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O. Roth, J. Derron, A. Fischlin, T. Nemecek & M. Ulrich

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Swiss Federal Institute of Technology Zurich
Departement für Umweltnaturwissenschaften / Department of Environmental Sciences
Institut für Terrestrische Ökologie / Institute of Terrestrial Ecology

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Adressen der Autoren / Addresses of the authors:

Dr. O. Roth, Dr. A. Fischlin
Systemökologie ETH Zürich
Institut für Terrestrische Ökologie
Grabenstrasse 3
CH-8952 Schlieren/Zürich
SWITZERLAND

e-mail: sysecol@ito.umnw.ethz.ch

Dr. J. Derron, Dr. T. Nemecek
Station fédérale de recherches agronomiques Changins
CH-1260 Nyon
SWITZERLAND

Dr. M. Ulrich
Institut für Gewässerschutz und Wassertechnologie
ETH Zürich
EAWAG
CH-8600 Dübendorf
SWITZERLAND

IMPLEMENTATION AND PARAMETER ADAPTATION OF A POTATO CROP SIMULATION MODEL COMBINED WITH A SOIL WATER SUBSYSTEM

O. Roth, J. Derron*, A. Fischlin, T. Nemecek and M. Ulrich€

Systems Ecology, Swiss Federal Institute of Technology Zürich ETHZ, CH-8092 Zurich, Switzerland
* Station fédérale de recherches agronomiques Changins, CH-1260 Nyon, Switzerland.
€ EAWAG, CH-8600 Dubendorf, Switzerland

ABSTRACT

For the study of virus epidemics in Swiss seed potatoes a simple, yet useful crop growth model was needed. It had to provide information on tuber yield, leaf area, leaf age (for age resistance) and responses to water excess or deficit. The model of JOHNSON et al. (1986) satisfied most of these criteria. However this model does not compute the water stress factor from easily available weather data. Therefore we built a submodel for the soil water balance based on published models (VAN KEULEN & WOLF, 1986) and combined it with a new implementation of the JOHNSON model.

For this purpose the simulation environment "ModelWorks" with its open system architecture and numerous interactive features e.g. for parameter settings and graphing, proved to be most useful. The model's parameters were identified by graphical examination and automatic iterative minimization of the squared differences of the simulated and the given crop calibration data sets.

For most situations the simulated results showed satisfactory agreement with the measured data. The simulated qulitative and quantitative behavior fitted the observations similarly for the calibration and their equivalent validation data sets, both for potential and drought conditions. The exception is the leaf area index, which is usually due to the considerably simple model structure simulated with less accuracy than the tubers or other plant parts. The coupled soil water balance model contains more details and fits the validation data in most cases very well. For the purpose of our study we consider the overall model output to be satisfactory.

1. INTRODUCTION

During our research program on virus epidemics in seed potato productions, arose the need 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 the testing of competing hypotheses on the role of the aphid vectors. On the other hand, we also envisaged to eventually apply 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 encompassing the epidemics of the PVY virus disease. This submodel had to serve several purposes at once: First it had to produce output on tuber yield, leaf area, leaf age (e.g. "age resistance") and responses to water excess or deficit in order to couple it to other submodels. Second it had to be kept as simple as possible in order to keep computing time low and in order to minimize the introduction of unwanted errors and artifacts due to a model complexity, which often tends to grow to unmanagable proportions. Hence we favored 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 presented model is to a large extent just a new synthesis and implementation of various models or submodels published and parameterized elsewhere. The potato growth model was adopted from an original version by JOHNSON et al. (1986, 1987). Later we added a soil water submodel, which has in essence been based on the model 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 potato varieties common in Switzerland (ROTH et al., in prep).

The "Potato Modelling Workshop" provided a challenge to test and validate our version of the unmodified model as calibrated to Swiss conditions with different conditions from other countries, in particular without changing the equations nor the model structure. As it is often too difficult, if not impossible, to reconstruct a simulation model only from publications, an additional benefit we exptected was to gain an overview and a detailed enough insight on potato crop models as developed by other authors.

2. MODEL

2.1 General structure

The overall model "PotatoSoilWat" consists of the submodels "PotatoMod" and "SoilWat" plus the parallel data submodels (pseudo models) "Weather" and "PotModValid". Fig. 1 shows an overview of the model structure of the combined potato and soil water models and the coupled pseudo models for input of weather and validation data (full listings of all these submodels are available from the authors). The analog representation of the modular implementation structure is given in chapter 2.6.

