOST calibration. The model calibration should be done in orders due to the variation of the model variables. Ideally, the model calibration needs to be done first for a potential production situation and second for the water limited production. However, in this study specifically water limited production experiments had not been designed and performed, therefore the calibration was done only for potential yield production.

3.4.4 Parameter sensitivity

Before the calibration, a sensitivity analysis was performed to rank the parameters in order of importance for TWSO (total dry weight of storage organs). In this sensitivity analysis only one parameter was changed each time with 5% (Increase & decrease) of the initial value with a total 9 reruns.

3.4.5 Calibration procedure

The calibration is in the following order:

I. Length of growing period and phenology. In this procedure, the sowing date or crop emergence is essential phenology input for WOFOST. In this study, TSUMEM was calibrated first. Based on the farm records, the sowing and emergence dates of several fields (the link to the source data were deleted by farmer so the number of the fields is unknown) were available for TSUMEM calibration. Emergence was observed at day 126 & 133 for sowing day 99 and 141 for sowing day 118. The sowing dates 99 and 118, were used as input in WOFOST. Other parameters that were calibrated in this procedure were TSUM1, SPAN and TSUM2. Fields for TSUM1 calibration were the same as for the TSUMEM calibration. However, there were no records of anthesis for these fields. Indirectly, a picture of anthesis (around day 171) was found for the fields with planting day of 118. In WOFOST, in order to ignore the influence from planting to emergence, a fixed emergence day of 141 (observed emergence day) was used. In order to keep coherence, the SPAN value was calibrated considering the results of previous steps (TSUMEM=220 ℃, TSUM1= 420 ℃), and with a fixed planting day of 118. As for TSUM2 calibration, the default value TSUM2 1550 ℃ was tested first, with the parameter's results of previous steps. In order to make the TSUM2 calibration representative and precise, all the fields in the farm available with observed maturity were chosen, averaged and classified into 7 groups. Each group represents the same sowing day. The difference of sowing dates between the consecutive groups was about 5-10 days. The number of the fields in each group depends on the data and was not exactly the same. In the farm, crop stages were recorded as values between 0-10, in this study, crop stage 10 indicates crop maturity.

II. Light interception and potential biomass production. In this procedure, LAI (leaf area index) should be calibrated to reproduce the observed value and the related parameter is SLATB (specific leaf area) which converts leaf mass in leaf area using the rerun facility in WOFOST. After that the total crop biomass will be calibrated (TAGP) using parameter AMAXTB (maximum leaf CO2 assimilation rate as a function of development stage of the crop).

In the step of AMAXTB calibration, the calibrated parameters values of previous steps were imported (phenology parameters). However, the planting, ending (haulm killing) and tuber yield measurement dates were different for the 9 fields. In order to simplify the AMAXTB calibration procedure, 3 ("geudens windmolens", "wauters achter stal" and "fabrie arendonk") among the 9 fields were selected based on the criteria of a linear tuber yield growth trend and similar growing period, because it is assumed that accumulative potential yield is linear increased with time course. Also the data of the three fields were averaged including sowing, ending and measurement dates and the measured WSO (dry weight of storage organs) values. AMAXTB calibration was first done for the 3 fields, and then evaluated for all the 9 fields until model performance was well enough for most of the fields.

III. Assimilate distribution between crop organs. In this part, the Harvest Index (HI) needs to be calibrated. The model parameters related to the partitioning are the FSTB (fraction stems), FOTB (fraction organs) and FLTB (fraction leaves), which are a function of the development stage (DVS).

3.5 Potential yield validation

To validate the calibration, data of the same cultivar Fontane from 2013 were used. Similar to the calibration, 5 fields with highest yields were chosen for validation. In 2013, fresh tuber yield and under water tuber weight were measured 4 times during the growing season, these values were transformed to dry matter yield with the same function, which is the only indicator for validation.

The fresh tuber yields ranged from 80.35 to 95.21 t/ha (Fig. 13). Planting dates, ending dates and WSO measurements dates were similar for these fields, but some dates data were unavailable. WSO was measured for four times (Fig. 14).

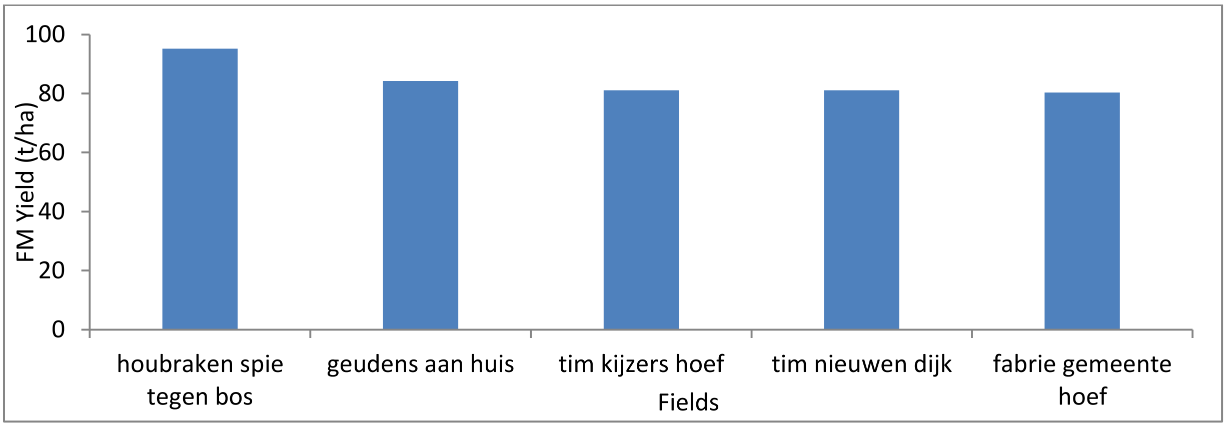

Fig. 13. Observed highest yields (FM t/ha) in year 2013.

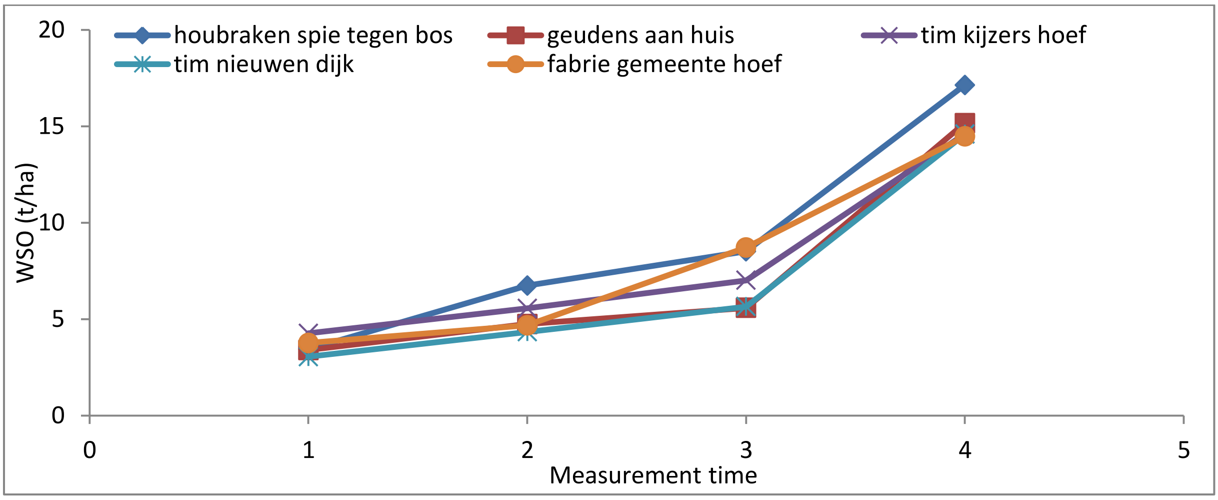

Fig. 14. Observed WSO (DM t/ha) of the five fields with highest yield in 2013.

3.6 Additional statistic methods

Evaluation of model performance was first done by visual assessment. Statistic methods were also used to evaluate parameter values and model efficiency through calibration, including SSE (sum of squared errors; eq 14) and EF (model efficiency; eq 15). Model performance is considered excellent if EF is higher than 0.9, acceptable if 0.8<EF<0.9, poor if EF<0.8

$$SSE = \sum_{i=1}^{N} \left[Y_{i,obs} (X_i) - Y_{i \cdot pred} (X_i, P) \right]^2 \qquad \text{Eq 14}$$

$$EF = \frac{\sum_{i=1}^{n} \left(Obs_i - \overline{Obs} \right)^2 - \sum_{i=1}^{n} (Pred_i - Obs)^2}{\sum_{i=1}^{n} \left(Obs_i - \overline{Obs} \right)^2} \qquad \text{Eq 15}$$

where obs is observation, $\overline{\text{obs}}$ is the mean of obs, pred is prediction (Reidsma et al., 2012).

3.7 Drought & oxygen stress simulation

After WOFOST calibration and validation, drought & oxygen stress simulation were performed.

As for water stress fields selection, unfortunately, no drought or oxygen stress trials were designed and performed in the farm. It was unclear which fields were certainly under water stress. Therefore a series of approaches were applied to select the fields which were possibly under water stress. Fields were selected using the following criteria: I: Actual yields and average yield were compared first; fields with yield under average were desirable choices. II: Secondly, the initial drought sensitivity assessment was taken into account; fields graded as dry and wet were ideal choices. III: Nutrient condition was another factor considered; initial field nutrients were assessed in the farm as poor, average and rich; fields marked as average and rich were better options. VI: In order to make the fields more representative and diverse, the location and the soil types of fields were also considered. Fields with different locations and different vertical soil profiles were more desirable options. V: Constrained by the data availability, fields closer to a metrological station (Dacom) and ground water level monitoring station were chosen. Moreover, the farmer's opinion was also taken into consideration. However, as the ground water level data and soil data were unavailable for Belgium, fields in Belgium were not taken into account. Simulations were performed both for the year 2013 & 2014. As a result, 10 fields were selected in 2013 and 17 fields in 2014.

Data used for the simulations were as follows: I: Initial drought sensitivity of different fields were assessed by the farmer as average, drought, and wet. Weather data were accessed from meteorological station Eindhoven. Parts of the precipitation data from Dacom were supplementary input for different fields. Most of the fields were within a distance of 10 km from a Dacom station (Appendix IV). Precipitation data recorded at fields "Blokseschuur tegen bos" and "Cor weg eersel" were used for simulations in 2013. As for 2014, precipitation data measured from Eindhoven and at fields "Voorsteheide", "Johan kuipers voorhuis" and "Jan luiksgestel achter bos" were used. Detailed information of the actual rainfall data used can be found in Appendix I. Soil property data were explained in section 3.1.3. In total, 15 different sol profiles were used in the simulations. Detailed soil data can be found in Appendix IV & V. Ground water level data were obtained from the Dino Loket website (https://www.dinoloket.nl/) and they were used to define the bottom boundary condition and the initial water content indirectly as a function in SWAP.

The models WOFOST and SWAP were integrated into SWAP-WOFOST for the simulations. Farm management was also specified for each field including sowing date, ending date and irrigation information (date & amount).

For the drought stress, simulations were first done without irrigation. Then in another round, simulations were done with irrigation. A comparison was done between the two types of simulations to find out the yield gap closure by irrigation. As for oxygen stress simulations, the procedure was similar as the drought stress simulations; non-drainage simulations were done first and followed with simulations with drainage, depending on the simulation results. Comparisons were also done for the different simulation scenarios.

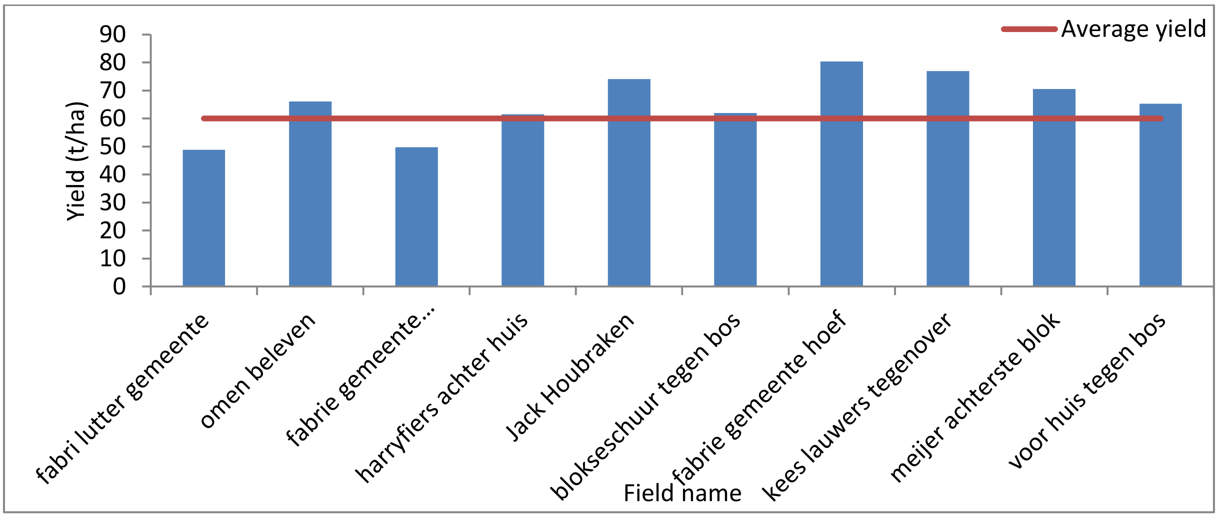

Fig. 15. Observed yield of the selected fields for water stress simulation in 2013

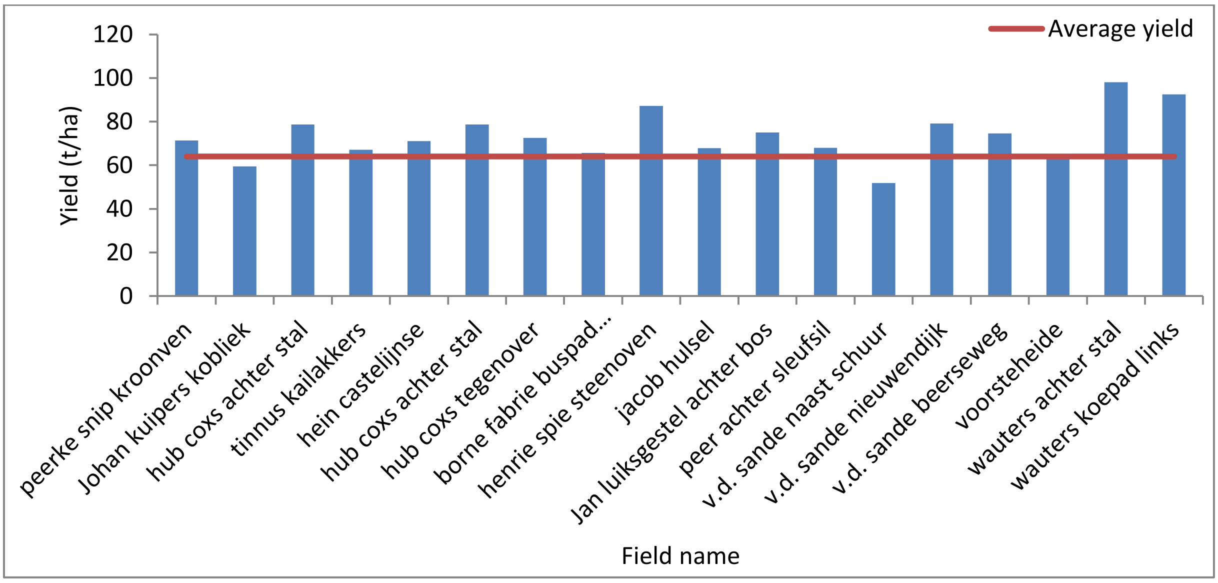

Fig. 16. Observed yield of the selected fields for water stress simulation in 2014

3.7.1 Drought stress sensitivity to precipitation and soil

In order to test the drought stress sensitivity to soil profile, simulations were done with the following settings: using weather data of 2013 and 2014 from Eindhoven to simulate the water limited yield for all the different soil types in this study. Within the same year, the influence of different soil inputs on yield can be compared. Between different years, the influence of different weather can be compared. But the impact of precipitation still cannot be presented. Thus another scenario was applied: in the year 2013, the water limited of field (“fabri lutter gemeente”) with different precipitation data from Dacom (“blokseschuur tegen bos” & “cor weg eersel”) were simulated and compared. Therefore, the impact of precipitation and soil inputs were both investigated.

