IV-7: Implementation and parameter adaptation of a potato crop model with a soil water subsystem

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1 Introduction

During our research program on virus epidemics in seed potato production, the need arose to include a good potato crop growth model. The overall goals of this research were to gain insight into the underlying epidemiological processes and the construction of research tools for testing of alternative hypotheses on the functioning of the aphid vectors. On the other hand, we also envisaged applying these models to the solution of practical problems, such as the forecasting or the optimization of the haulm killing date in Switzerland.

The potato crop model is only a submodel of a larger model system including modelling the epidemics of the potato virus (PVY). This submodel had to serve several purposes: first, it had to produce output on tuber yield, leaf area, leaf age (e.g. 'age resistance' against virus transport to the tubers) and the responses to water excess or deficit. Second, it had to be kept as simple as possible to keep computing time low and to minimize the introduction of undesirable errors and artifacts due to model complexity. Hence we favoured a structured 'Top Down' modelling approach with stepwise refinement. Thirdly, we wanted to use the implementation of the crop model to test and evaluate the simulation environment 'MODELWORKS' which is currently in development by our research team (Fischlin, 1991).

The current model is to a large extent a new synthesis and implementation of various models or submodels published and parameterized elsewhere. The potato growth model was based on the original version by Johnson et al. (1986, 1987). We added a soil water submodel based on the models proposed by Driessen (1986) and Berkhout & van Keulen (1986). However the resulting model represents a new unique combination. Moreover, it had to be adapted and parameterized for Swiss weather and for potato varieties common in Switzerland.

2 Model

2.1 General structure

The overall model 'PotatoSoilWat' consists of a plant submodel 'PotatoMod' and a soil water submodel 'SoilWat' plus the parallel data submodels 'Weather' and 'PotModValid'. Figure 1 shows an overview of the model structure of the combined potato and soil water models and the coupled submodels for input of weather and validation data. The analogue representation of the modular implementation structure is given in Section 2.5.

'PotatoMod': To minimize development effort and to satisfy most of the above mentioned criteria the model published by Johnson et al. (1986, 1987) was chosen. To run the model under various conditions (i.e. different years, locations, weather) it was coupled with a soil water model.

'SoilWat': The original potato crop model by Johnson et al. (1986) required the water potential as input to compute the water stress factor. Since this is rarely measured, a submodel 'SoilWat' for the soil water balance was constructed to compute the water stress factor from commonly available weather data (e.g. automatic weather recording network, ANETZ, in Switzerland). To minimize development time and parameter estimation effort, this submodel was mainly based on published and parameterized equations.

2.2 Governing equations

Throughout the following description of the model equations, the type of variable is denoted by a letter within braces, i.e. {S}tate, {R}ate, {A}uxiliary, {P}arameter and {I}nput.

2.2.1 PotatoMod

This model describes the growth of the potato crop. All plant entities are expressed on a per plant basis. 'PotatoMod' contains the state variables P (physiological age), W_a (assimilate pool) and W_l, W_s, W_r and W_{tu} (dry matter for leaves, stems, roots and tubers, respectively). The necessary inputs are described in Section 2.3.

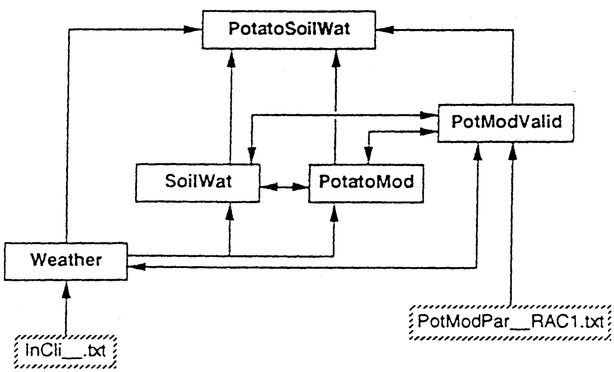

Figure 1. Structure of the whole model consisting of submodels for potato growth and soil water balance, and the pseudo models for input of weather plus validation data. Arrows indicate flow of information, solid boxes indicate models and dashed boxframes represent datafiles for inputs.

The potato crop model is built around the following basic growth equation:

$$\Delta W_p = R\ \varepsilon_{pot} \left(\frac{\Delta P}{\Delta \bar{P}} \right) D_{row}\ D_p\ f_w \tag{1}$$

where:
ΔW_p = daily net dry matter increase (g plant^{-1} d^{-1}) {I}
R = intercepted radiation (MJ m^{-2} d^{-1}) {I}
ε_{pot} = potential net growth rate (g MJ^{-1}) {A}
f_w = water stress factor scalar computed in 'SoilWat' (-) {I}
P = daily increment in physiological age (pA) {S}
$\Delta\bar{P}$ = average physiological age increase (pA d^{-1}) {P}
D_{row} = distance between rows (m) {P}
D_p = distance between plants within rows (m) {P}

The units of physiological age, although dimensionless, are denoted by pA. The interception of radiation R (MJ m^{-2} d^{-1}) {I} follows a de Beer's law function as given in Equation 2. The plant area index L_{l+s} (m^2 m^{-2}) {A} includes the area of both leaves and stems and R_G is the total daily incoming global radiation (J cm^{-2} d^{-1}) {I}. To obtain the correct units, the latter has to be adjusted by the factor 0.01.

$$R = 0.01\ R_G\ (1 - e^{-0.5 L_{l+s}}) \tag{2}$$

The leaf area index L_l (m^2 m^{-2}) {A} used in 'PotatoMod' only refers to leaf area and the plant area index L_{l+s} (m^2 m^{-2}) {A} used in 'SoilWat' are computed as follows:

$$L_l = W_l\ S_l\ /(D_{row}\ D_p) \tag{3}$$

$$L_{l+s} = L_l + W_s\ C_s\ S_l\ /(D_{row}\ D_p) \tag{4}$$

where:
W_l = dry matter of leaves (g plant^{-1}) {S}
W_s = dry matter of stems (g plant^{-1}) {S}
C_s = stem to leaf equivalents conversion factor (-) {P}
S_l = specific leaf area (m^2 g^{-1}) {P}

The expression 'D_{row} D_p' used in Equations 1, 3 and 4 is needed to adjust the input data provided per unit area to model variables (leaf, stem, etc.) which are computed per plant.

The potential net growth rate ε_{pot} (g MJ^{-1}) {A} is modelled after a relation published by Ng & Loomis (1984). In this relation the different productivity of different physiological age classes of leaves P_j {S} is taken into account by a trapezoidal function defined by the maximal potential net growth rate ε_{max} (g MJ^{-1}) {P} and the parameters $P_{l,1}$, $P_{l,2}$ and $P_{l,max}$ (all {P}):

$$\varepsilon_{pot} = \varepsilon_{max} \frac{P_{l,max} - P_j}{P_{l,max} - P_{l,1}} \quad : \quad P_{l,1} < P_j \leq P_{l,max}$$

$$\varepsilon_{pot} = \varepsilon_{max} \quad : \quad P_{l,2} \leq P_j \leq P_{l,1} \qquad (5)$$

$$\varepsilon_{pot} = \varepsilon_{max} \left(0.4 + 0.6 \frac{P_j}{P_{l,2}}\right) \quad : \quad 0 \leq P_j < P_{l,2}$$