“POTATOMOD”: To minimize developing efforts and, since it satisfies 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 an 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 normally available weather data (e.g. automatic weather recording network ANETZ in Switzerland). To minimize devlopment time and parameter estimation efforts, this submodel was mainly based on published and parameterized equations.

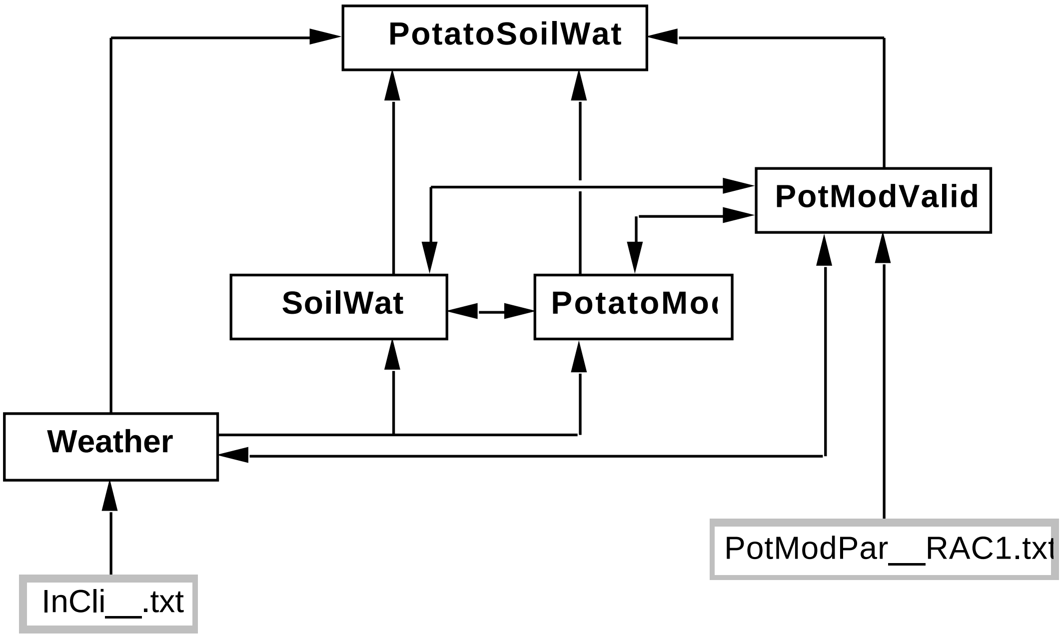

Fig. 1: Structure of the whole model consisting of submodels for potato growth and soil water balance, and the pseudo models for input of weather plus validation data. Arrows indicate flow of information, solid boxes indicate models and dashed boxframes represent datafiles for inputs.

2.2 Governing equations

Throughout the following description of the model equations, the type of a 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 *PhysAge* (physiological age) and *Assim,* (assimilate pool), *Leaf, Stem, Root,* and *Tuber* ($\sum = DM$; dry matter) for organ populations. The necessary inputs are described in chapter 2.3.

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

$$\Delta DM \;=\; iRad \cdot potNetGR \cdot \frac{dPhysAge}{dt \cdot averageDP} \cdot rowDist{\cdot}plantDist \cdot wStressF \qquad (1)$$

where: ΔDM: daily net dry matter increase [g pl^{-1} d^{-1}] {I}
$iRad$: intercepted radiation [J cm^{-1} d^{-1}] {I}
$potNetGR$: potential net growth rate [g MJ^{-1} d^{-1}] {A}
$wStressF$: water stress factor scalar computed in “SoilWat” [%/100] {I}
$PhysAge$: physiological age [pA] {S}
$averageDP$: average phys. age increase per day [pA] {P}
$rowDist$: distance between rows [m] {P}
$plantDist$: distance between plants within rows [m] {P}

The interception of radiation *iRad* [J cm^{-1} d^{-1}] {I} follows a De Beer's law function as given in eq. 2. *PAI* stands for plant area index [m^2 m^2] {A} and *RADG* is the total daily incoming global radiation [J cm^{-1} d^{-1}] {I}. To obtain correct units, the latter has to be adjusted by the factor 0.01.