3.7.2 Pressure head and ground water level

As described in section 3.3.3, SWAP-WOFOST uses soil water pressure head values to indicate drought and oxygen stress. However, it is unclear whether the model default values of pressure head (h) can be used directly without amendment. Therefore, sensitivity analyses were performed to evaluate the relationship between h and water limited yield. Value of h was increased or decreased with 1% or 10 % each time. Sensitivity analyses were not done for all of the different soil profiles, due to its large amounts. Sensitivity analysis was done for field “fabri lutter gemeente” “fabrie gemeente hoef” in 2013 and “wauters achter stal”, “v.d. sande naast schuur” in 2014.

The sensitivity of groundwater levels on water limited yield was also investigated. Two fields were chosen for each year, one with low yield and the other one with high yield. In 2013, fields “fabri lutter gemeente” (48.78 t/ha) and “fabrie gemeente hoef” (80.36 t/ha) were chosen. In 2014, “v.d. sande naast schuur” (51.81 t/ha) and “wauters achter stal“(98.1 t/ha) were chosen. Ground water levels were decreased or increased with steps of 10cm through the year.

3.7.3 Irrigation scheduling

Water balance simulation results can be used for irrigation schedules. The strategy employed in this study is the critical pressure head or moisture content. The automated irrigation is applied when the defined threshold is exceeded: $\theta_{sensor} \leq \theta_{min} \quad \text{or } h_{sensor} \leq h_{min}$

where θ_{sensor} and h_{sensor} are the threshold values for soil moisture and pressure head respectively (Van Dam et al., 2008).

As for the irrigation amount, It is a function of development stage. The soil water content will back to field capacity after automatic irrigation.

4 Results

4.1 Estimating potential yields without calibration

The potential yields of different fields were simulated using default model parameter values and compared with the observed yields (Fig. 18). Model performance is poor and the difference between simulation and observation varied from 16.4 % to 45.6 %, which is 15.35 t/ha and 45.8 t/ha respectively. As yields obtained in the fields cannot be higher than the simulated potential yields, calibration is needed to improve the simulations. Moreover, simulated potential yield of different fields also varied due to the different growing period (sowing & ending dates).

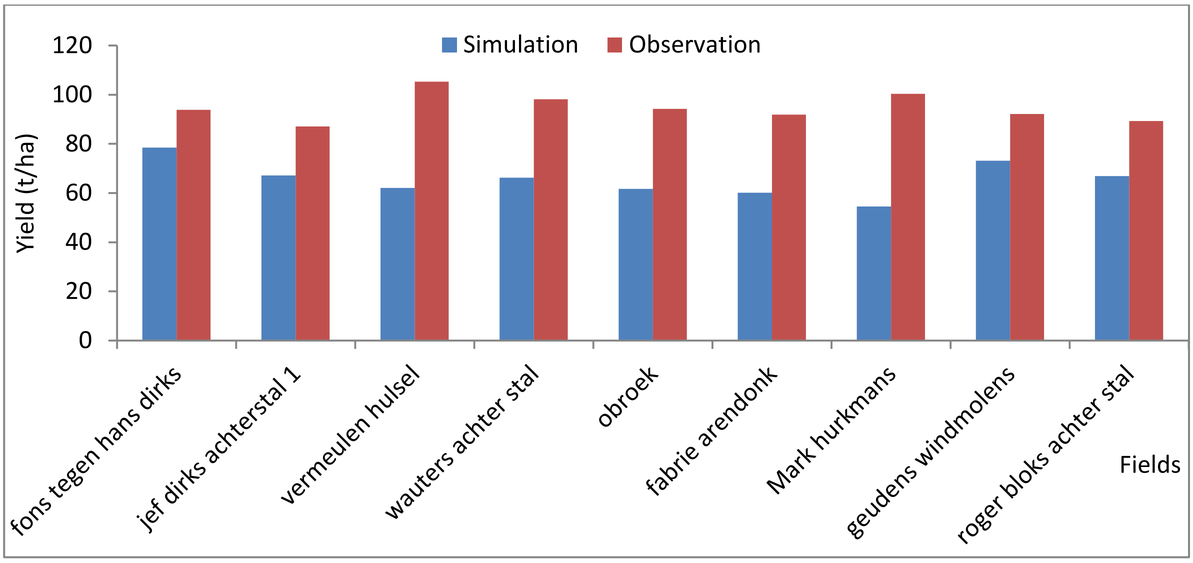

Fig. 18. Simulated potential yields compared to observed fresh yields in the highest yielding fields in 2014 (fields were placed in order of sowing dates; dry matter content was derived from last UWW measurement of each measurement and used to transform simulations from DM to FM).

4.2 Sensitivity analysis

The sensitivity analysis of TWSO to different parameter values was done. Only one parameter was changed each time with 5% (increase & decrease) based on the initial value (Fig. 19). TWSO was found most sensitive to the values of parameters TSUM2 and AMAXTB, around ±3.8 % and ±2.5 % change in TWSO respectively with a 5% change in parameter value. Moreover, TWSO gradually decreased while reducing SPAN value. Also, FOTB 2nd affects TWSO with approximately ±2% for each simulation. TWSO was not found sensitive to other parameters values. As for parameter SLATB, there are three different sub values in different DVS, thus SLATB results were presented as SLATB combined with different DVS. Results show that influence of changing values of SLATB on TWSO is small for all the DVS. Similarly, the parameter FOTB, FLTB, and FSTB have five different values in different DVS. These three parameters were presented with the value changed, for instance changing the first parameter value of FLTB was described as FLTB 1st. As for the results, the influence of FLTB 1st & 2nd , FSTB 1st ,2nd and 3rd on TWSO is small. Based on the results of sensitivity analysis, following step of WOFOST model calibration will focus more on the parameters AMAXTB, TSUM2, SPAN and FOTB 2nd.

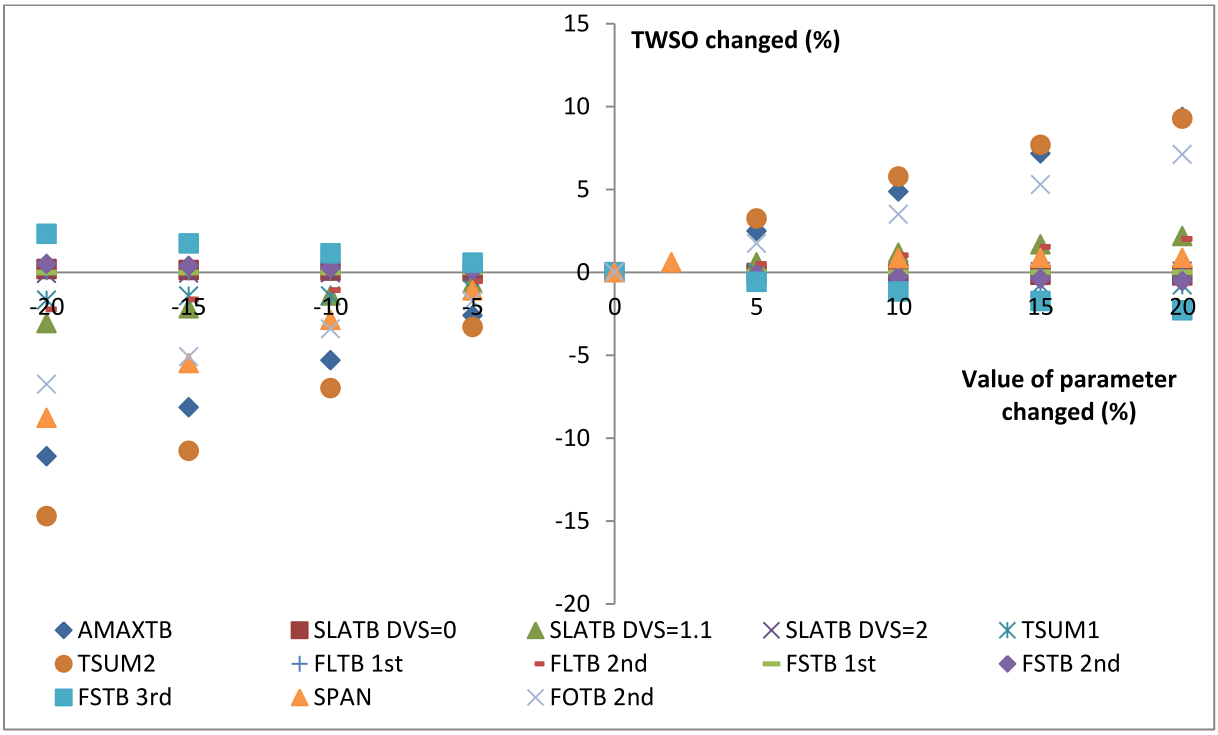

Fig. 19. Sensitivity of TWSO compared to initial default value by changing one parameter value 5% each time.

4.3 WOFOST calibration for potential yield simulation

4.3.1 TSUMEM calibration

Five different TSUMEM values (170 °C (default), 200 °C, 220 °C, 240 °C, 260 °C) were tested and compared (Fig. 20). TSUMEM 240 °C has the lowest SSE of 13, whereas SSE of TSUMEM 260 °C was 16, for TSUMEM of 220 °C it was 17, for TSUMEM of 200 °C it was 49 and for TSUMEM 170 °C it was 104. TSUMEM 220 °C was chosen even though its SSE was not the lowest, because the first observed emergence day varied (126 & 133) which influenced the results of SSE which are based on the average of both. If the first emergence day of 126 would be taken, TSUMEM 220 °C is the best value matching the reality.

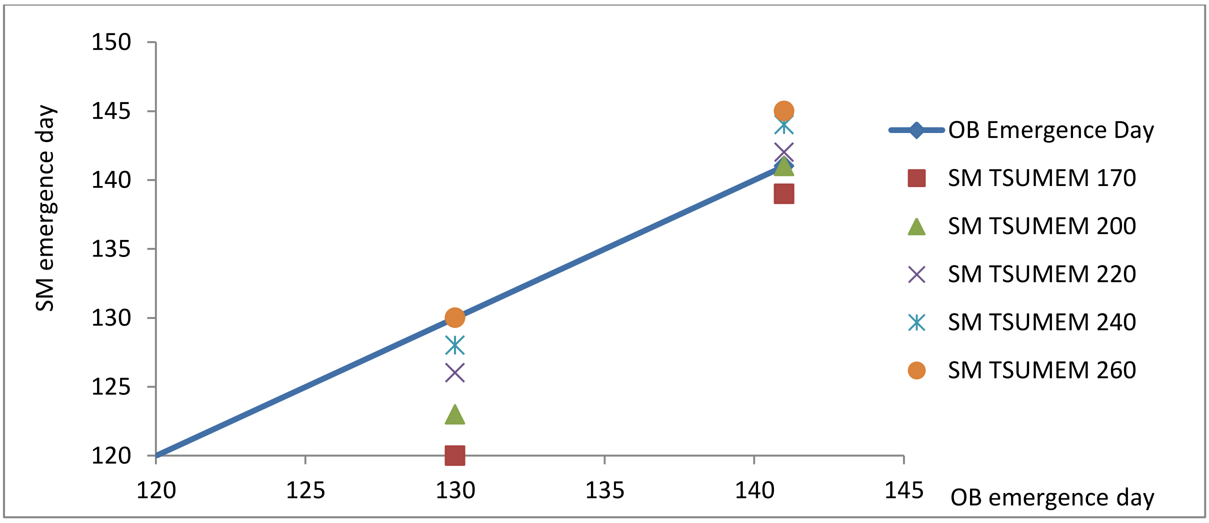

Fig. 20. Observed (OB) and simulated (SM) emergence day with two different planting days.

4.3.2 TSUM1 calibration

Five different TSUM1 values were tested (150 °C, 300 °C, 350 °C, 420 °C, 440 °C) and compared with the observed anthesis day (Fig. 21). With default TSUM 1 (150 °C), simulated anthesis differed 18 days with observation (Fig. 21). TSUM1 of 420 °C was selected and it was “spot on”.

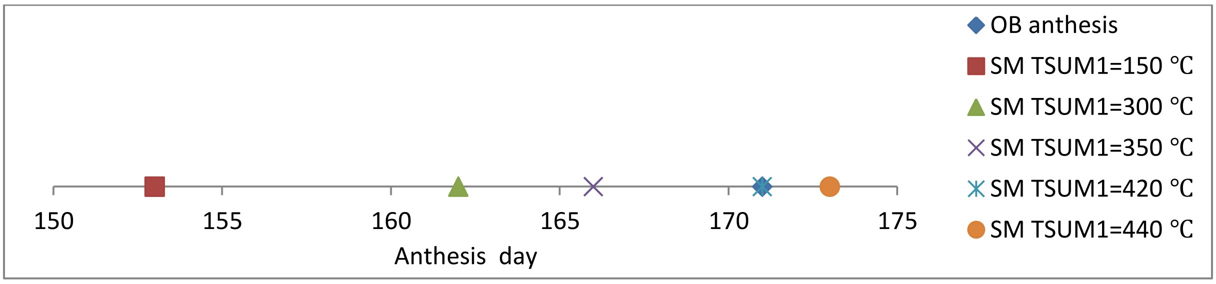

Fig. 21. Observed and simulated anthesis day with different TSUM1 values.

4.3.4 TSUM2 calibration

With the default TSUM2, simulated maturity days varied (3-9 days) from the observations which led to the following calibration. Seven different TSUM2 values were tested and compared with the observed maturity day (Fig. 22). The SSE of TUSM2 1450°C was lowest and SSE of TSUM2 1600 °C was largest (Appendix VI). Besides, the results of group 3 and group 7 were very different from others, the possible reason could be the different sowing depths or the initial tuber size.