The process of physiological ageing is described by a rather complicated procedure proposed by Sands et al. (1979). It is a weighted average of 4 physiological age fractions ΔP_i (pA) {A} computed at 4 points of the daily temperature course T_i (°C) {A}. The following equation generates the change in physiological age:

$$T_1 = T_{min}$$

$$T_2 = 0.67\ T_{min} + 0.33\ T_{max}$$

$$T_3 = 0.33\ T_{min} + 0.67\ T_{max} \qquad (6)$$

$$T_4 = T_{max}$$

$$\Delta P_i = 0 \quad : \quad T_i \geq T_{c,max}$$

$$\Delta P_i = 10 \left[1 - \left(\frac{T_i - T_{c,opt}}{T_{c,max} - T_{c,opt}}\right)^2\right] \quad : \quad T_{c,opt} < T_i < T_{c,max}$$

$$\Delta P_i = 10 \left[1 - \left(\frac{T_{c,opt} - T_i}{T_{c,opt} - T_{c,min}}\right)^2\right] \quad : \quad T_{c,min} < T_i \leq T_{c,opt} \qquad (7)$$

$$\Delta P_i = 0 \quad : \quad T_i \leq T_{c,min}$$

$$i = 1,2,3,4$$

$$\Delta P = (5\Delta P_1 + 8\Delta P_2 + 8\Delta P_3 + 3\Delta P_4) / 24 \tag{8}$$

The growth and partitioning before and just after emergence is modelled differently than during later crop growth. The fraction $C_{seed,be}$ (-) {P} of the seed tuber W_{seed} (g plant^{-1}) {P} is allocated with efficiency U_{seed} (-) {P} during germination to the growing organs and gives the auxiliary variable $W_{c,seed}$ (g plant^{-1}) {A}.

$$W_{c,seed} = \frac{W_{seed}\, C_{seed,be}\, U_{seed}}{W_{conc}} \tag{9}$$

where $W_{c\ nc}$ is the dry matter concentration in the tuber. The partitioning between organ types is realized by multiplication of the parameters $\beta_{l,seed}$, $\beta_{s,seed}$ and $\beta_{r,seed}$ (all ( ) {P}):

$$W_i(t=0) = W_{c,seed}\, \beta_{i,seed} \qquad i = l,s,r \tag{10}$$

After emergence and while physiological age is smaller than $P_{seed,end}$ (pA) {P} the daily contribution $\Delta W_{c,seed}$ (g plant^{-1} d^{-1}, {R} is taken from the seed tuber W_{seed} (g plant^{-1}) {P} and allocated to the different plant organs by applying the same partitioning parameters as before emergence.

$$\Delta W_{c,seed} = \frac{W_{seed}\, C_{seed,ae}\, U_{seed}}{W_{conc}} \left(\frac{\Delta \overline{P}}{P_{seed,end}} \right) \tag{11}$$

$$\Delta W_{c,i} = \Delta W_{c,seed}\, \beta_{i,seed} \qquad i = l,s,r \tag{12}$$

The partitioning among organ populations (given below) is computed by a series of equations derived from the famous 'Michaelis-Menten' equation, one for each population of organs, according to their sink strength (Figure 2):

$$\beta_l = \mu_l \frac{K f_w}{K + W_s + W_r + W_{tu}} \tag{13}$$

$$\beta_s = \mu_s \frac{W_s\, f_w}{K + W_s + K + W_{tu}} \tag{14}$$

$$\beta_r = \mu_r \frac{W_r\, f_w}{K + W_r + K + W_{tu}} \tag{15}$$

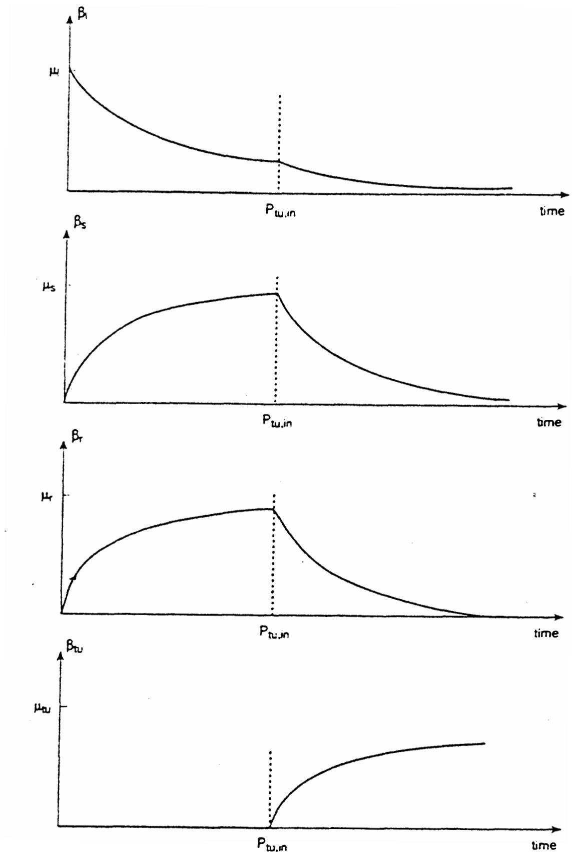

Figure 2. Schematic representation of the Michaelis-Menten type partitioning scheme adopted by the potato submodel 'PotatoMod'.

$$\beta_{tu} = \mu_{tu} \frac{W_{tu}}{K + W_{tu}} \tag{16}$$

$$\Delta W_i = \frac{\beta_i}{\beta_l + \beta_s + \beta_r + \beta_{tu}} f_a (W_a + \Delta W_p) \qquad i = l,s,r,tu \tag{17}$$

where:
W_l, W_s, W_r, W_{tu} = dry matter of leaf, stem, root, tuber (g plant^{-1}) {S}
K = Michaelis Menten half saturation parameter (g plant^{-1}) {P}
$ß_l, ß_s, ß_r, ß_{tu}$ = demand for growth of leaf, stem, root, tuber (-) {A}
$\mu_l, \mu_s, \mu_r, \mu_{tu}$ = maximum growth rate for leaf, stem root, tuber (-) {P}
f_a = assimilation pool usage per day (-) {P}
W_a = assimilate pool (g plant^{-1}) {S}
ΔW_p = daily net dry matter increase (Equation 1) (g plant^{-1} d^{-1}) {A}
f_w = water stress factor computed in 'SoilWat' ( ) {I}

The change in assimilate pool:

$$\Delta W_a = \Delta W_p - f_a (W_a + \Delta W_p) + \delta \Delta W_{l,sen} \qquad (18)$$

where:
δ = proportion of recycled dry matter (-) {P}
$\Delta W_{l,sen}$ = dry matter of senescing leaves (g plant^{-1} d^{-1}) {R}

The Equations 13 through 17 for partitioning were slightly modified compared to the original model: the demands of tubers to growth $ß_{tu}$ is no longer influenced by water stress (Equation 16).

To consider differing productivities of leaves of a different age (Equation 5) and to model the leaf senescence, the leaf biomass of a day is filled in a new 'box' of a 'box car train'. All 'boxes' older than $P_{l,max}$ (pA) {P} are then removed from the currently living leaves.

2.2.2 SoilWat

'SoilWat' is a water balance model consisting of one layer from the average soil surface down to the rooting depth of the crop. Descriptions of water balance, vertical water movement and water stress were taken from the model proposed by van Keulen and Wolf (1986) and Penning de Vries & van Laar (1982). The 'Penman' equations of evapotranspiration and water infiltration rate were derived from Doorenbos & Pruitt (1975) and Schroedter (1985). 'SoilWat' has the two state variables S_s (surface water storage) and S_r (rootzone water storage). The model presented at the workshop did not include capillary rise. As a consequence the model had difficulties reproducing realistic results for the data sets of the so-called drought conditions at Invergowrie. Therefore, after the workshop, we decided to extend the model by a routine which simulates vertical water flow.