$$iRad = (1 - e^{0.5 \cdot PAI}) \cdot RADG \cdot 0.01 \qquad (2)$$

The leaf area index LAI [m^2 m^{-2}] {A} and the plant area index PAI [m^2 m^{-2}] {A} are computed as follows:

$$LAI = leaf \cdot specLA \,/\, (rowDist{\cdot}plantDist) \qquad (3a)$$

$$PAI = LAI + (stem \cdot stemA) \cdot specLA \,/\, (rowDist{\cdot}plantDist) \qquad (3b)$$

where: leaf: dry matter of leaves [g/pl] {S}
stem: dry matter of stems [g/pl] {S}
stemA: stem to leaf conversion factor [-] {P}
specLA: specific leaf area [m^2/g] {P}
rowDist: distance between rows [m] {P}
plantDist: distance between plants within rows [m] {P}

The potential net growth rate *potNetGR* [g MJ^{-1} pA^{-1}] {A} is modelled after a relation published by NG & LOOMIS (1984). In this relation the different productivity of different physiological age classes $physAge_j$ of leaves $leaf_j$ is taken into account by a trapezoidal function defined by the maximal potential net growth rate *maxPotNetGR* [g MJ^{-1} d^{-1}] {P} and the parameters *lpAge1, lpAge2* , and *maxLeafPA* (all [pA] {P}):

$$\begin{aligned}
&physAge_j > lpAge1 &:\quad & potNetGR = maxPotNetGR \cdot \frac{maxLeafPA\text{-}physAge_j}{maxLeafPA\text{-}lpAge1} \cdot leaf_j \\
&physAge_j > lpAge2 &:\quad & potNetGR = maxPotNetGR \cdot leaf_j \\
&physAge_j > 0 &:\quad & potNetGR = maxPotNetGR \cdot (0.4 + \frac{0.6}{lpAge2} \cdot physAge_j) \cdot leaf_j
\end{aligned} \tag{4}$$

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 *dPA*$_i$ [pA/dt] {A} computed at 4 points of the daily temperature course T_i[°C] {A}. The units of the physiological age *PhysAge* {S} are denoted with pA.

$$T_1 = Tmin; \quad T_2 = 0.67 \cdot Tmin + 0.33 \cdot Tmax; \quad T_3 = 0.33 \cdot Tmin + 0.67 \cdot Tmax; \quad T_4 = Tmax \tag{5a}$$

$$\begin{aligned}
&T_i > maxGrT &:\quad & dPA_i = 0 \\
&T_i \geq optGrT &:\quad & dPA_i = 10 \cdot (1 - \frac{(T_i - optGrT)^2}{(maxGrT - optGrT)^2}) \\
&T_i \geq minGrT &:\quad & dPA_i = 10 \cdot (1 - \frac{(T_i - optGrT)^2}{(minGrT - optGrT)^2}) \\
&T_i < minGrT &:\quad & dPA_i = 0
\end{aligned} \tag{5b}$$

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

$$\frac{dPhysAge}{dt} = (5 \cdot dPA_1 + 8 \cdot dPA_2 + 8 \cdot dPA_3 + 3 \cdot dPA_4) / 24 \tag{5c}$$

The growth and partitioning before and just after emergence is modelled differently than during later crop growth. The proportion *propBefE* [%/100] {P} of the seed tuber *seedWeight* [g/pl] {P} is allocated with efficiency *effUtil* [%/100] {P} during initiation to the growing organs and gives the auxiliary variable seedD [g/pl] {A}. The partitioning is realized by multiplication of the parameters *propInLeaf, propInStem* and *propInRoot* (all [%/100] {P}).

$$seedD = effUtil \cdot seedWeight \cdot tuberDWtoFW^{-1} \cdot propBefE \tag{6}$$

$$\begin{aligned}
&Leaf(t=0) = propInLeaf \cdot seedD \\
&Stem(t=0) = propInStem \cdot seedD \\
&Root(t=0) = propInRoot \cdot seedD
\end{aligned} \tag{6a-c}$$

As long as the physiological age is smaller than *pASeedEnd* [pA] {P} the contribution *seedC* [g pl^{-1} d^{-1}] {R} is taken from the seed tuber *seedWeight* [g/pl] {P} and allocated to the different plant organs by applying the same partitioning parameters as before emergence.