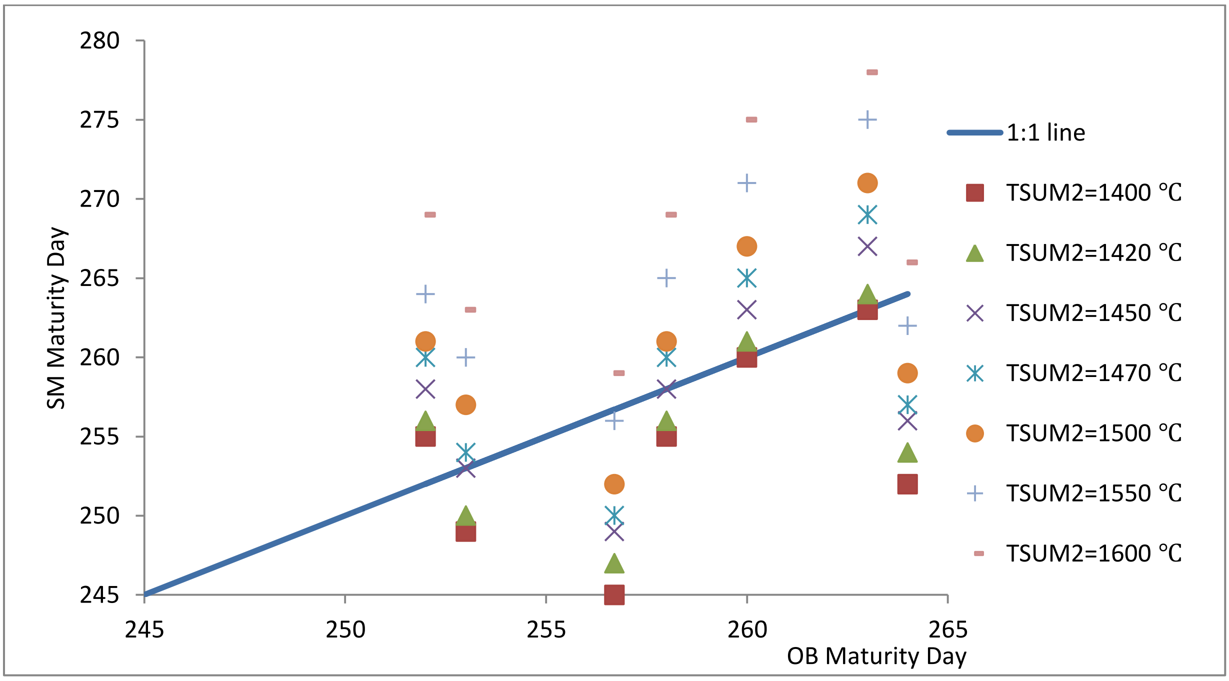

Fig. 22. Observed and simulated maturity with different TSUM2 values.

4.3.3 SPAN calibration

With a default SPAN value of 37 days, the results shows that LAI decreased sharply at day 262. However, according to the observation, with a sowing day of 118, leaves remained green and haulm killing was used to eliminate leaves at day 270. So SPAN needed to be enlarged to match reality. In this section, four different SPAN values were tested and compared with the observed maturity day. The decreasing point of LAI at the end of the growing season is the reference maturity day according to WOFOST. Observed average maturity was at day 270 for the sowing day 118 across the farm. In the simulation, the growing periods (sowing to maturity) of all the SPAN values under 41 days were shorter than the observation (Fig. 23). Thus, SPAN should be taken larger than 41. As there were variances in the fields, some had a late maturity than day 270. Hence, a SPAN value of 43 was chosen.

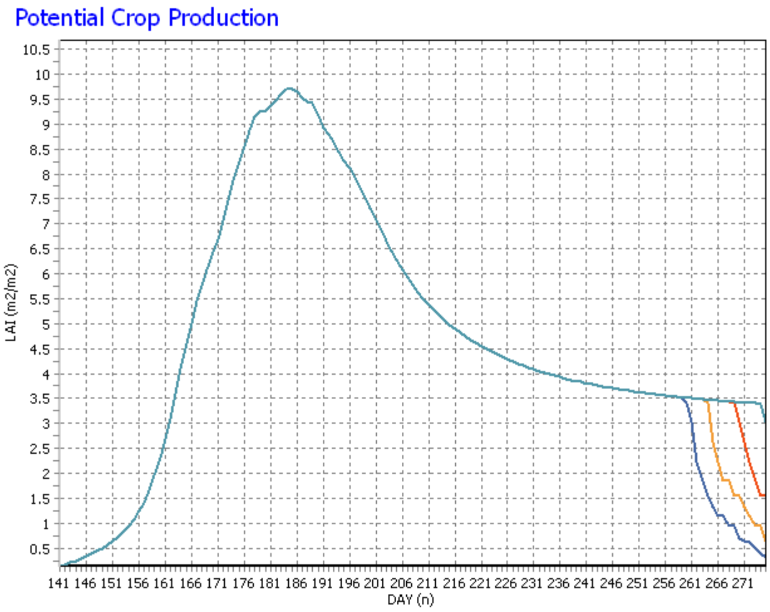

Fig. 23. Life span of leaves with different SPAN values (default SPAN=37 blue; SPAN=39 orange; SPAN=41 red; SPAN=43 green)

4.3.5 AMAXTB calibration

Parameter values were taken based on the previous calibration results (TSUMEM=220 °C, TSUM1=420 °C, TSUM2=1450 °C, SPAN 43 days**)**, and several different combined AMAXTB values were tested and compared with the observed WSO (Fig. 25). Model efficiency (0.9819, 0.9810, 0.9847) was only evaluated for simulations 5, 6 and 7 while simulations 1-4 were assessed visually due to its poor performance. Parameter AMAXTB values are a function of DVS of the crop. There are three different DVS (0.00; 1.57; 2.00) related to AMAXTB of potato in WOFOST. The overview of the parameter values changed during the AMAXTB calibration was summarized (Table. 1).

	SM1	SM2	SM3	SM4	SM5	SM6	SM7
AMAXTB	30; 30; 0	65; 65; 65	65; 65; 20	200;200;20	65; 65; 0	65; 65; 0	47; 47; 0
TSUM1	420 °C	420 °C	420 °C	420 °C	320 °C	320 °C	320 °C
TSUM2	1450 °C	1450 °C	1450 °C	1450 °C	1450 °C	1650 °C	1650 °C

Table 1. Values of parameter changed (indicated in red) during AMAXTB calibration.

AMAXTB with default values (30; 30; 0) was tested first (SM1) and results show that simulated TWSO was much lower (5686 Kg/ha, DM) than the observation (fig. 25). AMAXTB should be increased to reach a higher production level. AMAXTB (65; 65; 65) was tested secondly (SM2), but the results of the last two simulation points were too high (757 and 2235 Kg/ha, DM). In order to decrease the simulated WSO in later stage of the growing period, the third value of AMAXTB was decreased: AMAXTB (65; 65; 20) was tested (SM3). The results show that the last two simulations points decreased, but the first two were too low (1397 and 1680 Kg/ha, DM). In other words, the first two AMAXTB values need to be increased to achieve higher WSO in early tuber growth stage. Increasing AMAXTB (200; 200; 20), the first two simulated (SM4) values were still much lower (1331 and 1457 Kg/ha, DM) compared to the observation. As even with the first two values of AMAXTB to be 200 there was no significant improvement in the simulated values of the first two WSO, which means AMAXTB was apparently not the constraint in this growing phase.

There are two constraints for WSO accumulating; phenology and AMAXTB. In terms of phenology, an early tuber initiation will enable a longer period for tuber growth, which means a lower TSUM1 value. Hence, TSUM1 was decreased from 420 ℃ to several different values and tested with AMAXTB (65; 65; 0). With TSUM1=320 ℃ life span was 10 days shorter than the observation (SM5), but model efficiency reached 0.9819. In order to have a longer life span, parameter TSUM2 was increased to several different values and tested. Within these different values, in SM6, TSUM2 was increased to 1650 ℃ and with the same AMAXTB (65; 65; 0), model efficiency was 0.9810 and life span matched with reality, but the last two points of simulation were too high compared to the observation. Several AMAXTB values were tested again based on the new phenology parameter settings. As a result, ranges of the first two AMAXTB values (around 44-55) were found to reach high model efficiency (higher than 0.98). Reducing AMAXTB to (47; 47; 0), model efficiency slightly increased to 0.9847 (SM7). Since there was no significant difference in values around 47 kg/ha.hr, AMAXTB (47; 47; 0) was chosen after the calibration.

Model efficiency of the AMAXTB calibration was based on the data of three fields among all nine fields with highest yields. In order to check the model performance for all of the chosen fields with highest yield, after the AMAXTB calibration was done, all of the calibrated model parameters were included for the potential yield simulations. Simulated potential yields were compared with all the nine fields, specifically for the individual growing periods and tuber yield measurements (Fig. 26). Model efficiency was evaluated for all of the nine fields (Fig. 27). The model performed well for six fields with a model efficiency range of 0.84-0.94. However, model efficiency for the field “obroek” was only 0.69, for the field “fons tegen hans dirks” it was 0.43 and for field “vermeulen hulsel” it was 0.29. As for the results of fields with poor model efficiency, especially for the field “vermeulen hulsel”, the model underestimated reality to a great extent. The most possible reason is that the model calibration was based on the criterion of linearly growing trend, whereas the observation values were not. Also, the other fields chosen for calibration had relatively lower yields compared to this one.

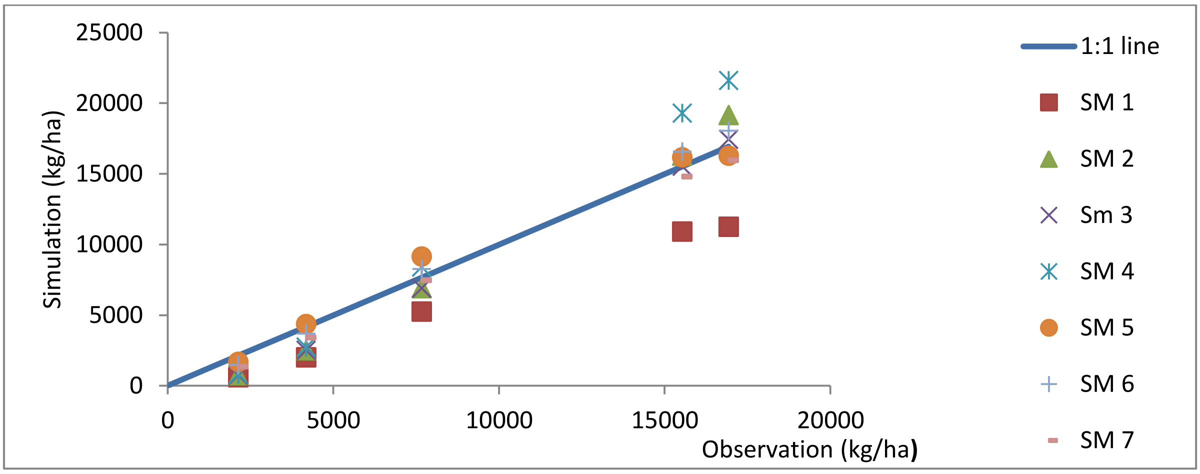

Fig. 25. Mean observed WSO of three selected fields and simulated WSO with different AMAXTB values (SM1 was the default).

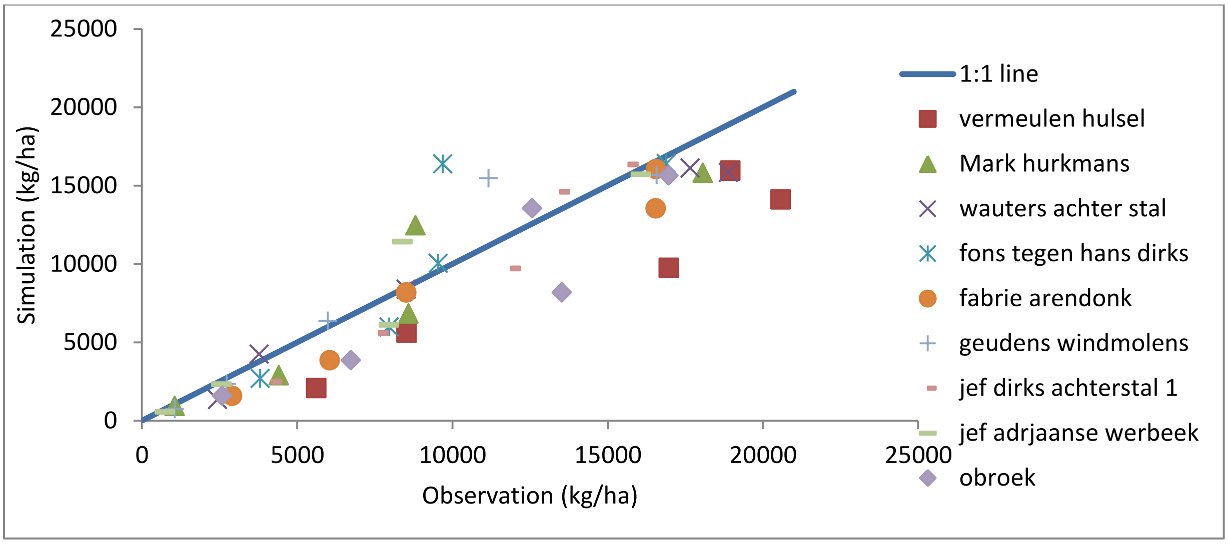

Fig. 26. Observed WSO of nine fields and simulated WSO with the calibrated AMAXTB.

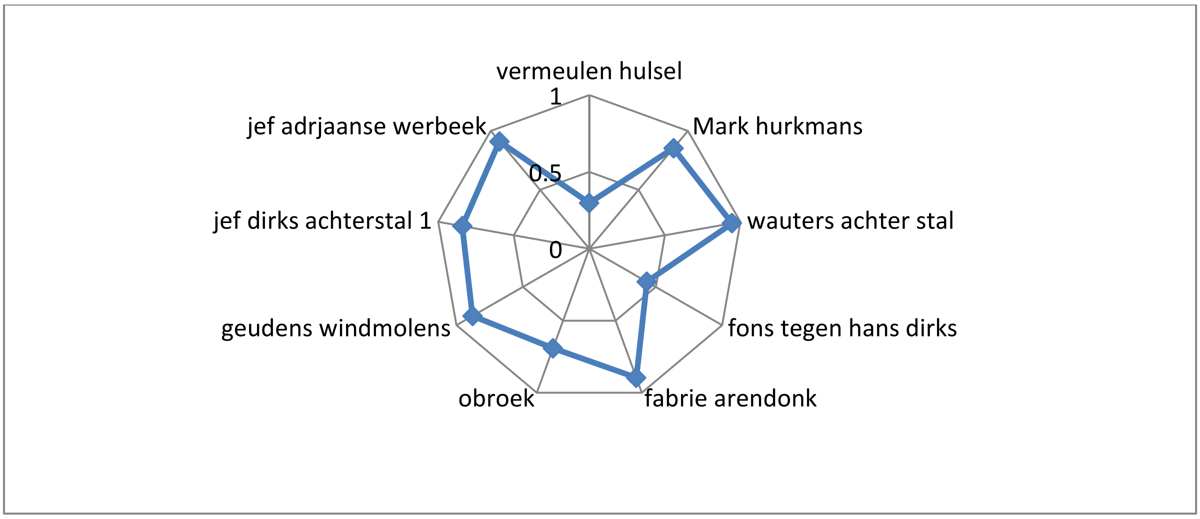

Fig. 27. Model efficiency for different fields with calibrated model parameters in 2014.

4.3.6 WOFOST validation

The calibrated model was validated with the data of selected five fields with highest yield in 2013 (Fig. 28). Due to the different growing periods and measurement dates, validation was performed for each field specifically. Model efficiency was considered excellent for most of the fields (4 out of 5). Field “fabrie gemeente hoef” and “houbraken spie tegen bos” reached a model efficiency of 0.95 and 0.93 respectively, model efficiency of fields “geudens aan huis” and “tim kijzers hoef” were both 0.89 and acceptable. However, model efficiency of field “tim nieuwen dijk” was poor, only 0.76. In general, model validation results show that calibration was well enough for the year 2013. However, one good validation for one year is no guarantee that the model is successfully calibrated for the long term period. The weather in both years was quite different however, especially the start of the spring. Highest yields in 2014 were 7 to 10 t/ha higher than in 2013, and this difference was well reflected in the model.