The equations for surface water storage (19) and rootzone water storage (20) are respectively:

$$S_S (t) = S_s(t-\Delta t) + Q_{c,pr+ir} - Q_{run} \quad Q_{in} \qquad (19)$$

where:
$Q_{e,pr+ir}$ = effective water supply (Equation 24) (mm d^{-1}) {R}
Q_{run} = surface run off (mm d^{-1}) {R}
Q_{in} = rate of water infiltration (mm d^{-1}) {R}

$$S_R\ (t) = S_R\ (t-\Delta t) + Q_{in} - E_a - T_a - Q_{out} \tag{20}$$

where:
E_a = rate of evaporation (mm d^{-1}) {R}
T_a = rate of transpiration (mm d^{-1}) {R}
Q_{out} = vertical water flow through lower boundary (percolation-capillary rise) (mm d^{-1}) {R}

The update of the balance equations follows precisely the descriptions given by Driessen (1986). The infiltration Q_{in} (mm d^{-1}) {R} cannot exceed the infiltration capacity of the soil. The amount of non-infiltrating water remains at the soil surface or, depending on soil topology, runs off (Q_{run} (mm d^{-1}) {R}). The subroutine SubSoil from WOFOST (van Keulen & Wolf, 1986) is used for the iterative computation of capillary rise or percolation, i.e. Q_{out} (mm d^{-1} {R}. The necessary function for hydraulic conductivity at matric suction is given in Equation 42.

The total water supply Q_{pr+ir} (mm d^{-1}) is the sum of precipitation Q_{pr} (mm d^{-1}) {I} and irrigation Q_{ir} (mm d^{-1}) {I}. The amount of water intercepted by the canopy Q_{int} (mm d^{-1}) {A} is then computed as a polynomial function of the plant area index L_{l+s} ( ) {I} (Doorenbos & Pruitt, 1975). The total water supply minus the intercepted amount yields the effective water supply $Q_{e,pr+ir}$ (mm d^{-1}) {R}.

$$Q_{pr+ir} = Q_{pr} + Q_{ir} \tag{21}$$

$$Q_{int} = -0.42 + 0.245Q_{pr+ir} + 0.2L_{l+s} + 0.0271Q_{pr+ir}\,L_{l+s} - 0.0111Q_{pr+ir}^2 - 0.0109L_{l+s}^2 \tag{22}$$

$$Q_{int} = \text{RLIMIT}\ (Q_{int},\ 0.0,\ Q_{pr+ir}) \tag{23}$$

where RLIMIT is a function which limits the range of Q_{int} between 0 and Q_{pr+ir}

$$Q_{e,pr+ir} = Q_{pr+ir} - Q_{int} \tag{24}$$

Now follows the 'Penman' equation, according to the formulation by e.g. Schroedter (1985): The psychrometric constant γ {A} and the slope of the vapour pressure curve Δ (mb °C^{-1}) {A} are influenced by the mean daily temperature T (computed as average of daily temperature extremes T_{min}, T_{max}; all (°C) {I}) and the atmospheric pressure P (mb) {A} (depending on the altitude ALT (m above sea level){P}):

$$T = \frac{T_{min} + T_{max}}{2} \tag{25}$$

$$P = 1013.0 - 0.1055ALT \tag{26}$$

$$\gamma = \frac{0.386P}{595.0 - 0.51T} \tag{27}$$

$$\Delta = 2(0.00738T + 0.8072)^2 - 0.00116 \tag{28}$$

The actual vapour pressure e_d (mb) {A} is computed from relative humidity r_H (%) {I} and saturated vapour pressure e_s (mb) {A}. The latter is the average of temperature extreme dependent saturation vapour pressures e_{Tmin} and e_{Tmax} (all (mb) {A}):

$$e_{Tmin} = e^{1.81528 + 0.07159T_{min} - 0.000328T_{min}^2} \tag{29}$$

$$e_{Tmax} = e^{1.81528 + 0.07159T_{max} - 0.000328T_{max}^2} \tag{30}$$

$$e_s = \frac{e_{Tmin} + e_{Tmax}}{2} \tag{31}$$

$$e_d = e_s \frac{r_H}{100} \tag{32}$$

The outgoing long wave radiation R_B (J cm ^{2} d^{-1}) {A} is given by:

$$R_B = 4.21\left(1.17\ 10^{-7}(T + 273)^4\right)\left(0.38 - 0.35\sqrt{e_d}\right)(1 - 0.9\Omega) \tag{33}$$

where:
T = mean daily temperature (°C)
e_d = actual vapour pressure (mb) {A}
Ω = fraction overcast day ( ) {A}

Ω is calculated after the procedure described by van Keulen et al. (1982) and depends on the theoretical and measured incoming global radiation. The incoming radiation R_N (J cm^{-2} d^{-1}) {A} is defined by the incident global radiation R_G (J cm^{-2} d^{-1}) {I}, the albedo r_a (-) {P} and the outgoing long wave radiation R_B (J cm^{-2} d^{-1}){A}:

$$R_N = R_G\ (1 - r_a) - R_B \tag{34}$$

The influence of wind speed U_2 (m s^{-1}) {A}, usually at 2 m height, is taken into account after the following correction for observed anemometer heights:

$$U_2 = U_z \, e^{0.2 \ln\left(\frac{2}{Z}\right)} \tag{35}$$

where:
U_z = daily average wind speed at height Z (m s^{-1}) {I}
Z = height above ground surface of wind measurements (m) {P}

The evapotranspiration due to radiation ET_R (mm d^{-1}){A} is given by:

$$ET_R = \frac{\Delta}{\Delta + \gamma} \; \frac{R_N}{245} \tag{36}$$

The evapotranspiration due to drying power of the air ET_D (mm d^{-1}) {A} is given by:

$$ET_D = \left(1 - \frac{\Delta}{\Delta + \gamma}\right) 0.27 \; (1 + 0.864 \; U_2) \; (e_s - e_d) \tag{37}$$

The potential evapotranspiration ET_P (mm d^{-1}) {A} consists of the sum of the evapotranspiration due to radiation and drying power of the air multiplied by the correction factor C_u for wind U_2 (m s^{-1}) {A} and incident radiation R_G (J cm^{-2} d^{-1}) {I}:

$$ET_p = (ET_R + ET_D) \; C_u \tag{38}$$

$$C_u = 0.876 + 0.023 \; \frac{R_G}{245} - (0.036 \; U_2) \; 1.2 \tag{39}$$

The soil moisture θ is expressed as water per soil volume (cm^3 cm^{-3}) {A}, and is computed from the water in the root zone, S_R (mm) {S}, and the effective rooting depth, Z_R (mm) {P}.

$$\theta = \frac{S_R}{Z_R} \tag{40}$$

The matric suction ψ (cm) {A} is computed as a function of soil moisture, total soil porosity θ_0 (cm^3 cm^{-3}) {P} and the soil specific pore characteristics Γ (cm^{-2}) {P}:

$$\psi = e^{\sqrt{\frac{-\ln(\theta/\theta_0)}{\Gamma}}} \tag{41}$$

The hydraulic conductivity at matric suction ψ, k_ψ (cm d^{-1}) {A} is modelled by a split relation (Driessen, 1986). For lower values of ψ (cm) {A} the first equation is valid, depending on the saturated hydraulic conductivity k_0 (cm d^{-1}) {P} and the texture specific parameter α (cm^{-1}) {P}. Above ψ_m (cm) {P} the second equation is used, depending on the texture specific parameter α (cm^{-1}) {P} only.

$$k_\psi = k_0 \, e^{-\alpha\psi} \quad : \quad \psi \leq \psi_m$$

$$k_\psi = \alpha\psi^{-1.4} \quad : \quad \psi > \psi_m \tag{42}$$

The potential evapotranspiration ET_p (mm d^{-1}) {A} is split into the maximal transpiration rate T_p (mm d^{-1}){A} and the maximal evaporation E_p (mm d^{-1}) {A} by a de Beer's law interception function of the plant area index L_l (-) {I}:

$$T_p = ET_p \, (1 - e^{-0.6 \, L_{l+s}}) \tag{43}$$

$$E_p = ET_p - T_p \tag{44}$$

The actual transpiration T_a (mm d^{-1}){A} is defined after Driessen (1986) as a trapezoidal function (see Figure 3) depending on the actual soil moisture content θ {A} (θ_{005} for nearly saturated soils; θ_F field capacity; θ_{CR} crop dependent critical soil moisture; θ_W wilting point; all ($cm^3 \, cm^{-3}$) {A}) and the maximal transpiration T_p (mm d^{-1}) {A}:

$$\begin{aligned} T_a &= 0.0 && : \theta > \theta_{005} \\ T_a &= T_p \, (\theta_{005} - \theta)/(\theta_{005} - \theta_F) && : \theta \geq \theta_F \\ T_a &= T_p && : \theta > \theta_{CR} \\ T_a &= T_p \, (\theta - \theta_w)/(\theta_{CR} - \theta_w) && : \theta \geq \theta_w \\ T_a &= 0.0 && : \theta < \theta_w \end{aligned} \tag{45}$$