$$seedC = effUtil \cdot seedWeight \cdot tuberDWtoFW^{-1} \cdot propAftE \cdot \frac{dPhysAge}{dt \cdot pASeedEnd} \tag{7}$$

$$dLeafC = propInLeaf \cdot seedC \qquad (7a\text{-}c)$$

$$dStemC = propInStem \cdot seedC$$

$$dRootC = propInRoot \cdot seedC$$

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 (Fig. 2):

$$dL = \mu L \cdot \frac{K \cdot wStressF}{K + Stem + Root + Tuber} \qquad (8a)$$

$$dS = \mu S \cdot \frac{Stem \cdot wStressF}{K + Stem + K \cdot Tuber} \qquad (8b)$$

$$dR = \mu R \cdot \frac{Root \cdot wStressF}{K + Root + K \cdot Tuber} \qquad (8c)$$

$$dT = \mu T \cdot \frac{Tuber}{K + Tuber} \qquad (8d)$$

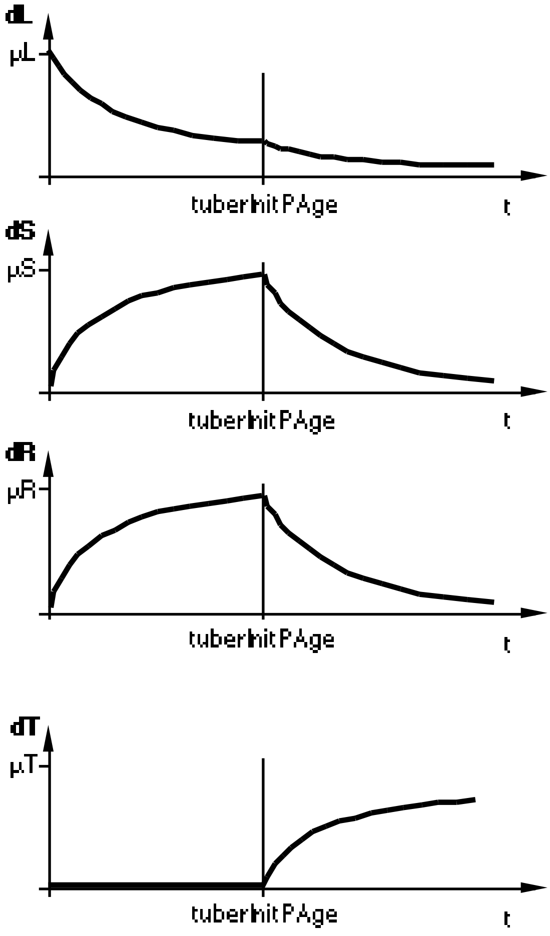

Fig. 2: Schematic representation of the Michaelis-Menten type partitioning scheme adopted by the potato submodel "PotatoMod".

$$\frac{dLeaf}{dt} = \frac{dL}{dL + dS + dR + dT} \cdot usage \cdot (Assim + \Delta DM \qquad (9a)$$

analogous to (9a) for stem, root and tuber (9b - 9d)

where:

$Leaf, Stem, Root, Tuber$:	dry matter of each population of organs [g/pl] {S}
K :	Michaelis Menten half saturation parameter [g/pl] {P}
dL, dS, dR, dT :	demand for growth of leaf, stem, root, tuber [-] {A}
$\mu L, \mu S, \mu R, \mu T$:	maximum growth rate for leaf, stem, root, tuber [-] {P}

usage : assimilation pool usage per day ([0,1]) [%/100] {P}
Assim : assimilate pool [g/pl] {S}
$\Delta \mathit{DM}$: daily net dry matter increase (eq. 1) [g pl^{-1} d^{-1}] {A}
$\mathit{wStressF}$: scalar computed in "SoilWat" ([0,1]) [%/100] {I}

$$\frac{dAssim}{dt} = \Delta DM - (Assim + \Delta DM) \cdot usage \cdot wStressF + leafRecycle \cdot dLeafSen \tag{10}$$

where: $\mathit{leafRecycle}$: proportion of recycled dry matter (parameter) [%/100] {P}
$\mathit{dLeafSen}$: dry matter of senescing leaves [g pl^{-1} d^{-1}] {R}

The equations 8-9 for partitioning were slightly modified compared to the original model: the demands of tubers to growth *dT* is no longer influenced by water stress.