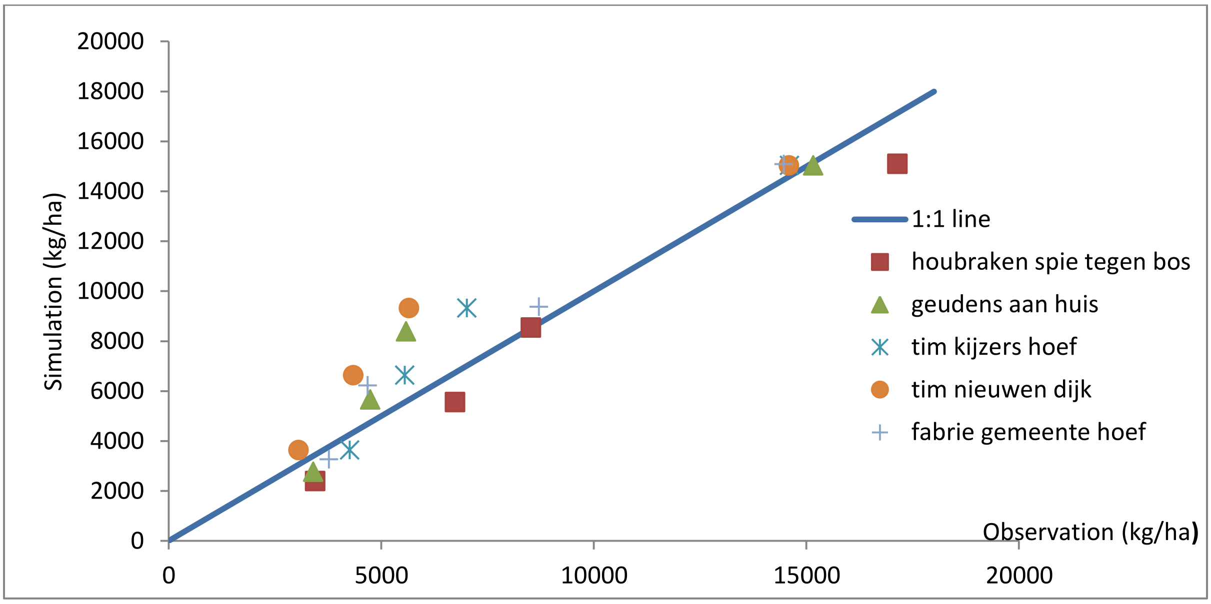

Fig. 28. Observed and simulated attainable yield of year 2013.

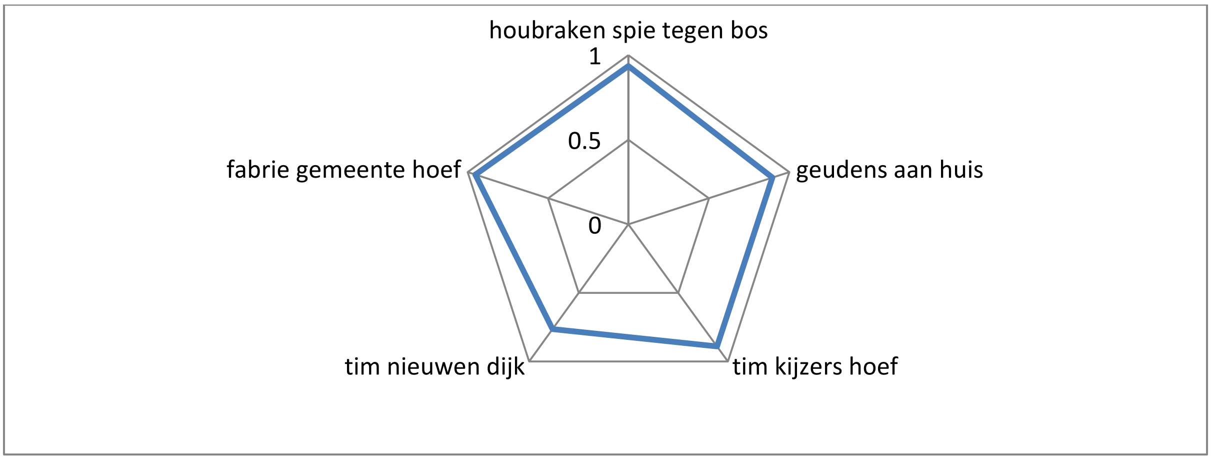

Fig. 29. Model efficiency of different fields with highest yield in 2013.

4.4 Drought & oxygen stress simulation

4.4.1 Water limited yield without irrigation

Potential and water limited yields of different fields were simulated and compared both for the year 2013 & 2014 (Fig. 30 & 31). In 2013, water limited yield of most selected fields (9 out of 11) was much lower than the potential yield, the difference ranging from 18.7 to 31.0 t/ha. In 2014, water was not a yield limiting factor, yield gap between potential and water limited existed (0.6-10.7 t/ha) but was not as significant as in 2013. Water limited yield in 2013 varied (up to 18.85 t/ha). The most likely reasons are different soil conditions, since the weather conditions were almost the same.

In order to investigate the reasons for variations in the water limited yields, the water balance (Fig. 32) was compared in the fields that differed most ("fabrie gemeente hoef" & "fabri lutter gemeente"). The bottom flux at field "fabri lutter gemeente" was 14.13 cm higher than field "fabrie gemeente hoef". Transpiration at field "fabri lutter gemeente" was 7.17 cm lower than field "fabrie gemeente hoef". In total, the water storage of field "fabri lutter gemeente" was -12.64 cm and -5.82 cm at field "fabrie gemeente hoef". Sowing dates were similar (one day difference). Initial groundwater levels can also be regarded as the same (-118 and -120 cm). However, these two fields have different profiles and soil hydraulic functions. The different hydrological parameter values relate to differences in the field's water holding capacity; and different vertical profiles lead to different depths and types of soil layers, which finally result in different soil water contents; different water stress levels thus the different yields. For other fields, other factors also play an important role. Different sowing dates lead to different DVS, and thus different water requirement and water stress sensitivity at the same time.

No significant oxygen stress was found both in the year 2013 and 2014. Slight oxygen stress only occurred in 2014 at 6 fields for few days (2 or 3) only. Compared to drought stress, oxygen stress happened at a different time, at the end of May or the beginning of June. Meanwhile, through the growing season the simulated most severe oxygen stress accounted no more than 0.07 cm in total for the difference between potential transpiration and actual transpiration. Possible explanation can be related to soil characteristics and climate conditions. The sandy soil is the dominant soil type in the south of the Netherlands. With its good aeration and low water holding capacity, potato is much more sensitive to drought stress compared to oxygen stress. Besides, with the temperate marine climate (few intensive showers), potato is less likely under oxygen stress compared to tropical rainforest climate or subtropics monsoon climate. Therefore, oxygen stress was not further explored.

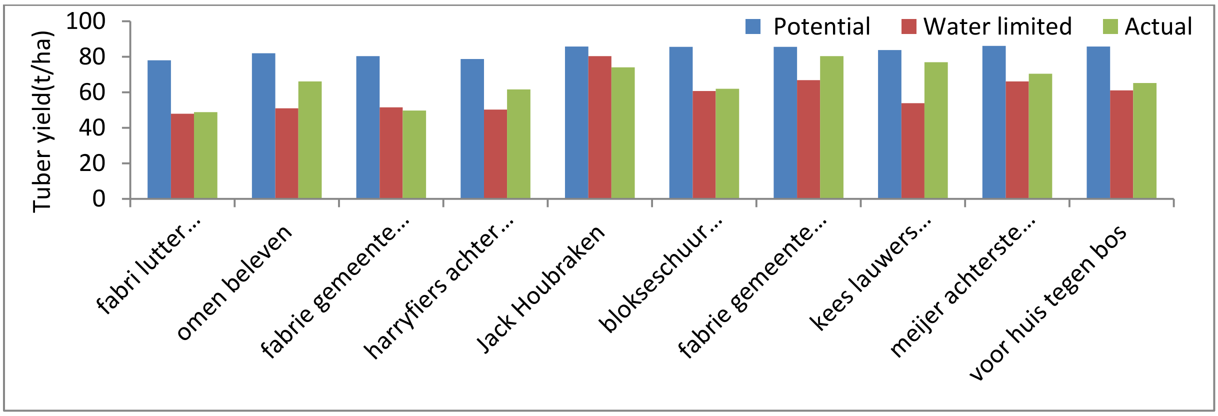

Fig. 30. Actual, water limited and potential yield in 2013.

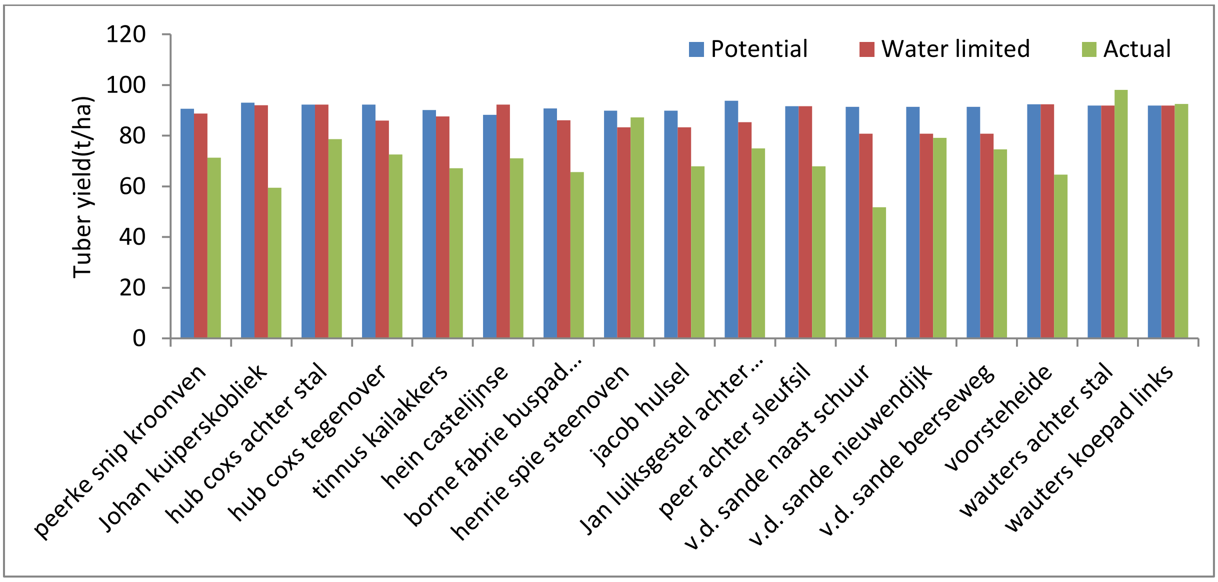

Fig. 31. Actual, water limited and potential yield in 2014.

Water balance components (cm)

In			Out		
Rain + snow	:	68.38	Interception	:	2.75
Runon	:	0.00	Runoff	:	0.00
Irrigation	:	0.00	Transpiration	:	29.82
Bottom flux	:	-38.32	Soil evaporation	:	10.13
			Crack flux	:	0.00
Sum	:	30.06	Sum	:	42.70

Water balance components (cm)

In			Out		
Rain + snow	:	68.38	Interception	:	3.17
Runon	:	0.00	Runoff	:	0.00
Irrigation	:	0.00	Transpiration	:	36.99
Bottom flux	:	-24.19	Soil evaporation	:	9.31
			Crack flux	:	0.00
Sum	:	44.19	Sum	:	49.47

Fig. 32. Water balance of field “fabri lutter gemeente” (left) and “fabrie gemeente hoef” (right) in 2013.

4.4.2 Sensitivity analysis of pressure head and underground water level

Only one value of H_1, H_2, H_{3l}, H_{3h}, H_4 was changed with ±1% at each time. Results showed that water limited yields with different h values were remain same. Considering field “fabri lutter gemeente” in 2013 was already under severe drought stress conditions, 1% changing of h values could have little impact on water limited yield. So a new sensitivity analysis with 10% change of h values was tested at each time. Results are as same as previous only slightly difference by changing H_4 values but it can be neglected. In order to make the sensitivity analysis more representative, other three fields: “wauters achter stal”, “v.d. sande naast schuur” in 2014 and “fabrie gemeente hoef” in 2013 were also performed with sensitivity analysis. Field “fabrie gemeente hoef” in 2013 were under middle drought stress level, while there were no drought stress in fields “wauters achter stal”, “v.d. sande naast schuur” in 2014. With 1 % changing of values of h1, h2, h3h ,h3l and h4, yield remained same for the fields in 2014. Simulated actual yield was found negatively related to h4 value in field “fabrie gemeente hoef” in 2013. But simulated Ya only increased 24 kg/ha with h4 value increased from 9600 to 10400, which can be ignored. Reason to explain the results is that with the same simulated h value, a predefined lower h4 value result in a higher α_{rw} value which means less drought stress and higher yield. Since only the value of h4 has impact on Yw while the field in under drought stress, more tests were done with the continuing increasing h4 value for field “fabrie gemeente hoef” in 2013 . Simulated yield was found gradually decreased. In short conclusion, finding the wilting point where the h4 value located is crucial for precise drought stress simulation. Based on the sensitivity analysis results, default h values would be used for water stress simulation. But experiment was recommended to detect the wilting point in the future.

In “fabri lutter gemeente”, no influential oxygen stress was found on the farm in both two years, the effect of another factor was investigated, underground water level (UWL) (Fig. 33). Yw is positively related to UWL in 2013. And it appears that Yw is not sensitive to the UWL in 2014. Possible reason to explain the different effects of underground water levels on Yw is related to the accumulated precipitation during the summer. Yw in 2013 of the two fields were under drought stress during the summer because of the deficiency of rainfall, thus the Yw of fields with low soil moisture content were more sensitive to UWL. In terms of the fields in 2014, yield of field “wauters achter stal” was at optimal level. With sufficient rainfall and good water holding capacity, Yw was not sensitive to UWL. However, field “v.d. sande naast schuur” was also under drought stress during the Julian days of mid to the end of June, which was the tuber initiation stage. But in the followed summer season, large amount of rainfall ensured desirable soil moisture maintained during the tuber filling stage. Therefore, UWL was of sub-importance and Yw was less sensitive to it compared to the fields in 2013.

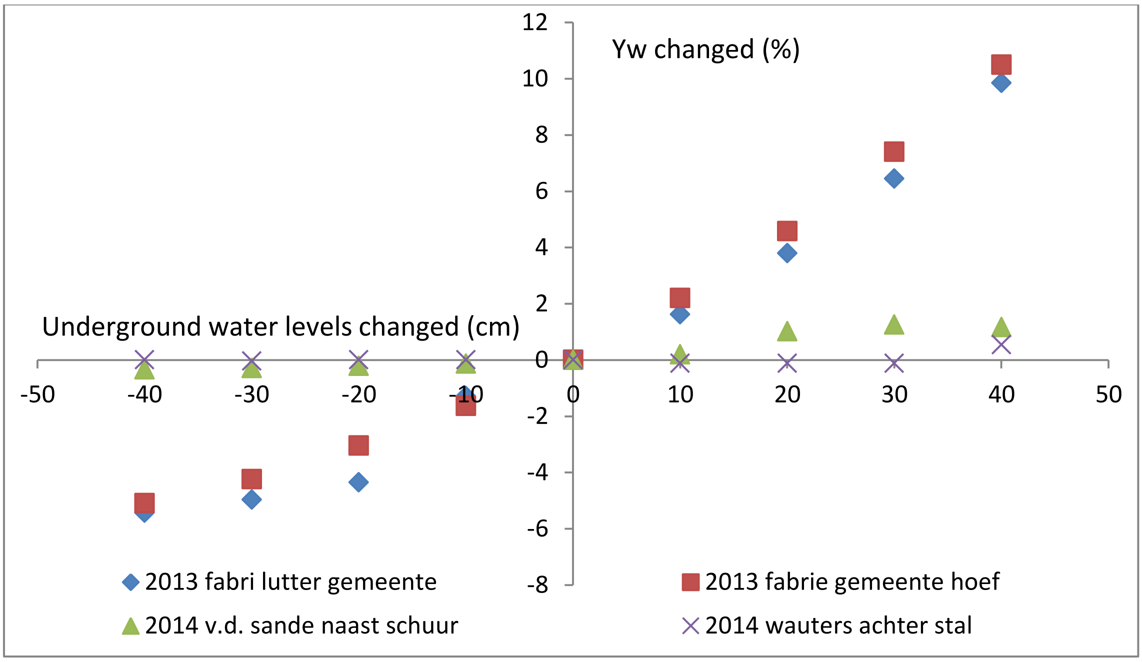

Fig. 33. Effects of underground water levels on water limited yield.