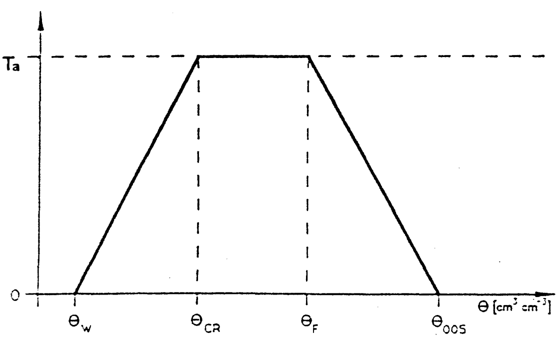

Figure 3. Graphical representation of actual transpiration Ta (solid line) dependent of the soil moisture θ. The other symbols stand for: θ_W = wilting point, θ_{CR} = crop specific critical soil moisture, θ_F = field capacity, θ_{005} = near saturated soil.

The actual evaporation E_a (mm d^{-1}) {A} is given as a function of moisture content of air dry soil θ_A (cm^3 cm^{-3}) {A}, total fraction of pore space θ_0 (cm^3 cm^{-3}) {P}, the actual moisture content θ (cm^3 cm^{-3}) {A} and the maximal evaporation E_p (mm d^{-1}) {A}.

$$E_a = E_p\left(\frac{\theta - \theta_A}{\theta_0 - \theta_A}\right) \tag{46}$$

$$\theta_A = 0.33\ \theta_W \tag{47}$$

The actual evapotranspiration ET_a (mm d^{-1}) {A} is the sum of the actual transpiration T_a (mm d^{-1}) {A} and actual evaporation E_a (mm d^{-1}) {A}.

$$ET_a = T_a + E_a \tag{48}$$

Finally the water stress factor f_w ( ) {A} is defined as the fraction of satisfied transpiration:

$$f_w = \frac{T_a}{T_p} \tag{49}$$

2.3 Input parameters and functions

Site specific, soil specific and crop specific parameters are stored in files, which also contain measured data if available. The parameters are read and set by the data handling model PotModValid (in case of incomplete information, default values are taken). This model also allows display of these data series during a simulation run (see also Section 2.5). Table 1 lists all input functions needed by the different submodels. Note that the data handling model 'Weather' reads the data from the weather file and performs the necessary unit conversions. The other models compute their outputs dynamically. All parameters used are described and listed together with their values in Table 2 of Section 3.2.

Table 1. Input functions exchanged between submodels of the PotatoSoilWat-model.

Variable	Unit	Explanation	Source Model	Used in Model
T_{min}	(°C)	daily temperature minimum	Weather	SoilWat, Potato
T_{max}	(°C)	daily temperature maximum	Weather	SoilWat, Potato
U_2	(m s^{-1})	daily average wind speed	Weather	SoilWat
Q_{pr}	(mm d^{-1})	total daily precipitation	Weather	SoilWat
Q_{ir}	(mm d^{-1})	total daily irrigation	Weather	SoilWat
R_a	(J cm^{-2} d^{-1})	total daily global radiation	Weather	SoilWat, Potato
rH	(%)	average relative humidity	Weather	SoilWat
L_{l+s}		plant area index	Potato	SoilWat
f_w	( )	water stress factor	SoilWat	Potato

2.4 Output and verifiable variables

PotatoMod: The state variables W_l, W_s, W_r, W_{tu}, are simulated on a per plant basis. Therefore, for verifications, e.g. with the data provided from Invergowrie, these outputs have to be converted to other units, e.g. g m^{-2}. The computed L_l can be compared directly with the observed data. The variable W_{conc} is computed to allow for further verifications with the fresh weight of the tuber yield.

SoilWat: The verification of both state variables S_R (rootzone water storage) and S_S (surface water storage) is possible. Of the numerous auxiliary variables only a few are directly comparable to directly measured data: θ (soil moisture content in the root zone) and Q_{run} (surface runoff).

2.5 Time step, timescale and program language

The potato growth model is formulated in the form of differential equations; however it was originally implemented as a discrete-time form with a fixed time step of 1 day (Δt). The simulation time starts at 50% emergence and stops at the haulm killing date.

The soil water model is formulated in a discrete time form with the same time step (Δt) as 'PotatoMod', i.e. one day.

We translated the original potato model from Fortran to Modula-2 into the form required by the simulation environment 'MODELWORKS' (Fischlin et al., 1990); Fischlin, 1991). The latter produces instantaneous graphs and allows modification of interactive parameters from run to run or even in the middle of a simulation run. The soil water balance model was built from the equations in the above cited publications and implemented in Modula-2 and coupled with the potato model. MODELWORKS is a modelling and simulation environment based on the programming language Modula-2 (Wirth, 1988) and is specifically designed to be run interactively on personal computers and workstations. It supports modular modelling by featuring a coupling mechanism between submodels and unrestricted number of state variables, model parameters etc. up to the limits of the computer resources. It allows for the formulation of continuous time, discrete time as well as continuous and discrete time mixed models. MODELWORKS features a completely open system architecture based on the Dialog Machine (Fischlin, 1986). This simulation environment can be easily expanded and freely customized with a minimum of programming effort. The modular structure of the model formulation of 'PotatoSoilWat' using Modula-2 and MODELWORKS is shown in Figure 4.

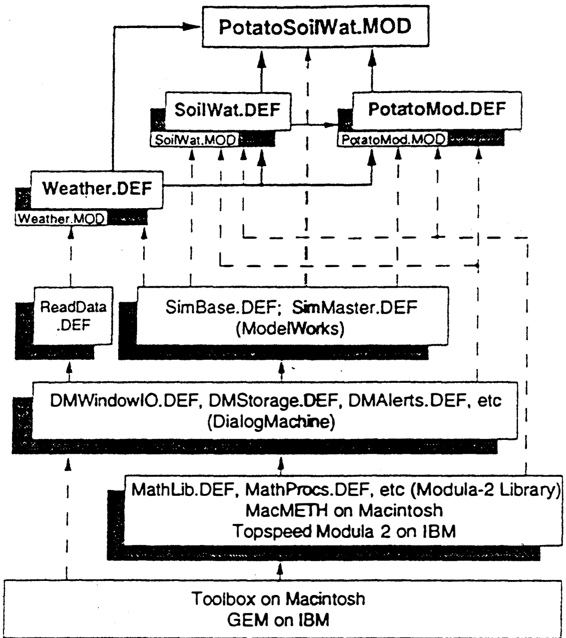

Figure 4. Structure of the modules of the PotatoSoilWat model. Arrows indicate imports from other modules (solid lines were used in between (sub) models, broken lines stand for imports from library modules), boxes stand for single modules or a module library, underlying grey boxes represent the corresponding implementation modules (file extension .MOD). For simplicity the pseudo model 'PotatoModValid' (see Figure 1) is omitted here.

The figure depicts the different software layers from the most general at the bottom to the most specialized at the top: at the bottom is the machine dependent layer toolbox which depends on the general purpose programming language Modula-2.
The next layer up consists of the 'DialogMachine', a procedure library for interactive (dialog based) programs (Fischlin, 1986). On top resides the model definition program written by the modeller. All this is embedded in the MODELWORKS environment supporting interactive modelling, simulation, plus interactive post-simulation analysis (Fischlin, 1991).