To consider differing productivities of leaves of a different age (eq. 4) 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 *maxLeafPA* [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. For the water balance, vertical water movements and waterstress the model proposed in Van Keulen & Wolf (1986) and Penning De Vries & Van Laar (1982) was used. The 'Penman' equation for evapotranspiration and the water infiltration rate were derived from Doorenbos & Pruitt (1975) and Schroedter (1985). "SoilWat" has the two state variables *SSTO* (surface water storage) and *WR* (water in the root zone). The model presented at the workshop did not include capillary rise. As a consequence the model has difficulties to reproduce 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 also the vertical water flow.

The surface storage (10) and water (11) balance equations are:

$$SSTO(t) = SSTO(t\text{-}\Delta t) + EWSUP - SRO - RINF \tag{11}$$

where: EWSUP : effective water supply (precipitation and irrigation) [mm/d]{R}
SRO : surface runoff [mm/d] {R}
RINF: rate of water infiltration [mm/d] {R}

$$WR(t) = WR(t\text{-}\Delta t) + RINF - EA - TA - VWM \tag{12}$$

where: EA : rate of evaporation [mm/d] {R}
TA : rate of transpiration [mm/d] {R}
VWM : vertical water flow (percolation-capillary rise) [mm/d] {R}

The update of the balance equations follows precisely the descriptions given by DRIESSEN (1986). The infiltration *RINF* [mm/d] {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 (*SRO* [mm/d] {R}). The subroutine SubSoil from WOFOST (VAN KEULEN & WOLF, 1986) is used for the iterative computation of capillary rise or percolation, i.e. *VWM* [mm/d] {R}. The necessary function for hydraulic conductivity at matric suction is given in eq. 34.

The total water supply *WSUP* [mm/d] is the sum of precipitation *PREC* [mm/d] {I} and irrigation *IRIG* [mm/d] {I}. The amount of intercepted water supply *WINT* [mm/d] {A} is then computed as a polynomial function of the plant area index *PAI* [-] {I} (DOORENBOS & PRUITT; 1975), the result being forced to the range inbetween 0 and *WSUP* [mm/d] {A}. The total water supply minus the intercepted amount yields the effective water supply *EWSUP* [mm/d] {R}.

$$WSUP = PREC + IRIG \tag{13}$$

$$WINT = -0.42 + 0.245 \cdot WSUP + 0.2 \cdot PAI + 0.0271 \cdot WSUP \cdot PAI - 0.0111 \cdot WSUP^2 - 0.0109 \cdot PAI^2 \tag{14}$$

$$WINT = RLimit(\ WINT, 0.0, WSUP\ ) \tag{15}$$

$$EWSUP = WSUP - WINT \tag{16}$$

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 *Tmin, Tmax*; all [°C] {I}) and the atmospheric pressure *P* [mb] {A} (depending on the altitude *ALT* [m a.s.l.] {P}:

$$T = \frac{Tmin + Tmax}{2} \tag{17}$$

$$P = 1013.0 - 0.1055 \cdot ALT \tag{18}$$

$$\gamma = \frac{0.386 \cdot P}{595.0 - 0.51 \cdot T} \tag{19}$$

$$\Delta = 2 \cdot (0.00738 \cdot T + 0.8072)^7 - 0.00116 \tag{20}$$

The actual vapour pressure e_d [mb] {A} is computed from relative humidity *rH* [%] {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}):

$$e_{Tmin} = \mathbf{Exp}\left(1.81528 + 0.07159 \cdot Tmin - 0.000238 \cdot Tmin^2\right) \tag{21}$$

$$e_{Tmax} = \boldsymbol{Exp}\left(1.81528 + 0.07159 \cdot Tmax - 0.000238 \cdot Tmax^2 \right) \qquad (22)$$

$$e_S = \frac{e_{Tmin} + e_{Tmax}}{2.0} \qquad (23)$$

$$e_d = e_S \cdot \frac{rH}{100} \qquad (24)$$

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

$$R_B = 4.2 \cdot 1.17E\text{-}7 \cdot (T+273)^4 \cdot \left(0.38 - 0.035 \cdot \sqrt{e_d}\right) \cdot (1 - 0.9 \cdot FOV) \qquad (25)$$

where: T : mean daily temperature [°C] {A}
e_d : actual vapour pressure [mb] {A}
FOV : fraction overcast day [%/100] {A}