4.4.3 Evapotranspiration & soil water content

As the field “fabri lutter gemeente” had the lowest water limited yield in 2013, evapotranspiration is presented (Fig. 34). Potential transpiration was much higher (0-5.0 cm per day) than the actual during the most of the period from Julian day 190 to 250. Potential soil evaporation was higher (0-1.7 mm per day) than the actual during Julian day 50-165 and some days around 250, and also most days between 264-294. Drought stress (0-5.4 mm per day) occurred since Julian day 192 until 252. Drought stress peaks arose at days 197, 203, 228 and 248 (Fig. 36). Soil volumetric water content in the depth of 0-50 cm was low (under 0.15) since day 190.

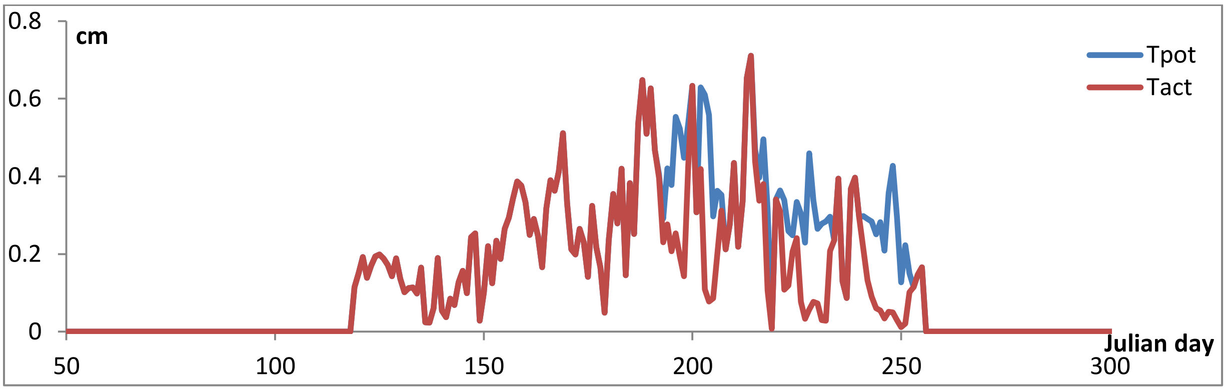

Fig. 34. potential and actual transpiration of field “fabri lutter gemeente” in 2013 without irrigation

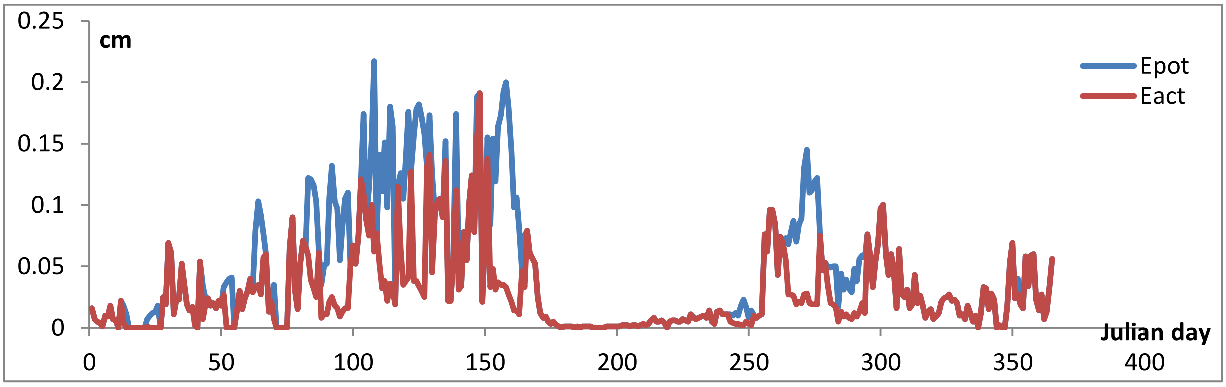

Fig. 35. potential and actual evaporation of field “fabri lutter gemeente” in 2013 without irrigation

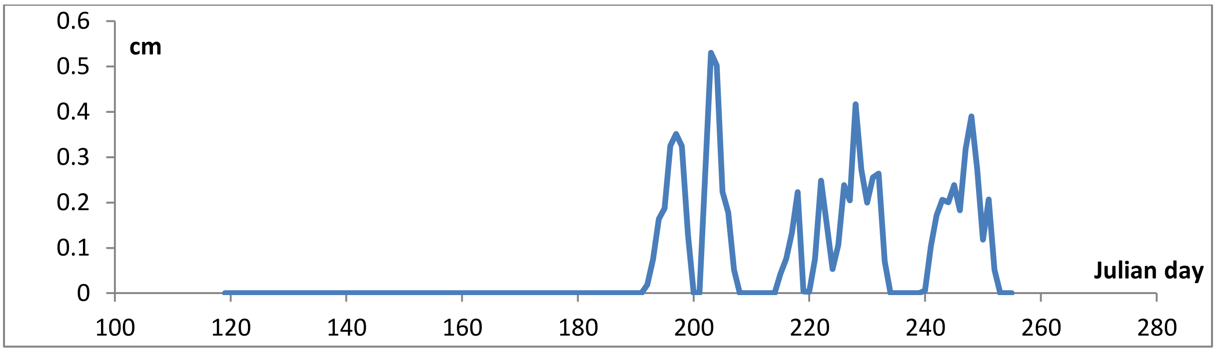

Fig. 36. Day under drought stress in field “fabri lutter gemeente” in 2013 without irrigation.

Soil water content of field “fabri lutter gemeente” was also compared with field “fabrie gemeente hoef” due to their large difference in drought stress result (Fig. 37). Generally, field “fabrie gemeente hoef” had a shallower (around 10 cm) ground water level throughout the year 2013. Critical soil moisture (red mark) periods were between Julian days 190 to 260 in both fields. But field “fabri lutter gemeente” had more severe drought stress, a longer period and extending to deeper sublayers. As mentioned in section 4.4.1, the difference in soil water balance is due to the differences in soil conditions as weather is the same in both fields. There are 5 different soil layers for both two fields and different height of each layers as follows: “fabrie gemeente hoef”: 25; 75; 90; 105; 120 cm; “fabri lutter gemeente”: 25; 35; 55; 90; 120 cm. As for the detailed hydrological functions, OSAT values of layers 2 to 5 at field “fabrie gemeente hoef” are higher, 19.4 % higher in the second layer, than “fabri lutter gemeente”, which means higher water holding capacity. Also the thicker second layer (40 cm) with higher OSAT value makes a difference for the water holding capacity (Appendix VII). Furthermore, most of the KSAT values at field “fabri lutter gemeente” are higher than the ones at field “fabrie gemeente hoef”. According to Neumann’s condition, higher KSAT values result in a higher bottom flux (14.13 cm), and thus less available water stored in the upper layers.

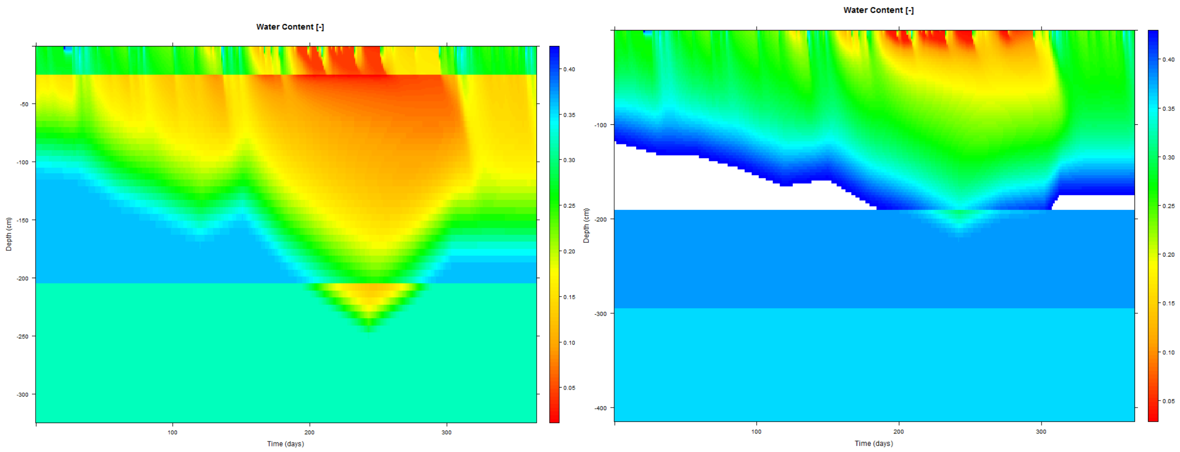

Fig. 37. Soil water content of field “fabri lutter gemeente” (left) and “fabrie gemeente hoef” (right) in the year 2013.

4.4.4 The impact of rainfall and soil type on drought stress

Severe drought stress was found in several potato fields in the year 2013 and the stress level varied among them (Fig. 30). There are two main reasons behind the different levels of drought stress at different fields. The first reason is the difference in rainfall inputs. Two weather stations with recorded rainfall data from Dacom were used. Between these two stations (4 km in distance) rainfall data varied (Fig. 38). There were 3 peaks of rainfall recorded between days 191 to 217 at field “Cor weg eersel”. In order to test the influence of these two different rainfall data on drought stress, field “fabri lutter gemeente” was simulated twice with different sets of rainfall data. Significant different water limited yield was obtained in the model. DM yield of 8531 Kg/ha and 13120 Kg/ha were simulated with weather input from location “blokseschuur tegen bos” (BTB) and “cor weg eersel” (CWE) respectively. Drought stress was compared between the two simulations (Fig. 39). Simulation with BTB rainfall inputs suffered longer (more than one month) and more severe drought stress (67 mm higher in total). Therefore, the variability of rainfall data has direct and strong influence on the drought stress results and water limited yield simulation. In order to achieve most precise and reliable simulations, high quality rainfall data are essential and weather data sources should be cautiously selected.

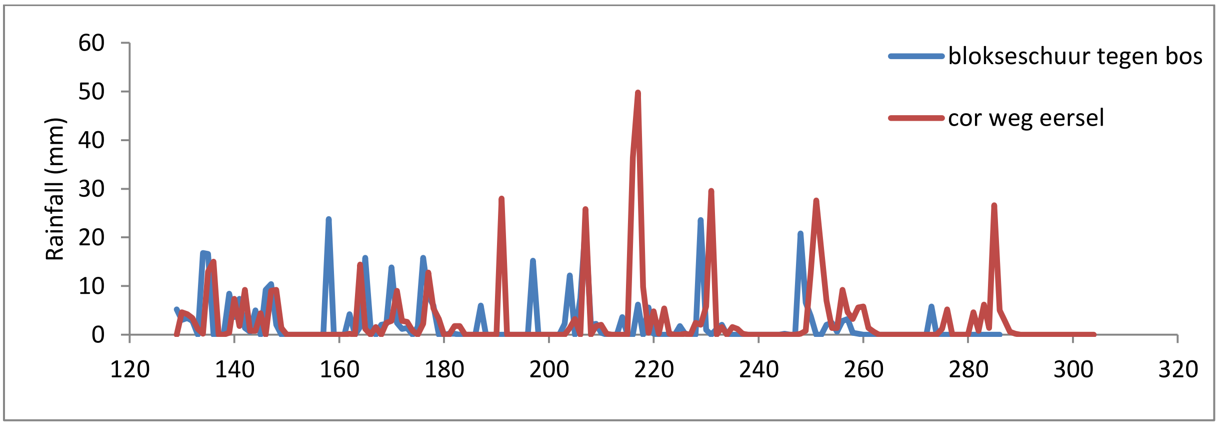

Fig. 38. Recorded rainfall in 2013 for two different locations

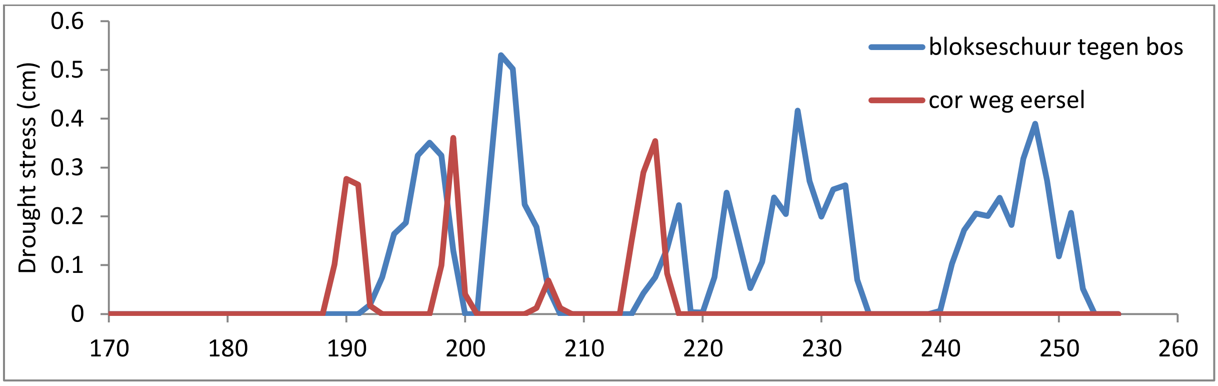

Fig. 39. Drought stress of field “fabri lutter gemeente” with different rainfall inputs

In order to quantify the influence of different soil profiles on the water limited yield, a sensitivity analysis using Eindhoven weather data was done (Fig. 40). There were 15 different soil profiles used in the simulation. Growing period and ground water level were the same for the same year. In the year 2013, simulated water limited yield differed with a range of 0-26.4 t/ha due to the different soil profile inputs. As for the year 2014, the range was smaller with 0-9.4 t/ha. In the context of the same year, water limited yield is sensitive to the soil profile inputs. In the context of different years, besides other factors water limited yield was determined by the rainfall firstly, and then the soil inputs.

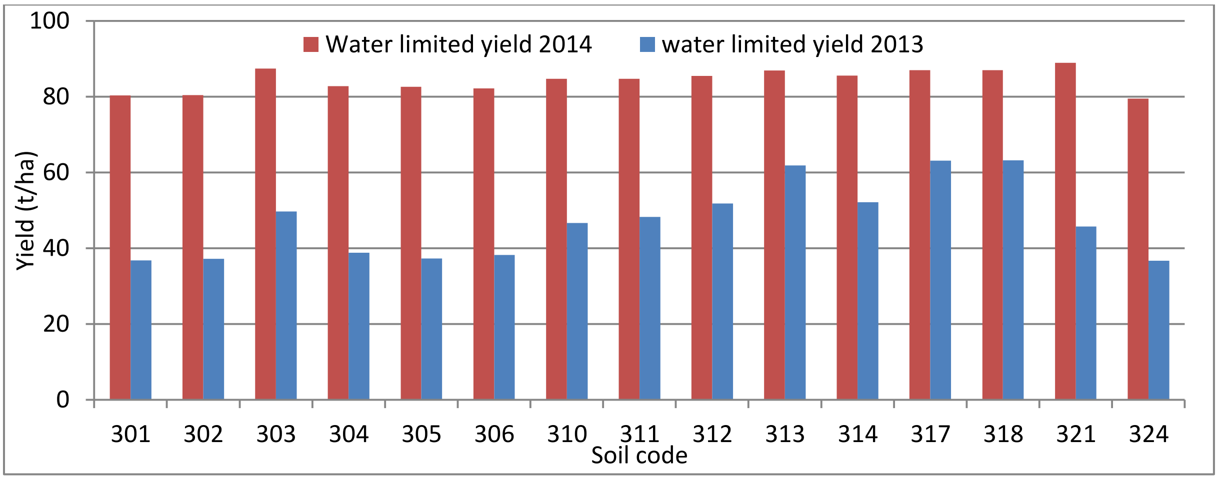

Fig. 40. Simulated water limited yield based on same weather inputs (Eindhoven) for different soil type (DM content 18 %). Detailed information related to soil codes can be found in Appendix IV

As for the difference between the years, water limited yields in year 2014 were more than 20 t/ha and up to 45 t/ha higher than in 2013. Total rainfall in 2013 recorded at Eindhoven was 704.35 mm whereas in 2014 it was 805.7 mm. Moreover, the distribution of rainfall was also different in these two years (Fig. 3), especially in July and August. During these two months, precipitation was 80.4 mm in 2013 and 301 mm in 2014. Most potato fields were sown in April in both years (one month sowing window), and tuber initiation started at the end of June and beginning of July. The dry period during filling stage largely accounted for the severe yield loss in 2013.