Approximately 250 lines of the source code of the potato submodel (PotatoMod) contain actually executable instructions, of which only approximately half of the lines define the model equations. About the same proportions hold for the soil water submodel (SoilWat), but with only a total of ca. 200 lines of executable source code. ModelWorks is available for the Apple Macintosh and in a slightly limited version for the IBM PC and compatibles.

3 Parameterization and calibration

3.1 Parameterization and calibration in general

Parameterization means finding values for parameters of general validity whereas calibration covers the action of fine tuning of some selected parameters. This means that parameters typical for a particular potato variety and planting condition have to be calibrated. Since the models presented are nonlinear, parameterization proves to be rather difficult, mainly because of the numerous local minima in the parameter space. The potato growth model is especially difficult to parameterize due to the many feedbacks in the partitioning equations. The potato model was published by Johnson et al. (1986) with parameter sets for two varieties of potatoes (Russet Burbank & Norland) and two planting regimes. For the application of 'PotatoMod' in Switzerland we had to parameterize the model for the variety Bintje (Roth et al., 1993). On the other hand we changed very few parameters of the soil water submodel because (i) until recently we had limited access to suitable soil data and (ii) we considered the equations sufficiently well parameterized by the authors of the original models (Berkhout & van Keulen, 1986; Driessen, 1986; Schroedter, 1985; Stroosnijder, 1982).

3.2 Parameterization and calibration with workshop data

The potato-model had to be adapted to the variety 'Maris Piper' grown near Invergowrie (Scotland) in the years 1984 (N4 treatment) and 1986 under WET (optimal) and DRY (drought) conditions. We started with the parameters listed in the original publication (Johnson et al., 1986) for the varieties Russet Burbank & Norland and those we found for the variety Bintje under Swiss conditions. The calibration was done by graphical examination of model output and observed data as well as with two parameter identification algorithms: first a simple halving doubling procedure and second a downhill simplex method procedure ('Amoeba') described in Press et al. (1988).

The performance criteria used was the sum of squares of deviations of the sum W_s + W_{tu} dry weights to measured data plus the 10-fold sum of squares from the differences between simulated and measured L_l. Three single simulation runs for all the given calibration data sets (i.e. 1984 N4, 1986 WET, 1986 DRY) allowed one performance function evaluation. All the parameters of the Michaelis-Menten type partitioning (K, μ_l, etc.) were identified by optimization. This approach appears reasonable since Johnson et al. (1986) used a similar procedure to find values for these parameters and other values for each variety (Russet Burbank & Norland).

Obviously, potato varieties differ especially in their partitioning scheme. Hence the adopted partitioning parameters during emergence, such as $\beta_{l,seed}$, were taken from the variety Russet Burbank rather than taking the values found for the variety Bintje. The longevity of leaves ($P_{l,max}$) of Maris Piper is variable but clearly longer than the 400 physiological age units given for Russet Burbank.

Growth processes in the Johnson model are very sensitive to the value of ε_{max} (real potential net growth). Therefore real potential net growth of European potato varieties needed to be calibrated for each variety and included the parameters ε_{max} and $P_{l,1}$ in the set of parameters to be identified by optimization. After 147 iterations of the algorithm 'Amoeba' the parameter values obtained are given in Table 2.

The specific leaf area S_l was directly determined from the available data (0.035). The average of all ratios of measured leaf dry matter versus leaf area were taken except the last points of each calibration data set which were discarded because of the obvious effects of senescence.

The water balance model was not further parameterized. The parameters depending on type of soil (fine sandy loam) were all taken from the tables given by Driessen (1986). One parameter was not easily available: Z_T, the depth of the groundwater table. The examination of the different layers of the soil water data provided and pore space characteristics suggested the presence of a perched water table. These data and the graphical evaluation, especially the DRY conditions, led to a Z_T value of 100 cm.

4 Results

Calibration results (i.e. tuber dry matter, W_{tu}, leaf area index, L_l and the water storage in the root zone, S_R) were compared to the calibration data provided (Figure 5a, b and c for the 1984 N4 treatment; Figure 6a, b and c for the 1986 WET treatment and Figures 7a, b and c for the 1986 DRY treatment). Final simulated tuber dry matter production corresponds well with the measured data for the three treatments as does water storage in the root zone. However, simulated L_l does not correspond well with observed data (underestimated for the 1984 N4 treatment (Figure 5b) and overestimated for both the 1986 WET and DRY treatments, Figures 6b and 7b respectively).

As with the calibration results, for validation W_{tu}, L_l and S_R were also compared. Figures 8a, b and c show results for the 1985 N4 treatment, Figures 9a, b and c for the 1987 WET treatment and Figures 10a, b and c for the 1987 DRY treatment. The simulated tuber dry matter (Figures 8a, 9a and 10a) tended to flatten out towards the end of the growing season. The simulated L_l (Figures 8b, 9b and 10b) showed considerable variation during the growing season. For validation purposes the soil layers 1 to 3 were averaged and compared to the single layer of 'SoilWat'. The simulated water in the root zone was clearly overestimated for the year 1985 N4 (Figure 8c) but was not too far from the observed data of both treatments (WET and DRY) in 1987 (Figures 9c and 10c).

Table 2. Parameters of 'PotatoMod' and 'SoilWat' with information on parameterization

1	2	3	4	5	6	7	8	9
process	eq'n no.	parameter	description parameter	value of paramet.	method of estimation	data source	method of re-estimation	new value
PotatoMod								
partitioning	13-16	K (g pl^{-1})	Michaelis Menten half saturation	50.0	non-linear iteration	Johnson (1986)	optimisation	56.0
	13	μ_l (g pl^{-1} d^{-1})	max. growth rate of leaves	1.0	non-linear iteration	Johnson (1986)	optimisation	1.25
	14	μ_s (g pl^{-1} d^{-1})	max. growth rate of stems	6.0	non-linear iteration	Johnson (1986)	optimisation	30.0
	15	μ_r (g pl^{-1} d^{-1})	max. growth rate of root	1.0	non-linear iteration	Johnson (1986)	optimisation	6.1
	16	μ_{tu} (g pl^{-1} d^{-1})	max. growth rate of tuber	6.0	non-linear iteration	Johnson (1986)	optimisation	12.0
		$P_{tu,in}$ (pA)	start of tuber growth	200.0 225.0	field observations	Johnson (1986)	optimisation	100.0
	17	f_a	maximal usage of assimilate pool	0.75	guessing	Johnson (1986)	no change	
partitioning		$W_{tu,in}$ (g pl^{-1})	start weight of new tubers	0.5	field observations	Johnson (1986)	no change	
senescence	5	$P_{l,max}$ (pA)	maximum leaf age observations	400.0	field observations	Johnson (1986)	optimisation	600.0
		$P_{p,max}$ (pA)	maximum plant age	675.0- 810.0	field observations	Johnson (1986)	optimisation	1000.0

Continue Tabel 2

1 process	2 eq'n no.	3 parameter	4 description parameter	5 value of paramet.	6 method of estimation	7 data source	8 method of re-estimation	9 new value
PotatoMod								
net assimilation	5	ε_{max} (g MJ^{-1})	maximum potential net growth rate	1.56	literature	Johnson (1986,1987) Ng & Loomis (1984)	optimisation	1.83
	5	$P_{l,1}$ (pA)	maximum leaf age of ε_{max}	160.0	literature	Johnson (1986,1987) Ng & Loomis (1984)	optimisation	386.0
	5	$P_{l,2}$ (pA)	minimum leaf age of ε_{max}	80.0	literature	Johnson (1986,1987) Ng & Loomis (1984)	optimisation	75.0
	18	δ	proportion of senescend leaves recycled	0.5	guessed	Johnson (1986)	no change	
net assimilation	1	ΔP (pA d^{-1})	average phys. age increase per day	8.0	meteo data	Johnson (1986)	calibration data	7.0
	3	S_l (m^2 g^{-1})	specific leaf area	0.023	field data	Johnson (1986)	calibration data	0.028
	4	C_s (g g^{-1})	stem to leaf area equivalent	0.0869	field data	Johnson (1986)	no change	
emergence		$P_{seed,end}$ (pA)	duration of assim ilate contribution	200.0	field data	Johnson (1986)	Bintje, unpubl.	120.0
	9	$C_{seed,be}$ (-)	proportion allocated before emergence	0.2	field data	Johnson (1986)	no change	
	11	$C_{seed,ae}$ (-)	proportion allocated after emergence	0.6	field data & literature	Johnson (1986)	no change	