FOV is calculated after the procedure described by VAN KEULEN et al. (1982) and depends on the theoretical and measured incoming global radiation. The net incoming radiation R_N [J cm^{-2} d^{-1}] {A} is defined by the incident global radiation *RADG* [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}:

$$R_N = RADG \cdot (1-r_a) - R_B \qquad (26)$$

The influence of wind υ_C [m/s] {A} is taken into account after the following correction for anemometer heights:

$$\upsilon_C = VEN \cdot \boldsymbol{Exp}\left(0.2 \cdot \boldsymbol{Ln}(2 \cdot Z^{-1})\right) \qquad (27)$$

where: VEN : daily average wind speed [m/s] {I}
Z : height above ground of wind measurements [m] {P}

The evapotranspiration due to radiation *EVAPR* [mm d^{-1}] {A} is given by:

$$EVAPR = \frac{\Delta}{\Delta + \gamma} \cdot \frac{R_N}{245} \qquad (28)$$

The evapotranspiration due to drying power of the air *EVAPD* [mm d^{-1}] {A} is given by:

$$EVAPD = \left(1 - \frac{\Delta}{\Delta + \gamma}\right) \cdot 0.27 \cdot \left(1 + \upsilon_C \cdot \frac{86.4}{100}\right) \cdot (e_S - e_d) \qquad (29)$$

The potential evapotranspiration *ETP* [mm/d] {A} consists of the sum of the evapotranspiration due to radiation and drying power of the air multiplied by the correction factor *Cfao* for wind υ_C [m/s] {A} and incident radiation *RADG* [J cm^{-2} d^{-1}] {I}:

$$Cfao = 0.867 + 0.023 \cdot \frac{RADG}{245} - 0.036 \cdot \upsilon_C \cdot 1.2 \tag{30}$$

$$ETP = (EVAPR + EVAPD) \cdot Cfao \tag{31}$$

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 *WR* [mm] {S} and the effective rooting depth *ERD* [mm] {P}.

$$\Theta = \frac{WR}{ERD} \tag{32}$$

The matric suction ψ [cm] {A} is computed as function of soil moisture Θ [cm^3 cm^{-3}] {A}, total soil porosity Θ_0 [cm^3 cm^{-3}] {P} and the soil specific pore characteristics Γ [cm^{-2}] {P}:

$$\psi = \boldsymbol{Exp}\left(\sqrt{\frac{-\boldsymbol{Ln}(\Theta \cdot \Theta_0^{-1})}{\Gamma}}\right) \tag{33}$$

The hydraulic conductivity at matric suction $k\psi$ [cm/d] {A} is modelled by a split relation (DRIESSEN, 1986): above ψ_m [cm] {P} the second equation is used; it depends only on the texture specific parameter *a* [cm$^{2.4}$ d^{-1}] {P}. For lower values of ψ [cm] {A} the first equation is valid. It depends on k_0 [cm d^{-1}] {P}, the saturated hydraulic conductivity, and the texture specific parameter α [cm^{-1}] {P} .

$$\left\{\begin{array}{ll} \psi \geq \psi_m : & k\psi = k_0 \cdot \boldsymbol{Exp}(-\alpha \cdot \psi) \\ \psi > \psi_m : & k\psi = a \cdot \psi^{-1.4} \end{array}\right\} \tag{34}$$

The potential evapotranspiration *ETP* [mm/d] {A} is split into the maximal transpiration rate *TM* [mm/d] {A} and the maximal evaporation *EM* [mm/d] {A} by a De Beer´s law interception function of the plant area index *PAI* [-] {I}:

$$TM = ETP \cdot (1.0 - \boldsymbol{Exp}(-0.6 \cdot PAI)) \tag{35}$$

$$EM = ETP - TM \tag{36}$$

The actual transpiration *TA* [mm/d] {A} is defined after DRIESSEN (1986) as a trapezoidal function depending on the actual hydraulic matric head Θ {A} (Θ_{005} for nearly saturated soils; Θ_F field capacity; Θ_{CR} crop dependent critical soil moisture ($\Theta_W \leq \Theta_{CR} \leq \Theta_F$); Θ_W wilting point; all [cm^3 cm^{-3}] {A}) and the maximal transpiration *TM* [mm/d] {A}:

$$\begin{array}{lll} \Theta > \Theta_{005} & : & TA = 0.0 \\ \Theta \geq \Theta_F & : & TA = TM \cdot (\Theta_{005} - \Theta)/(\Theta_{005} - \Theta_F) \\ \Theta > \Theta_{CR} & : & TA = TM \end{array} \tag{37}$$