4.4.5 Simulation with irrigation

Accumulative WSO was simulated with and without model scheduled irrigation. Observed WSO in the field “fabri lutter gemeente” was compared with the simulated WSO of the two different scenarios (Fig. 45). Between the two simulated WSO, a 5742 Kg/ha higher DM yield was obtained with the automatic irrigation. The first two irrigations eliminate the early drought stress and enable unlimited tuber initiation and linearly primary tuber growth. The third and fourth irrigation were applied at the middle stage of tuber growth, which was the most severe drought stress period. Without irrigation, tuber growing speed decreased sharply after the first drought stress day (192).

Actual WSO was observed four times at Julian day 205, 218, 231 and 255. In general, three (except the second one) out of four observations had a similar growing trend with the simulation without irrigation, and WSO values as well. However, the second observed WSO was much higher than the two simulations, 6501 kg/ha higher than the non-irrigated simulation and 4505 Kg/ha higher than the irrigated one, which is abnormal and interesting to investigate. One of the possible reasons is that this point is simply an outlier. By checking the UWW of the second observation, a UWW value of 505 was recorded whereas an average of 318 was calculated at farm level. The extreme high UWW leads to the high DM content (28.05 % at second observation pint), whereas a DM of 17.67 % was obtained with the average UWW (318).

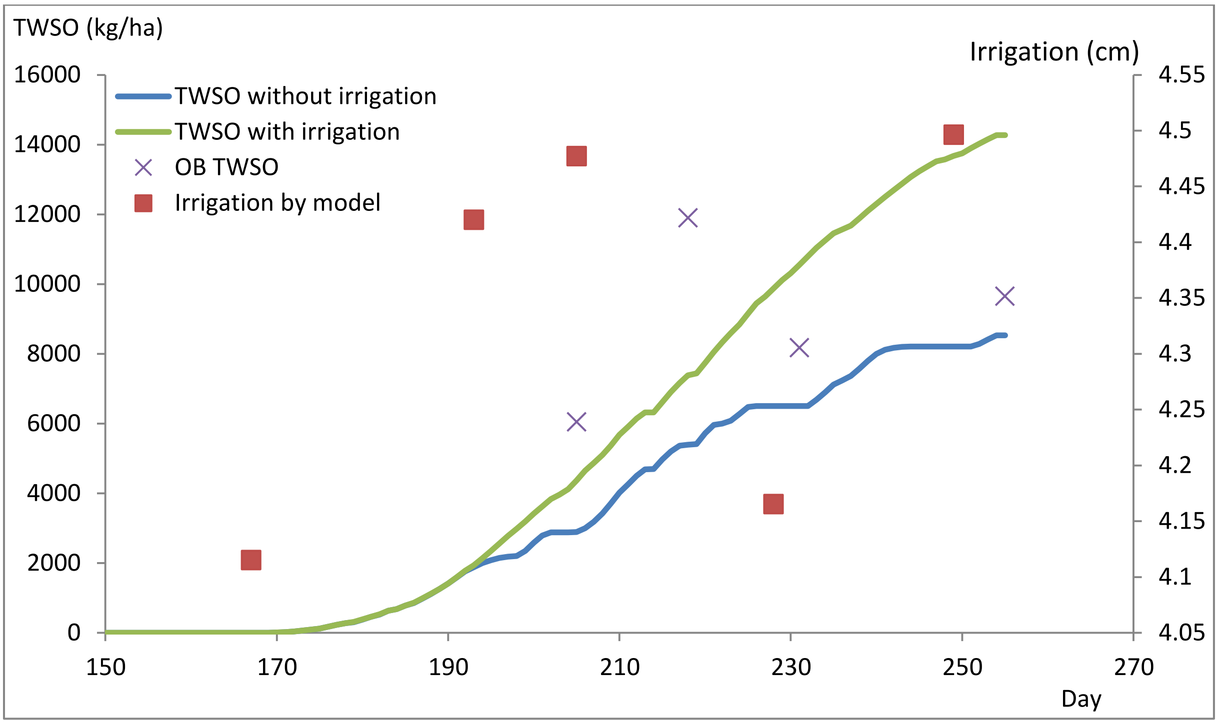

Fig. 45. Modelling accumulative water limited WSO with & without irrigation also the observed WSO of field “fabri lutter gemeente” in 2013.

In order to estimate the required irrigation, an automatic irrigation schedule using the critical pressure head criterial was generated in SWAP-WOFOST (Fig. 41). Drought stress was eliminated with irrigation. The yield gap caused by water stress was closed in 2013 for all of the selected fields. As for year the 2014, the yield gap between potential and water limited can be neglected, only 1 to 2 t/ha existed for three fields. As for the field “fabri lutter gemeente” in 2013, irrigation generated by the model was applied 5 times and at a dose of 4.3 cm each time. With irrigation, actual transpiration was increased to potential. Actual evaporation remained the same (Fig. 42 & 43). Irrigation was applied at the beginning stage of filling and during other drought stress periods, which were critical periods for tuber growth.

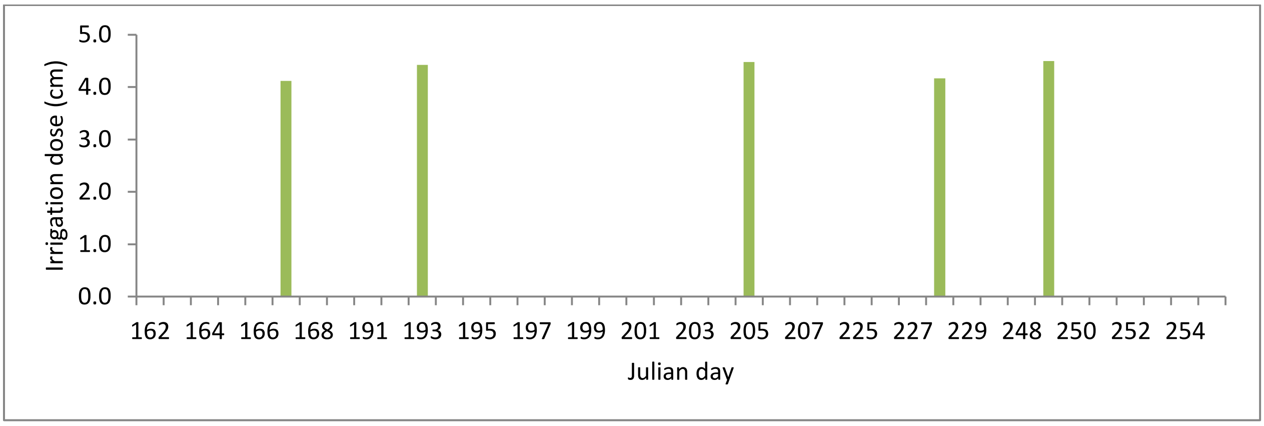

Fig. 41. Automatical irrigation schedule for field “fabri lutter gemeente”

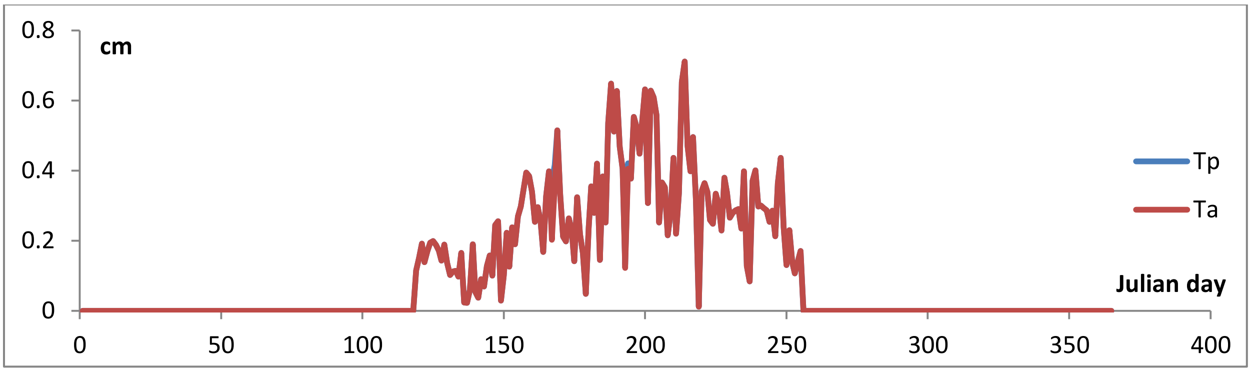

Fig. 42. Potential and actual transpiration of field “fabri lutter gemeente” in 2013 with irrigation

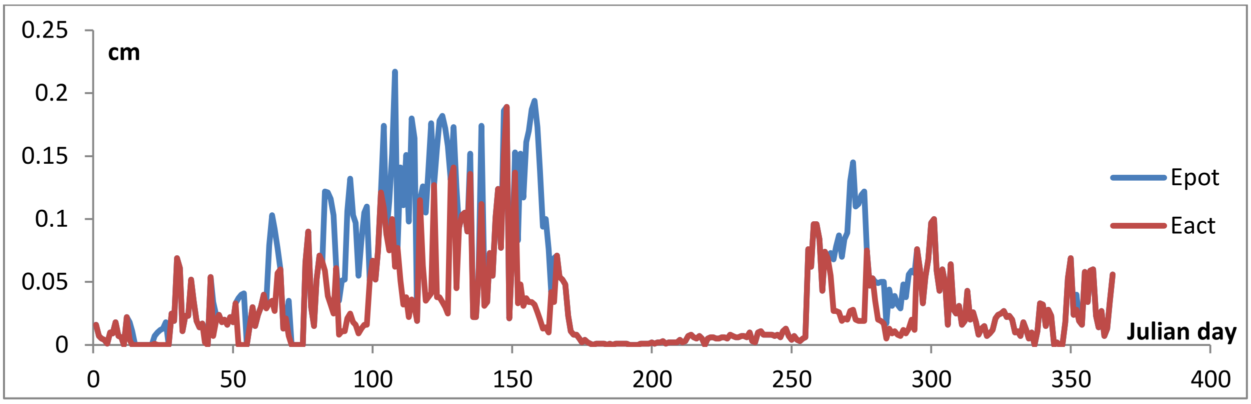

Fig. 43. Potential and actual evaporation of field “fabri lutter gemeente” in 2013 with irrigation

According to farmer’s records, no irrigation was performed in the field “fabri lutter gemeente”. In order to compare the irrigation schedules between farmer’s and model results, irrigation schedules of three water limited fields in the year 2013 were investigated (Fig. 44). Firstly at field “jack houbraken” irrigation was applied two times by the famer at days 164 and 193 at a dose of 25 mm and 0.516 mm (ground water) respectively. As recommended by the model, irrigation should be applied 5 times and the dose is around 43 mm for each time. The first irrigation time of the farmer (day 164) was the same as model results but the dose was different (18 mm). Secondly, in the field “blokseschuur tegen bos”, irrigation was recorded at days 159, 160, 170, 190 at a dose around 23 mm each time. However, the model suggests only one time irrigation at day 198 with a dose of 46 mm. Lastly, in the field "kees lauwers tegenover" was irrigated twice, at day 190 with 25 mm and at day 218 with 3.5 mm. The model proposes 4 times irrigation at days 190, 199, 223, 247 with the doses of 34, 46, 42 and 43 mm respectively. In concluding the previous irrigation comparisons, the farmer's and model's irrigation schedules vary quantitatively and temporally to a large extent. Irrigation water use efficiency of these fields was compared by the definition of fresh matter yield produced per unit irrigation water applied (Table 2). Two of the three model irrigation schedules had lower water use efficiency compared to reality. However, model irrigation closed the water limited yield gaps whereas farmer's irrigation increased the water limited yield but the gap was not closed.

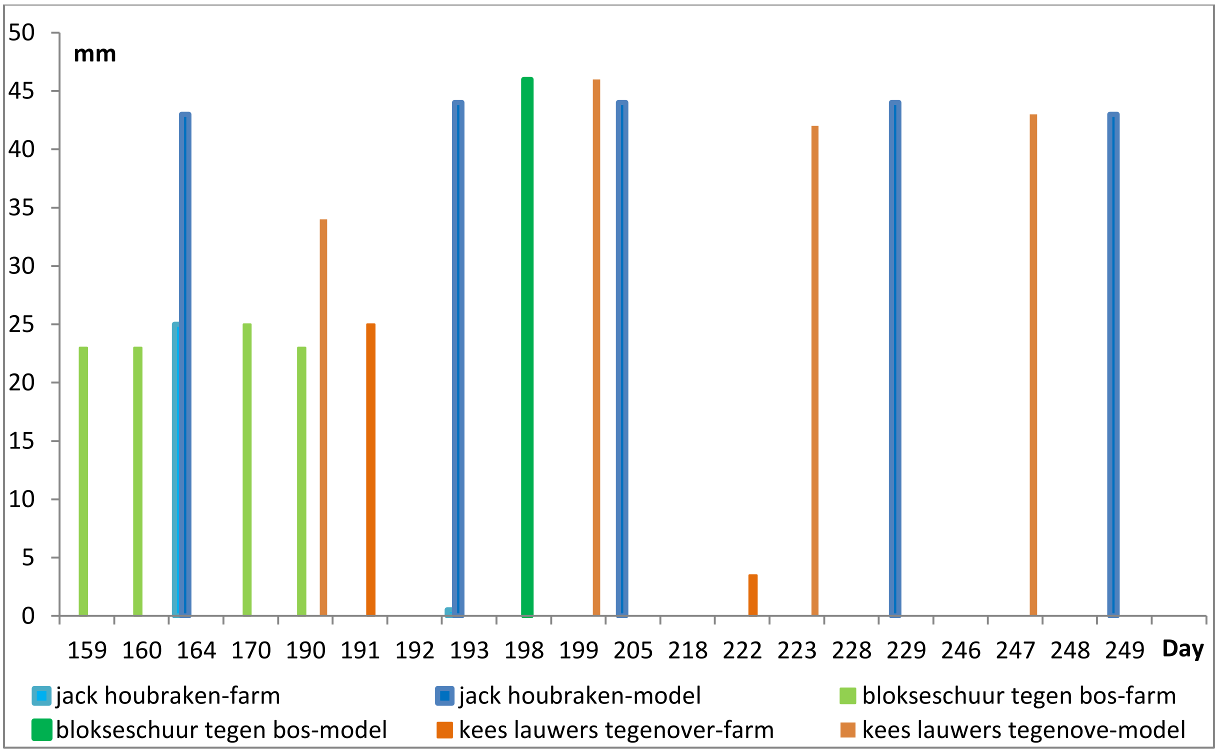

Fig. 44. Farmers' irrigation records and model irrigation schedule for three fields in 2013.