Continue Tabel 2

1	2	3	4	5	6	7	8	9
process	eq'n no.	parameter	description parameter	value of paramet. [a]	method of estimation	data source	method of re estimation	new value
PotatoMod								
emergence	10	$\beta_{l,seed}$ (-)	proportion allocated to leaves	0.2	field data literature	Johnson (1986)	no change	
	10	$\beta_{s,seed}$ (-)	proportion allocated to stems	0.4	field data	Johnson (1986)	no change	
	10	$\beta_{r,seed}$ (-)	proportion allocated to roots	0.4	field data	Johnson (1986)	no change	
	9	U_{seed} (-)	efficiency of utilization of seed tuber reserves	0.4	field data	Johnson (1986)	no change	
ageing	7	$T_{c,min}$ (°C)	minimum growth temperature	7.0	literature	Johnson (1986) Sands et al. (1979)	Bintje, unpublished	4.0
	7	$T_{c,max}$ (°C)	maximum growth temperature	30.0	literature	Johnson (1986) Sands et al. (1979)	Bintje, unpublished	30.0
	7	$T_{c,opt}$ (°C)	optimal growth temperature	21.0	literature	Johnson (1986) Sands et al. (1979)	Bintje, unpublished	20.0
planting	1	D_{row} (m)	planting distance between rows	1.0	planting data	Johnson (1986)	husbandry data	0.75
	1	D_p (m)	planting distance between plants	0.3	planting data	Johnson (1986)	husbandry data	0.33
		ρ (pl m^{-2})	plant density	3.33	planting data	Johnson (1986)	husbandry data	4.04

Continue Tabel 2

1	2	3	4	5	6	7	8	9
process	eq'n no.	parameter	description parameter	value of paramet.	method of estimation	data source	method of re estimation	new value
PotatoMod								
	9	W_{seed} (g pl ^{1})	seed weight per plant	0.60 0.80	planting data	Johnson (1986)	husbandry data	45.0
validation	9	W_{conc}	tuber dry to fresh weight conversion	5.0	field data	Johnson (1986)	husbandry data	5.0
SoilWat								
soil water balance		soilNR (1..9)	number of soil				soil data	1
	40	Z_R (mm)	rooting depth			van Keulen & Wolf (1986)	45.0	
		f_s (%)	proportion of stones				soil data	10.0
surface water storage		S_{rou} (-)	surface roughness				soil data	20.0
		S_f (%)	slope of the field				husbandry data	0.0
		α_f (°)	clod/furrow angle				husbandry data	0.524
capillarity		Z_r (cm)	ground water table height				graphical estimation	100.0
evapotrans piration	34	r_a (-)	albedo			Schroedter (1985)	0.2	
energy balance		LAT (°N)	latitude				husbandry data	56.0
	26	ALT (m)	altitude above sea level				husbandry data	24.0

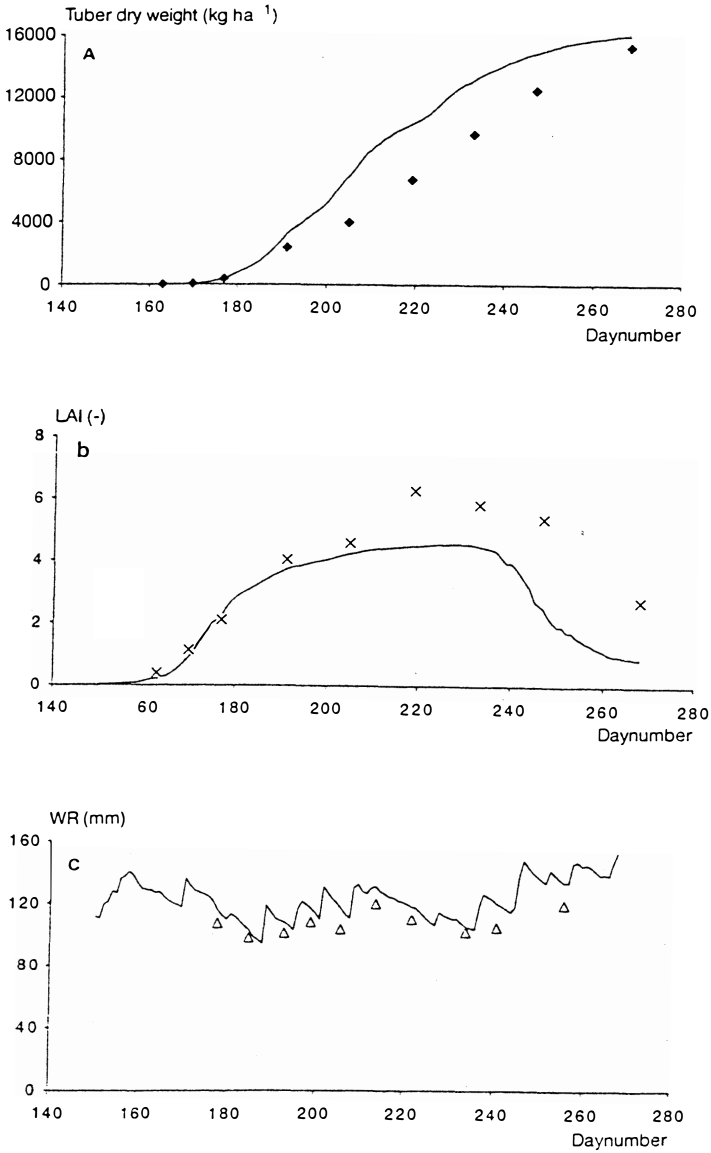

Figure 5. Calibration results 84 N4: cv. Maris Piper grown near Invergowrie in 1984 under potential conditions (a) tuber dry weight, W_{tu}, (b) leaf area index, L_p (c) water storage in the root zone, S_R (symbols denote observations, lines are simulated).