$\Theta \geq \Theta_W \quad : \quad TA = TM \cdot (\Theta - \Theta_W)/(\Theta_{CR} - \Theta_W)$

$\Theta < \Theta_W \quad : \quad TA = 0.0$

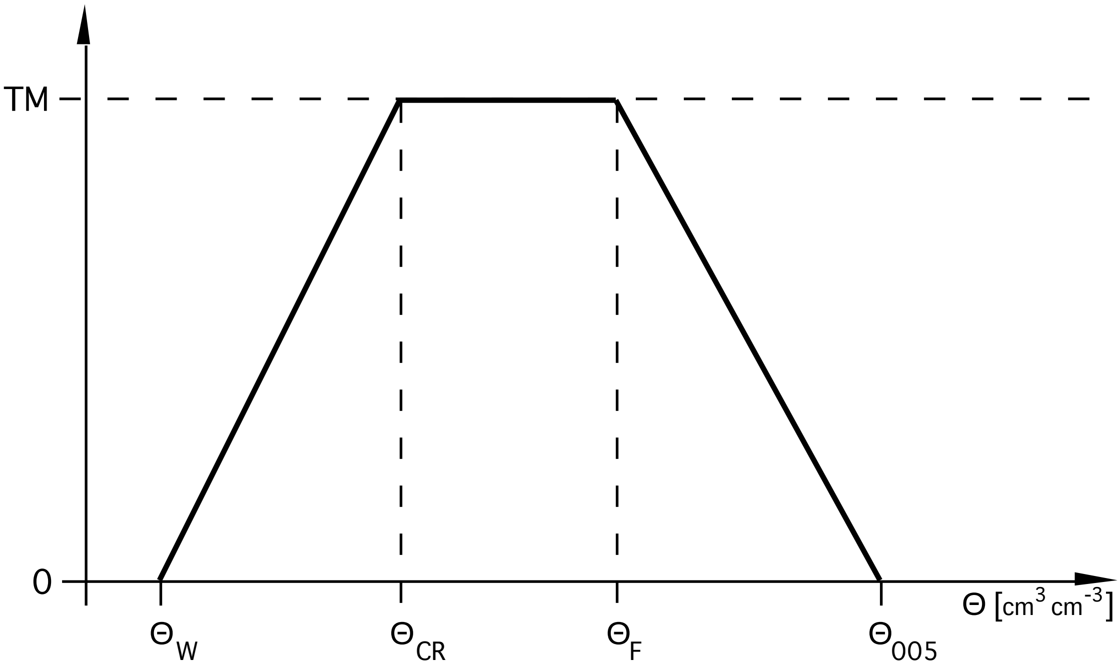

Fig 3: Graphical representation of actual transpiration *TM* dependent of the soil moistureΘ. The other symbols stand for~: Θ_W = wilting point, Θ_{CR} = crop specific critical soil moisture, Θ_F = field capacity, Θ_{005} = near saturated soil.

The actual evaporation *EA* [mm/d] {A} is given as a relation 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 hydraulic matric head Θ [cm^3 cm^{-3}] {A}, and the maximal evaporation *EM* [mm/d] {A}.

$$\Theta_A = 0.33 \cdot \Theta_W \tag{38}$$

$$EA = EM \cdot \frac{(\Theta - \Theta_A)}{(\Theta_0 - \Theta_A)} \tag{39}$$

The actual evapotranspiration*ETR* [mm/d] {A} is the sum of the actual transpiration *TA* [mm/d] {A} and actual evaporation *EA* [mm/d] {A}.

$$ETR = TA + EA \tag{40}$$

Finally the water stress factor *wStress* [%/100] {A} is defined as the fraction of satisfied transpiration:

$$wStressF = \frac{TA}{TM} \tag{41}$$

where: wStressF [0,1]
TA: actual transpiration [cm d^{-1}] {A}
TM: maximal transpiration [cm d^{-1}] {A}

2.3 Input parameters and functions

Parameter consisting of site specific, soil specific and crop specific parameters are stored in files, which also contain the eventually measured data series. The parameters are read and set by the pseudo model PotModValid (in case of incomplete information, default values are taken). This pseudo model allows also to display such data series during a simulation run (see also chapter 2.6).