Field	jack houbraken		blokseschuur tegen bos		kees lauwers tegenover	
Water use efficiency (t ha^{-1} mm^{-1})	model	farm	model	farm	model	farm
	0.21	2.90	1.86	0.67	0.51	2.70

Table 2. Comparison of water use efficiency between model's and farmer's irrigation for different fields in 2013.

5. Discussion

5.1 WOFOST calibration and validation for potential yield simulation

The WOFOST calibration was done for potential yield calibration because model parameters values were obtained at field experiments more than 20 years ago (Boons-Prins et al. 1993). The calibration data were based on the farmer's phenology records and tuber yields at different times during the growing season. Potential yields after calibration reached 88-94 t/ha in 2014 and 78-86 t/ha in 2013, with a DM of 18 %. However, the highest yield obtained at the farm was 100 t/ha in 2014 and 95 t/ha in 2013, several tons higher than the simulation results, which was not desirable. The reason is that model calibration was based on a series of fields with highest yield whereas the yield of 100 t/ha and 95 t/ha were from one field.

Highest yield achieved at field level cannot equal to farm level. According to Lobell et al. (2009), the exploitable yield is 80 % of potential yield on a national scale. If the highest yield in the farm is considered as exploitable, potential yield of cultivar Fontane should be increased 20 % which is 105.6-112.8 t/ha in 2014 and 93.6-103.2 in 2013. The differences in simulated potential yields between the two years were 9.6-12 t/ha. The cultivars Miranda, Ludmilla and Lady Anna were also planted in several fields, however, due to their small scale and relatively lower yield compared to Fontane, no calibration was performed, and potential yields for these three cultivars could not be determined.

Even though the model efficiency was higher than 0.9 for most of the fields at the validation (Figure 28), model uncertainty cannot be neglected. At the step of CO2 assimilation parameter AMAXTB calibration, a contradictory condition occurred between the phenology parameter TSUM1 and observed anthesis date. The TSUM1 value was reset from the calibrated value (420 ℃) to 320 ℃ at this step in order to match the observed accumulative WSO. TSUM1 was changed with 100 ℃ from the calibrated value, which was not desired. A possible reason could be that the observed anthesis date, which was obtained indirectly from pictures, was incorrect.

Besides parameter TSUM1, another issue of model uncertainty is related to the observed data of WSO. WSO is the key indicator at the AMAXTB calibration, however, within the selected fields for calibration, sowing dates were different, as well as WSO measuring dates and the UWW. Heterogeneous WSO data were averaged (sowing date & measurement data) for calibration, however, the simplified procedure could also cause model uncertainty. Simply averaging all the data results in underestimated potential yield to the mean level within these fields. This is why the simulated potential yield is lower than the observed highest yield in both of two years for some fields. Moreover, not all of the parameters suggested by the Wolf (2003) were calibrated due to unavailability of data. These parameters include SLATB, FSTB, FOTB and FLTB. Model calibration can be improved with additional data.

Moreover, WOFOST underestimated the potential yield at fields "vermeulen hulsel", "mark hurkmans" and "wauters achter stal" in 2013 (Fig. 26). These three fields had highest yields with non-linearly accumulated tuber mass growing tendency (Fig.11), whereas WOFOST calibration was based on the criterial of selecting data from fields with linearly increasing tuber growth trend. The underestimation results should be further investigated with experiments under potential production conditions.

5.2 Water limited yield simulation

According to the simulation results, farm Van den Borne Aardappelen suffered severe drought stress in the year 2013 which caused 18.7 to 31.0 t/ha yield loss. In contrast, in the year 2014 no significant yield loss was caused by drought, and the average yield obtained in 2014 was 10 t/ha higher than 2013. However, no drought stress or oxygen stress experiment was designed and performed in the farm, thus simulated water limited yield cannot be quantitatively validated by reality. It is unclear whether the model can simulate drought and oxygen stress adequately in the context of observed water limited yield. In order to evaluate model performance for water stress simulation, an indirect assessment by comparing Dacom soil moisture data and model results was done. The soil moisture data in 2014 at different soil depths of field "Jan luiksgestel achter bos" was compared (Appendix VIII), because the rainfall was measured at this field and soil moisture data are available. Observed soil moisture value was much higher at all the different depths compared to the simulation results, but they have a similar trend. According to the soil map from Wösten et al. (2012), saturated soil water content at this field is 0.43 cm^3/cm^3 for the first layer and 0.36 cm^3/cm^3 for the sublayers. The topsoil layer is 8.0 cm deep and the rest are 215 cm. As for observation, soil moisture was higher than 0.5 cm^{-3}/cm^{-3} at the depth of 10 cm for most of the days after 8th of July, which is even higher than the saturated value. Similarly, soil moisture at other depths were also relatively high.

It may be that the Dacom soil moisture sensor was not calibrated before measuring. Thus, using the soil moisture data of this field is risky and model simulated water content can only compared with measurements in a relative sense. The model performance assessment was aborted due to anomalous high soil water content data. There are however also other possible explanations for the differences between observed and simulated soil water contents. The soil map of Wösten et al. (2012) was made years before. During the years of soil management (e.g. fertilization & tillage), soil properties (soil hydraulic functions & top boundary condition) could already have changed, causing the big difference between the simulations and observations. The theory behind is that the changes of soil hydraulic functions and the top boundary conditions have significant influence on the simulated phreatic surface fluctuations at shallow groundwater tables (Van Dam et al., 2008). Meanwhile, another possibility is that SWAP performed poor in this field without calibration. In order to inspect this issue, further experiments and research are required, for instance detecting the soil hydrological properties and calibrating SWAP.

As for the oxygen stress, underground water levels for all the fields in these two years were far more below the root zone (30 cm in all simulations). Underground water levels were found at the depths around 100cm in the study area, which was not able to cause waterlogging problem. However, based on the opinion of the farmer and literature, 30 cm of the maximum rooting depth was used in all the simulations without collecting data at fields. Further studies can investigate the influences of deeper or shallower rooting depth on oxygen stress or drought stress level. Besides, potato waterlogging problem (oxygen stress) is less likely occurred under temperate marine climate conditions with sandy soil. High quality of soil moisture data are required if water stress (drought & oxygen) will be further investigated.

Four among the 10 observed actual yields in 2013 were much higher (up to 23 t/ha) than the simulated water limited yield. A possible reason is that the actual yield is achieved with applied irrigation, and thus the yield gap due to water stress is closed to some extent. The irrigated fields were “blokseschuur tegen bos” and “kees lauwers tegenover”. While in the latter one, actual yield was indeed much higher than water limited yield , in the first one they were similar. Another reason could be that the model has not been calibrated for water limited yield, and the model overestimates yield gaps caused by water. Another reason could be that the weather input, especially in precipitation data were not accurate enough for some fields. Other reasons could be the pests, diseases and weeds are not included in the model. While in 2013, water limitation seems to play a major role in the actual yields, in 2014 water was not the crucial constraint and the yield gaps is caused by these later other factors.

Previous studies also found that drought stress on potato tuber initiation and filling stages have the most significant effect on yield (MacKerron and Jefferies, 1986; Haverkort et al., 1990; Lynch et al., 1995; Yuan et al., 2003). Moreover, most drought stress periods were also found during July and August. Maximum rooting depth in all the simulations was assumed to be 30 cm. In principle this value should be adjusted to match different situation in different fields. However, it is unfeasible without relevant data. Thus, 30 cm was used based on the farmer’s opinion and literature (Opena & Porter, 1999). Another uncertainty relates to the groundwater level data. Not all of the groundwater data were measured right on the fields. Some of them were even hundreds meters away from the field. These two uncertainties can be solved by improved data collection.

5.4 Implement SWAP-WOFOST for irrigation schedule

The main purpose of this study was to understand to what extent drought reduced yield in the years 2013 and 2014. A sub-aim was to provide a solution by implementing SWAP-WOFOST to achieve better water management in order to close the yield gap. There are currently different ways for agricultural water management. One of them is using drainage. Different scenarios of drainage water management can be applied at different periods for different purposes (Fig. 46). The outlets can be raised after harvest to reduce nitrate leaching, lowered in early spring and fall to allow free drainage before planting or harvest, or raised after planting to increase soil water content for the summer (Frankenberger et al,. 2004). However, this method is expensive and time consuming for infrastructure construction, while the farm has unfixed and a large amount of fields, so this type of drainage management is not economically efficient.

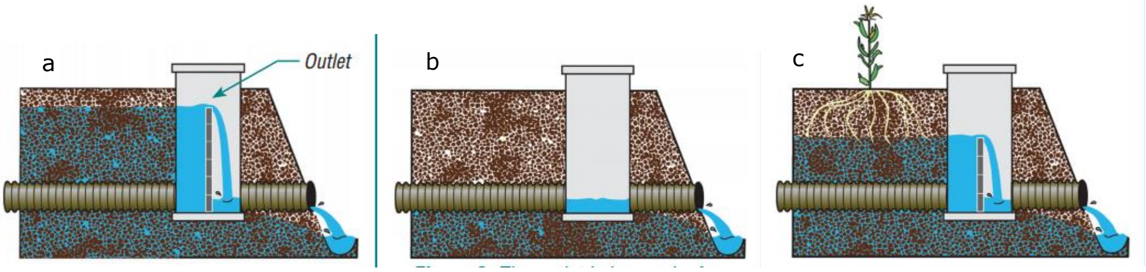

Fig. 46. Drainage water management at different periods, after harvest (a); early spring and fall (b); after planting (c) (Frankenberger et al., 2004)

Another water management method is using drip irrigation, but drip irrigation is most suitable for row crops, trees and vine crops. A drip system further requires high investment, which is also not a desirable choice. Thus the solution should meet the requirements of being time efficient, inexpensive and suitable. A Modelling approach is then considered.

Since one of the functions of a model is prediction, SWAP-WOFOST can be used for soil moisture estimation. Based on the soil moisture conditions, an irrigation schedule can be generated from the model with a certain dose and time for application. In order to make an irrigation schedule, prediction of weather in a certain period is pre-required. At the same time, for the purpose of precise estimations, SWAP should be calibrated before implementation. If the predicted weather data is 14 days available in advance, this would be a great advantage for scheduling irrigation. At the same time, the model irrigation schedule highly depends on the weather prediction. 14 days would allow the farmer to have more time to plan irrigation management in the context of the large scale of the farm and saving time for other farm operations. However, in case weather forecasting is not available, SWAP-WOFOST can also use currently measured weather data to estimate soil water condition and give irrigation advice. Since Van den Borne is a large scale precision farm, and spatial variability in water management exists, one of the solutions could be using GIS to assist irrigation. Fortes et al. (2005) integrated GIS with the irrigation scheduling simulation model ISAREG to improve water usage in Uzbekistan. The integrated model GISAREG was applied to assess alternative irrigation scenarios. GIS enables the model to be more applicable for a large scale area. Moreover, the clear overview distribution of spatial water demand can be visualized with the assistance of GIS. The various water managements at the farm or regional level can also be localized, and can thus support further analysis of water and irrigation requirements. Therefore, combing SWAP-WOFOST and GIS will be a useful tool for the irrigation scheduling and preferably with predicting weather data.

6. Conclusions & Recommendations

The aim of this study was to evaluate the impact of drought and oxygen stress on potato yield and improve water management. The following conclusions can be derived:

- Potential fresh yield of potato cultivar Fontane was determined at the farm with a range of 90-120 t/ha, depending on the growing period and weather.
- While simulated potential yields with WOFOST were far below the observed levels with default parameters, calibration result in yields similar to observations in the highest yielding fields. Exact calibration however requires experiments.
- Simulated yield gap caused by water was 18.7 to 31.0 t/ha in 2013 and 0.6-10.7 t/ha in 2014. Results of water limited yield simulations however cannot be verified with the current database.
- In 2013, the farm was found under severe drought stress for a long period (more than 30 days). Slight oxygen stress was found for both years, but has insignificant effect on yield.
- Potato water limited yield is highly influenced by the level of water stress during the tuber initiation and filling stage. Farm management should focus more on fields water states during summer.
- Data used for crop model calibration should be carefully selected and the reliability of the data are essential, as these have a direct influence on model outputs. Within them, the phenology data and tuber yield data were most crucial.
- Potential yield can be well simulated by SWAP-WOFOST after calibration at the large scale farm.
- Sufficient data are required for model application. High resolution of soil data and accurate precipitation data are two of the most important inputs for water limited yield simulation.
- Without experiments performed in reality considering water stress, It is impossible to validate model results which leave a huge uncertainty of the reliability of model performance.
- Whether SWAP-WOFOST can adequately simulate drought-or oxygen stress cannot be determined in this case study. Further experiments and studies are required to answer this question.
- Researches such as the soil map from Wösten et al. (2012) can provide essential information to support the application of SWAP-WOFOST, but the accuracy of the data should be checked with additional lab work.
- SWAP-WOFOST can efficiently improve water management in terms of irrigation scheduling and lead to higher yield.
- Detailed weather prediction for a short period can enhance model application for irrigation
- A modeling approach should be integrated with GIS in terms of large scale precision farm to achieve higher yield.
- As for yield gap analysis, future studies should include more yield affecting factors into the modelling approach. A whole system approach including water, nutrients, pests, management and diseases should be developed and applied.

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APPENDIX

Appendix I

Year	Field name	Recorded precipitation data period	Amount of rainfall for simulation (supplemented with Eindhoven data)
2013	blokseschuur tegen bos	May.11-Aug.07 & Aug.10-Oct.17	683.8 mm
2013	cor weg eersel	May.10-Dec.01	863.03 mm
2014	jan luiksgestel achter bos	May.14-Sep.19	762.2 mm
2014	johan kuipers voorhuis	May.14-Sep.20	820.09 mm
2014	voorsteheide	Apr.26-Sep.28	609.9 mm
2013	Eindhoven	Whole year	704.35 mm
2014	Eindhoven	Whole year	722.1 mm

Table 3: Precipitation records by Dacom and Eindhoven (data in Belgium were not presented).

In 2013, data of "blokseschuur tegen bos" were used for all the selected fields in 2013. Data of "cor weg eersel" were only used, because its abnormal high value, for field "fabri lutter gemeente" while comparing the influence of different rainfall inputs on water limited yield in 2013 at chapter 4.4.4.

In 2014, data of Eindhoven were used for fields "v.d. sande naast schuur", "v.d. sande nieuwendijk" and "v.d. sande beerseweg". Data of "Jan luiksgestel achter bos" were used for the field with same name. Data of "Johan kuipers voorhuis" were used for field 'Johan kuipers kobliek". Data of "voorsteheide" were used for the rest of the fields.