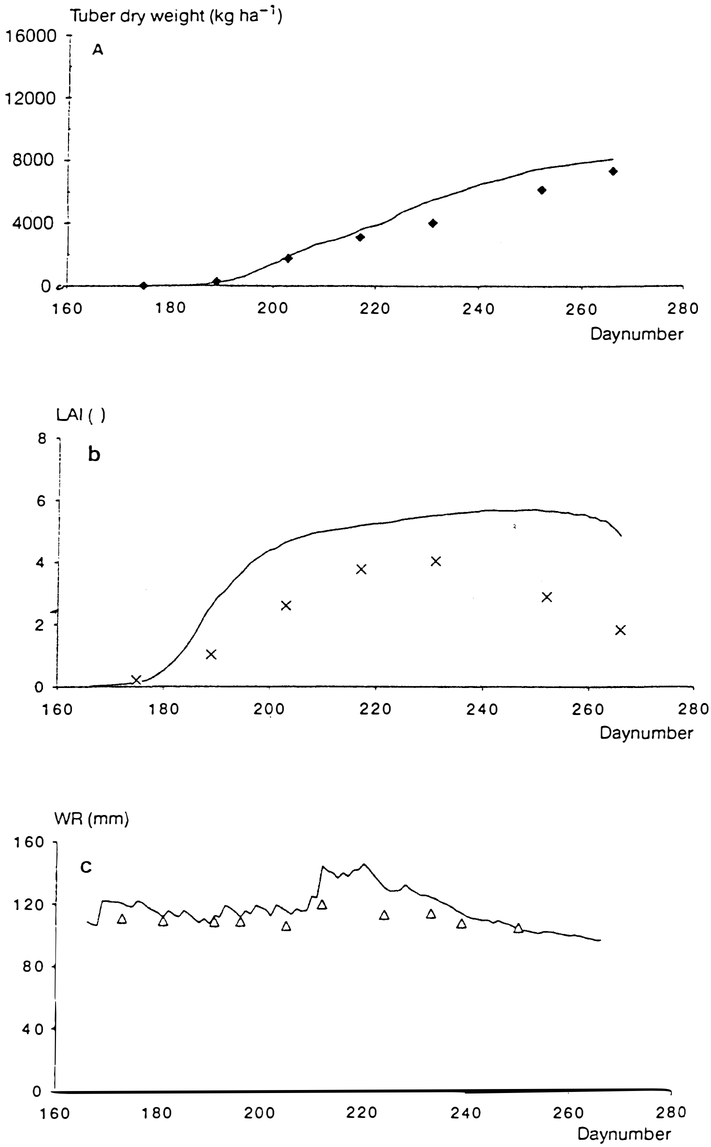

Figure 6. Calibration data 86W: cv. Maris Piper grown near Invergowrie in 1986 under potential conditions (a) tuber dry weight, W_{tu}, (b) leaf area index, L_p (c) water storage in the root zone, S_R (symbols denote observations, lines are simulated).

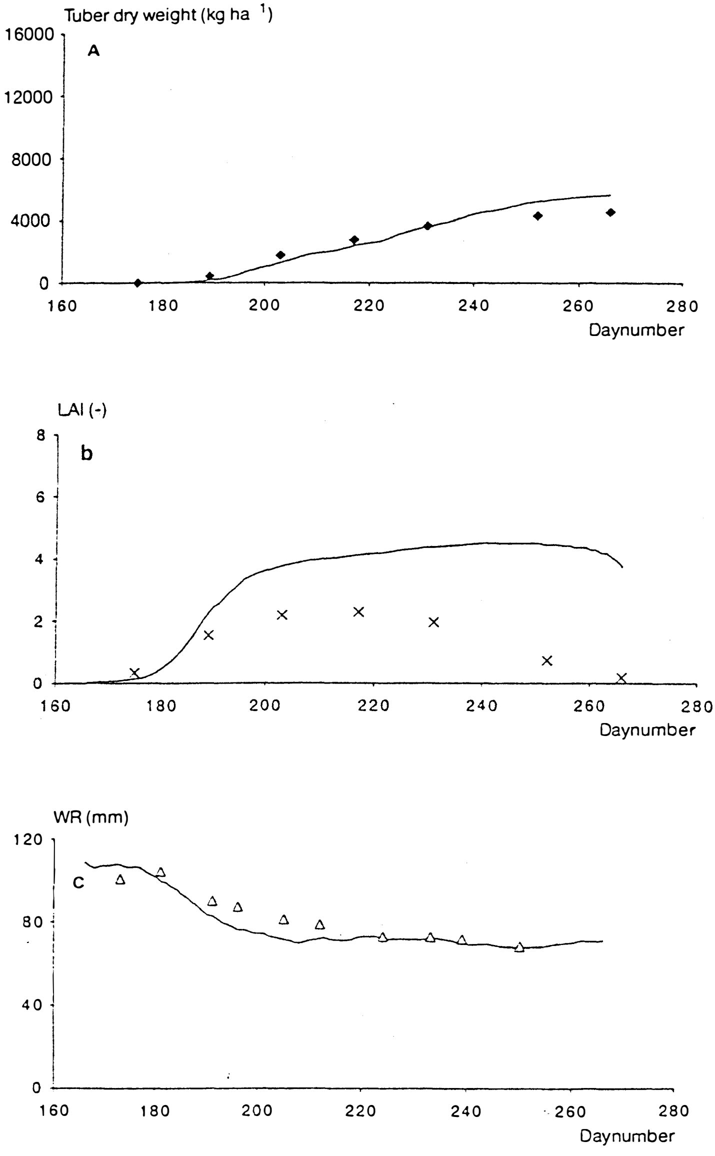

Figure 7. Calibration data 86D: cv. Maris Piper grown near Invergowrie in 1986 under 'drought' conditions (a) tuber dry weight, W_{tu}, (b) leaf area index, L_b (c) water storage in the root zone, S_R (symbols denote observations, lines are simulated).

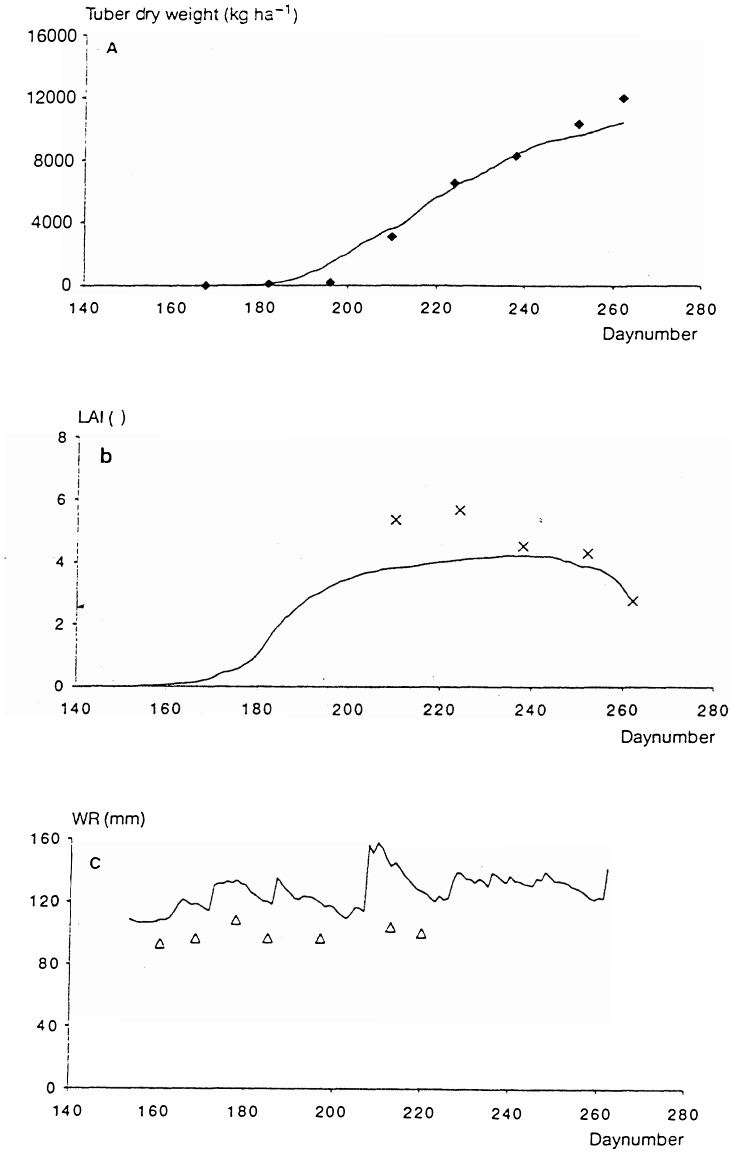

Figure 8. Validation data 85 N4: cv. Maris Piper grown near Invergowrie in 1985 under potential conditions (a) tuber dry weight, W_{tu}, (b) leaf area index, L_p (c) water storage in the root zone, S_R (symbols denote observations, lines are simulated).