Appendix II

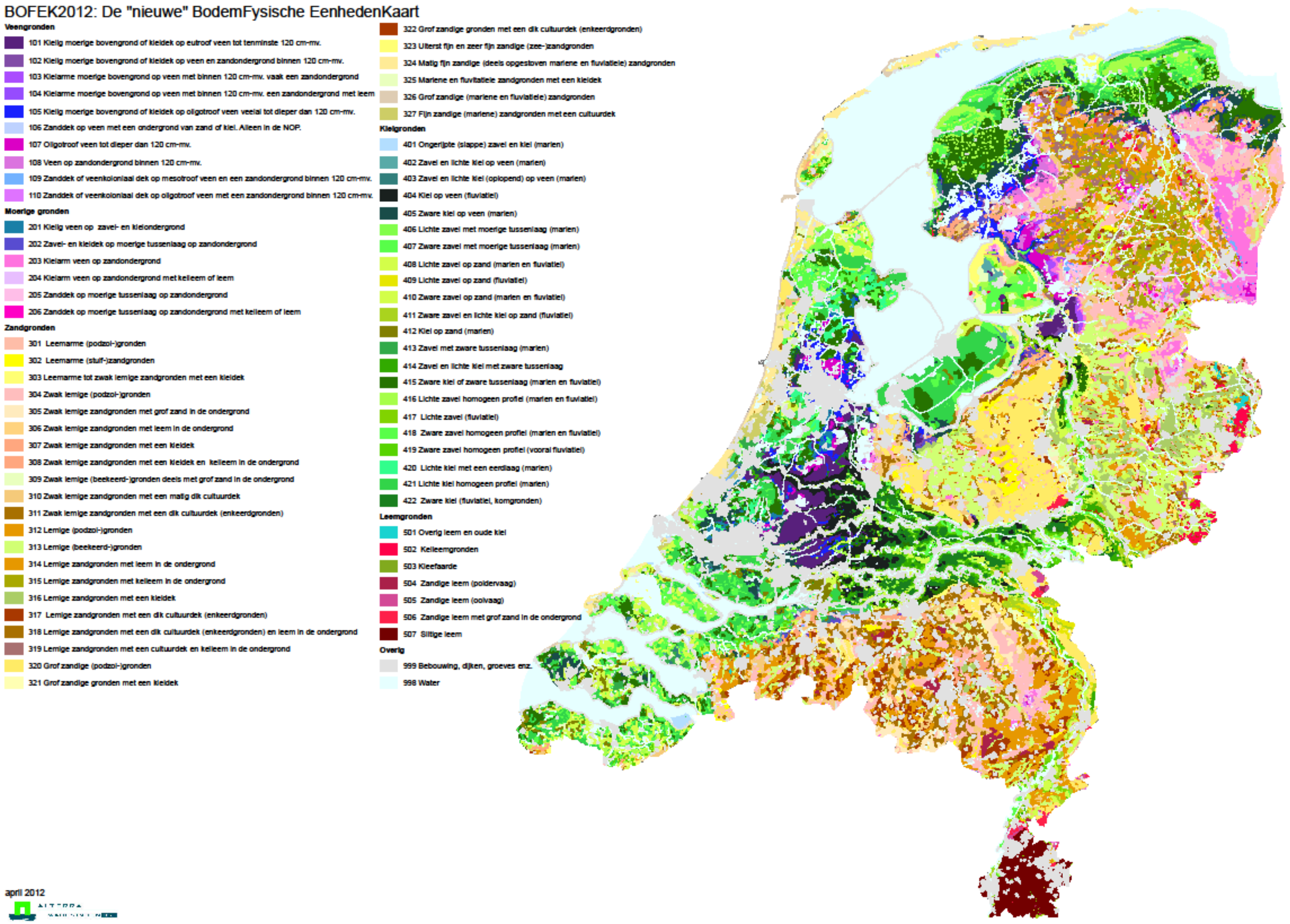

Fig. 47. Soil map of the Netherlands (Wösten et al., 2012).

Appendix III

Soil cod	layer code	depth (cm)	Soil code	layer code	depth (cm)	Soil code	layer code	depth (cm)
301	B1	8	306	B2	20	313	B3	20
	O1	15		O2	40		B3	30
	O1	30		O2	50		O3	60
	O1	50		O2	100		O2	120
	O1	120		O14	120	314	B3	20
302	B1	6	310	B2	25		O3	30
	O1	10		B2	40		O3	50
	O1	15		O1	60		O3	90
	O1	120		O1	75		O14	120
303	B9	15		O1	120	317	B3	25
	O10	35	311	B2	25		B3	70
	O1	120		B2	75		B3	90
304	B2	25		B2	90		O3	110
	O2	40		O2	105		O3	120
	O2	60		O1	120	318	B3	25
	O1	120	312	B3	20		B3	60
305	B2	25		O3	40		B3	75
	O1	35		O3	55		O3	90
	O1	55		O2	120		O14	120
	O1	90				321	B9	15
	O5	120					O10	35
							O5	120
						324	B1	5
							O1	50
							O1	120

comment	ORES	OSAT	ALFAD	NPAR	KSAT	LEXP	ALFAW	H_ENPR
topsoil_sand_B1	0.01	0.43	0.0249	1.507	17.46	-0.14	0.0498	0
topsoil_sand_B2	0.02	0.43	0.0227	1.548	9.65	-0.983	0.0454	0
topsoil_sand_B3	0.01	0.45	0.0152	1.412	17.81	-0.213	0.0304	0
topsoil_loam_B9	0	0.43	0.0065	1.325	1.54	-2.161	0.013	0
subsoil_sand_O1	0.01	0.36	0.0224	2.167	13.21	0	0.0448	0
subsoil_sand_O2	0.02	0.38	0.0214	2.075	15.56	0.039	0.0428	0
subsoil_sand_O3	0.01	0.34	0.0211	1.564	18.3	-0.522	0.0422	0
subsoil_sand_O5	0.01	0.32	0.0597	2.059	43.55	0.343	0.1194	0
subsoil_loam_O10	0	0.49	0.0107	1.28	2.22	-2.123	0.0214	0
subsoil_silt_O14	0	0.38	0.0025	1.686	0.36	0.057	0.005	0

Table 4. Soil data used in this thesis study including: type and depth of the soil layers and hydraulic parameters

Appendix IV

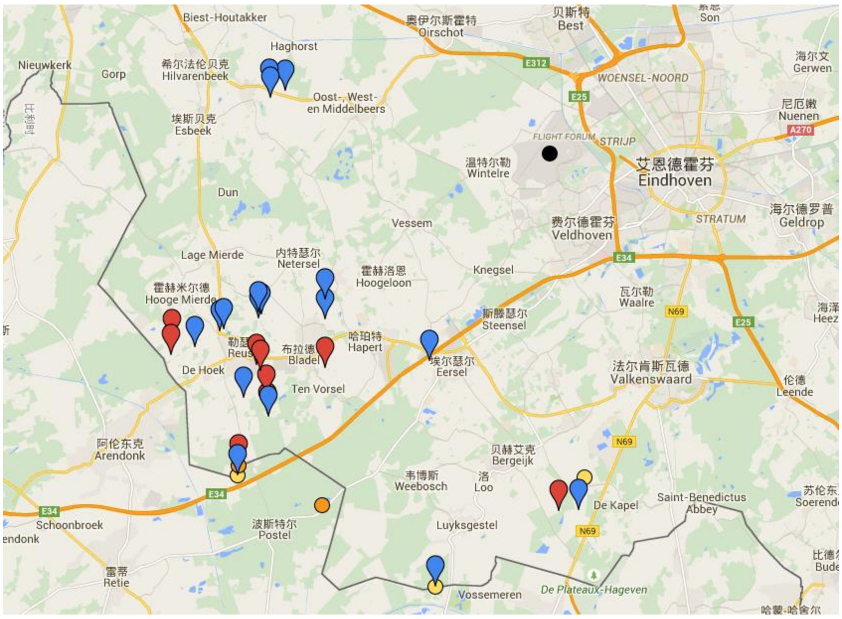

Fig. 48. Fields which was assumed under drought or oxygen stress in year 2013 (red mark) & 2014 (blue mark). Dacom rainfall station (2013 orange circle; 2014 yellow circle) and Eindhoven station (black circle)

Appendix V

2013	Field name	soil code	2014	Field name	soil code
	fabri lutter gemeente	305		peerke snip kroonven	305
	omen beleven	304		Johan kuiperskobliek	305
	fabrie gemeente Hamelendijk	305		hub coxs achter stal	311
	harryfiers achter huis	305		hub coxs tegenover	311
	Jack Houbraken	305		tinnus kailakkers	304
	blokseschuur tegen bos	305		hein castelijnse	317
	fabrie gemeente hoef	311		borne fabrie buspad gemeente	301
	kees lauwers tegenover	305		henrie spie steenoven	313
	meijer achterste blok	311		jacob hulsel	313
	voor huis tegen bos	305		Jan luiksgestel achter bos	301
				peer achter sleufsil	318
				v.d. sande naast schuur	306
				v.d. sande nieuwendijk	306
				v.d. sande beerseweg	306
				voorsteheide	305
				wauters achter stal	312
				wauters koepad links	312

Table 5. Soil codes of the fields used for water limited yield simulation

Appendix VI

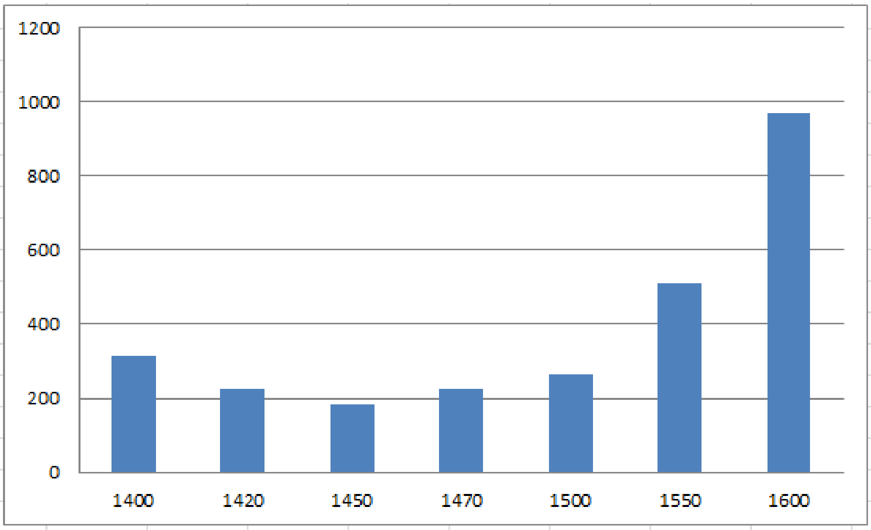

Fig. 49. SSE of different TSUM2 values (x axis: TSUM2 y axis: SSE).

Appendix VII

“fabri lutter gemeente”	soil layres	ORES	OSAT	ALFA	NPAR	KSAT	LEXP	ALFAW	H_ENPR
	1	0.02	0.43	0.0227	1.548	9.65	-0.983	0.0454	0
	2	0.01	0.36	0.0224	2.167	13.21	0	0.0448	0
	3	0.01	0.36	0.0224	2.167	13.21	0	0.0448	0
	4	0.01	0.36	0.0224	2.167	13.21	0	0.0448	0
	5	0.01	0.32	0.0597	2.059	43.55	0.343	0.1194	0
“fabrie gemeente hoef”	soil layers	ORES	OSAT	ALFA	NPAR	KSAT	LEXP	ALFAW	H_ENPR
	1	0.02	0.43	0.0227	1.548	9.65	-0.983	0.0454	0
	2	0.02	0.43	0.0227	1.548	9.65	-0.983	0.0454	0
	3	0.02	0.43	0.0227	1.548	9.65	-0.983	0.0454	0
	4	0.02	0.38	0.0214	2.075	15.56	0.039	0.0428	0
	5	0.01	0.36	0.0224	2.167	13.21	0	0.0448	0

Table 6. Hydrological parameters used for fields “fabrie gemeente hoef” and “fabri lutter gemeente”

Abbreviations used here: ORES (residual water content, cm^3/cm^3), OSAT (saturated water content, cm^3/cm^3), ALFA (shape parameter alfa of main drying curve, cm^{-1}), NPAR (shape parameter n), KSAT (saturated vertical hydraulic conductivity, cm/d), LEXP (exponent in hydraulic conductivity function), ALFAW (alfa parameter of main wetting curve in case of hysteresis, cm^{-1}), H_ENPR (entry pressure head, cm).

Appendix VIII

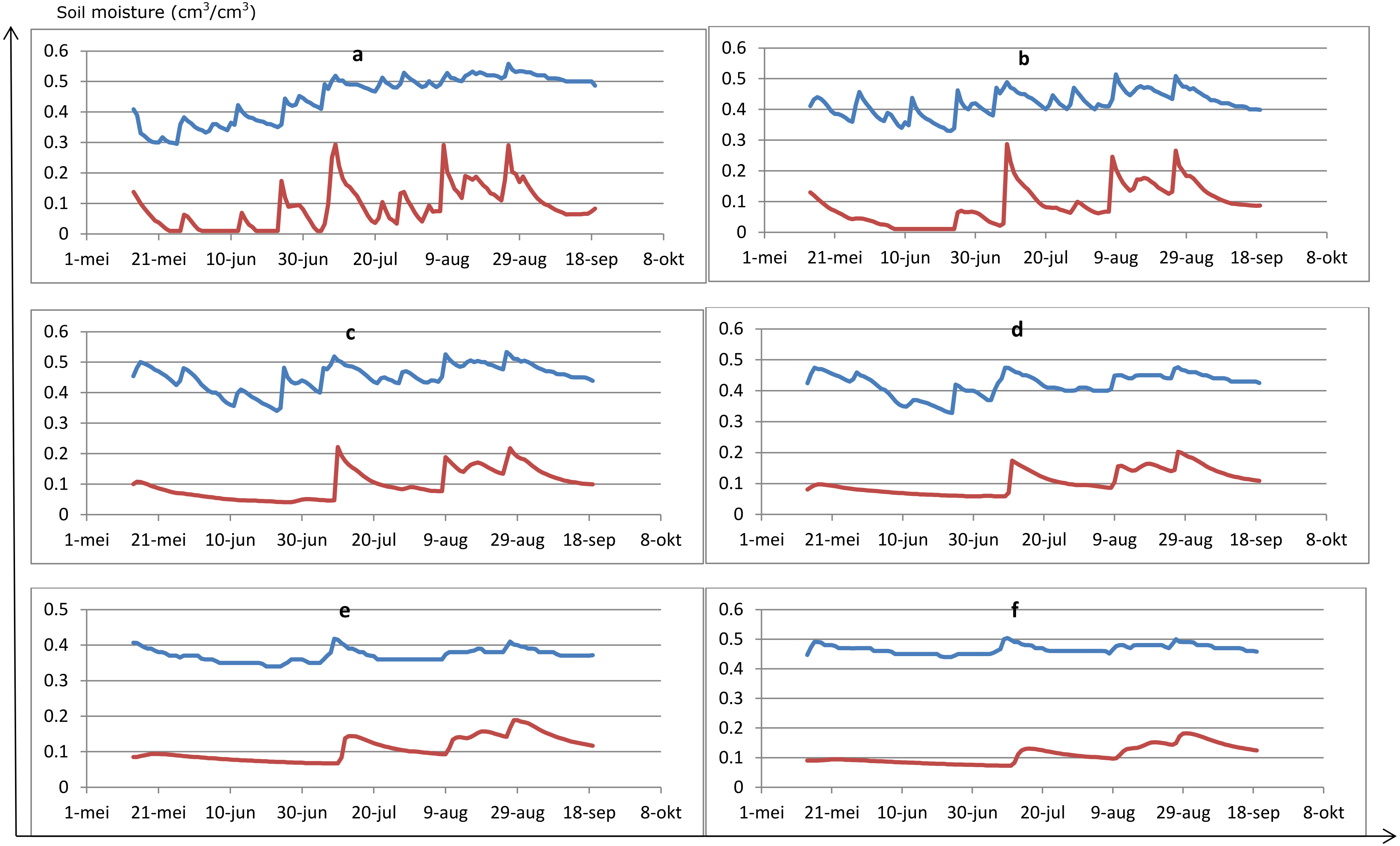

Fig. 50. Soil moisture at field "Jan luiksgestel achter bos" for different soil depths in 2014. Blue line presents observations, red line presents simulations. Different soil depths were illustrated with a(10 cm), b(20 cm), c(30 cm), d(40 cm), e(50 cm), f(60 cm) .