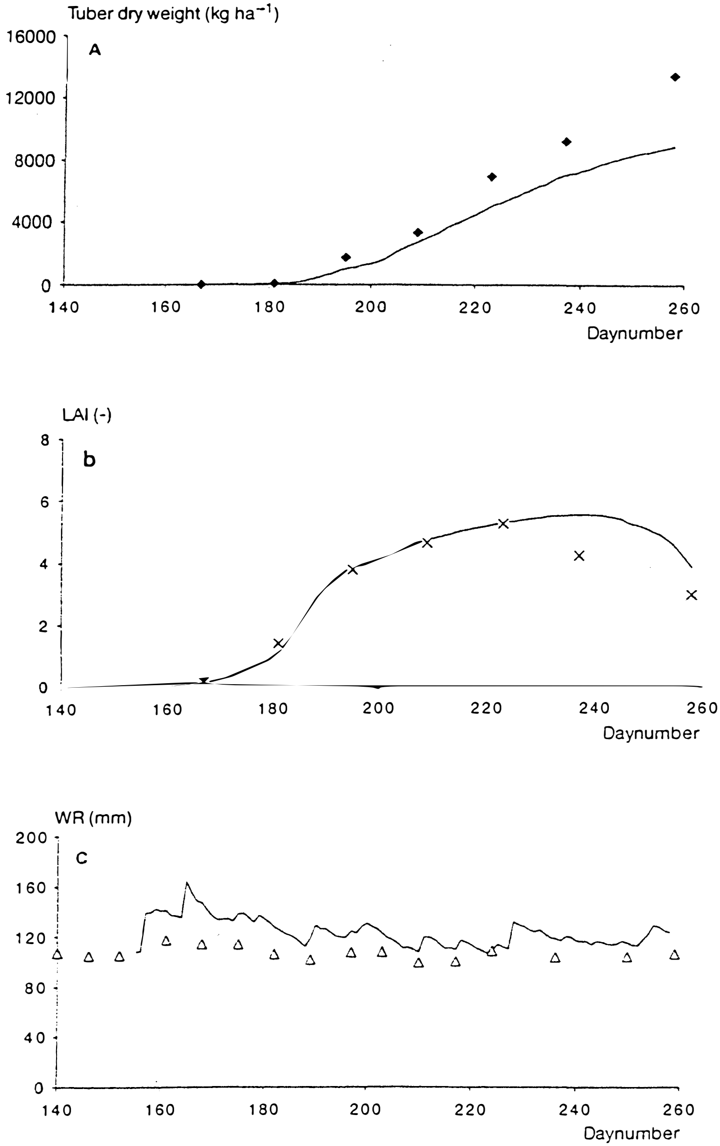

Figure 9. Validation data 87W: cv. Maris Piper grown near Invergowrie in 1987 under potential conditions (a) tuber dry weight, W_{tu}, (b) leaf area index, L_p (c) water storage in the root zone, S_R (symbols denote observations, lines are simulated).

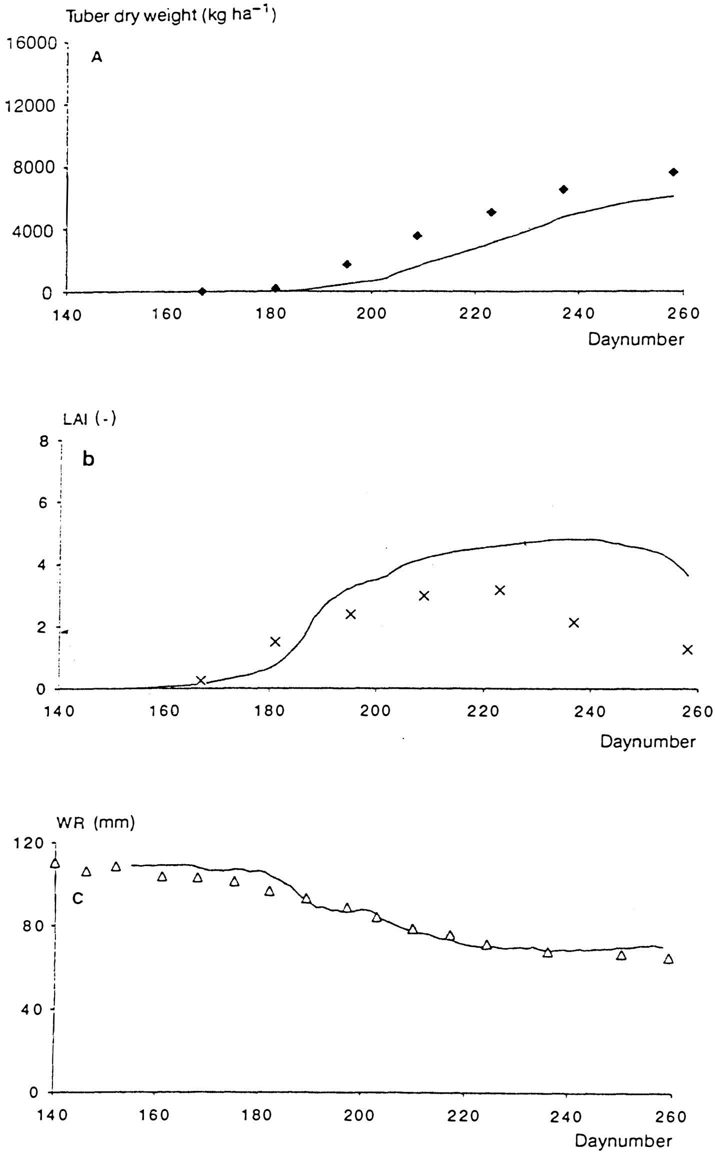

Figure 10. Validation data 87D: cv. Maris Piper grown near Invergowrie in 1987 under 'drought' conditions (a) tuber dry weight, W_{tu}, (b) leaf area index, L_p, (c) water storage in the root zone, S_R (symbols denote observations, lines are simulated).

5 Discussion and conclusion

Many other promising models could have been of interest for our purposes (e.g. crop growth models: Racsko & Semenov, 1989; Gutierrex et al., 1984; Ng & Loomis, 1984; soil water effects: Lhomme, 1991; van Genuchten & Nielsen, 1985; Ritchie, 1972). These models would have demanded much more work for adaptation, or included more detail than necessary for our goals. Especially for the soil water models any alternative would have demanded large efforts in parameterization requiring data which is not readily available.

The potato growth model presented in this paper simulated the behaviour of the provided data series reasonably well. Towards the end of the growing season the model behaved less realistically. One possible explanation is that the modelled phenology depends mainly on fixed parameters, to be expressed in physiological time. Secondly, discrepancies between model simulations and measurements tended in general to accumulate rather than cancel each other out. Thirdly, physiological effects of the conditioning during early growth or other adaptive phenomena were neglected in this simple potato growth model. For instance, the specific leaf area of the measured data fluctuated considerably, whereas in the model, it is assumed to be constant. Differences in leaf area indices which were greater than about four had no major impact on the model behaviour. The light interception ratio reaches 86% at a leaf area index of about four such that tuber growth (and growth of other crop organs) is in most cases fairly close to the observed increases. Nevertheless, the big differences among the other data sets, especially the large difference between the data from 1984 and 1985, could not be sufficiently reproduced by the Johnson model. However, some of these deviations were remarkably consistent. The deviations between simulated and observed water in the root zone for 1984 and 1985 was inversely proportional to deviations in simulated and measured leaf area index: i.e. higher simulated L_l values caused higher transpiration values resulting in lower S_R values and vice versa.

The model presented during the workshop did not allow for any vertical water movement calculations. Hence it failed mostly under the so called DRY conditions. During the workshop it became clear that a perched groundwater table was present in the simulated profiles. After the workshop a routine for capillary rise and percolation was added to the model. New runs were made and gave results as presented in Section 4.

For this case study the equations and parameter settings were kept identical for all situations (years, water regimes) to which the model was applied. Only the initial conditions and the input variables were left open for modification. Changing the equations or parameters according to potential or water limited conditions could have led to an improved fit between the simulated and provided data sets; but such an approach would have hampered the generality and applicability of the model severely.

During parameterization and calibration the interactive parameter setting facilities from 'MODELWORKS' proved to be very useful. Especially the open system architecture allowed for the combination of the automatic parameter identification algorithms with the interactive parameter settings and the interactive graphics facilities.

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