All parameters are described and listed together with their values in table 2 of chapter 3.2.

The following table lists all input functions needed by the different submodels. Note that the pseudo model Weather does actually only read the data from the weather file and performs the necessary unit conversions. The other models compute their outputs dynamically.

Tab. 1 Input functions exchanged between submodels (or pseudo submodels) of the PotatoSoilWat-model

Variable	Unit	Explanation	Source Model	Used in Model
Tmin	[°C]	daily temperature minimum	Weather	SoilWat, Potato
Tmax	[°C]	daily temperature minimum	Weather	SoilWat, Potato
VEN	[m/s]	daily average wind speed	Weather	SoilWat
PREC	[mm/d]	total daily precipitation	Weather	SoilWat
IRIG	[mm/d]	total daily irrigation	Weather	SoilWat
RADG	[J cm^{-1} d^{-1}]	total daily global radiation	Weather	SoilWat, Potato
rH	[%]	average relative humidity	Weather	SoilWat
PAI	[m^2 m^2]	plant area index	Potato	SoilWat
wStress	[%/100]	water stress factor	SoilWat	Potato

2.4 Output, verifiable variables

PotatoMod: The state variables *Leaf*, *Stem*, *Root*, *Tuber*, are simulated on a per plant base. Therefore, for verifications, e. g. with the provided data from Invergowrie, these outputs must be transformed to other units, e.g. g/m^2. The computed LAI can be directly compared with the observed data. The variable *tuberFW* is computed to allow for further verifications with the fresh weight of the tuber yield.

SoilWat: The verification of both state variables *WR* (water in the root zone) and *SSTO* (surface storage) is possible. Of the numerous auxiliary variables only a few are directly comparable to directly measured data: Θ (matric head in the root zone), *SRO* (surface runoff).

2.5 Time step and time scale

The potato growth model is formulated in the form of differential equations, however implemented as its original only in a discrete-time form of difference equations with a fixed time step of 1 day (*dt*). The simulation time starts at 50% emergence and stops at the haulm killing date.

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

2.6 Program language, number of statements

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 to modify interactively parameters from run to run or even in the middle of a simulation run. Morevoer, complex experiments such as a model identification, which may consist of multitude of simulation runs, can be easily organized and installed in form of so-called "simulation experiments". The soil water balance model was built from the equations in the above cited publications and implemented in Modula-2. Finally it was 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 modern 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. Simulation models are defined through declarations of models, procedures (initialization of a simulation run, input, dynamic, output, termination of a simulation run) and variables (states, rates, parameters, monitoring). Finally MODELWORKS offers in its interactive simulation environment a handy user interface featuring efficient alterations of model and simulation run parameters as well as instantaneous graphical or tabular representation of model results. Modularity is enabled by the underlying programming language (Modula-2) where one defines the (sub)model's interface to other (sub)models in a definition module. The implementations are in separate files and allow the exchange of different model versions without recompilation. Finally 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. For a better understanding and a description of the numerous features of "ModelWorks" please order the detailed manual from the authors (FISCHLIN et al., 1990). ModelWorks is available for the Apple Macintosh and in a slightly limited version for the IBM PC and compatibles.

The modular structure of the model formulation of *"PotatoSoilWat"* using Modula-2 and MODELWORKS is shown in Fig. 4. The underlying module libraries are ModelWorks, auxiliary library modules such as ReadData, the DialogMachine, a basic, general Modula-2 library forming the interface to the operating system and the toolbox. 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*. On the latter depends the general purpose programming language *Modula-2*. The next higher layer consists of the *"DialogMachine"* a procedure library for interactive (dialog based) programs (FISCHLIN, 1986). The above described simulation environment "ModelWorks" uses the "DialogMachine". On top resides the model definition program written by the modeller. All this is embedded in the MODELWORKS environment supporting interactive modeling, simulation, plus interactive post-simulation analysis (FISCHLIN, 1991).

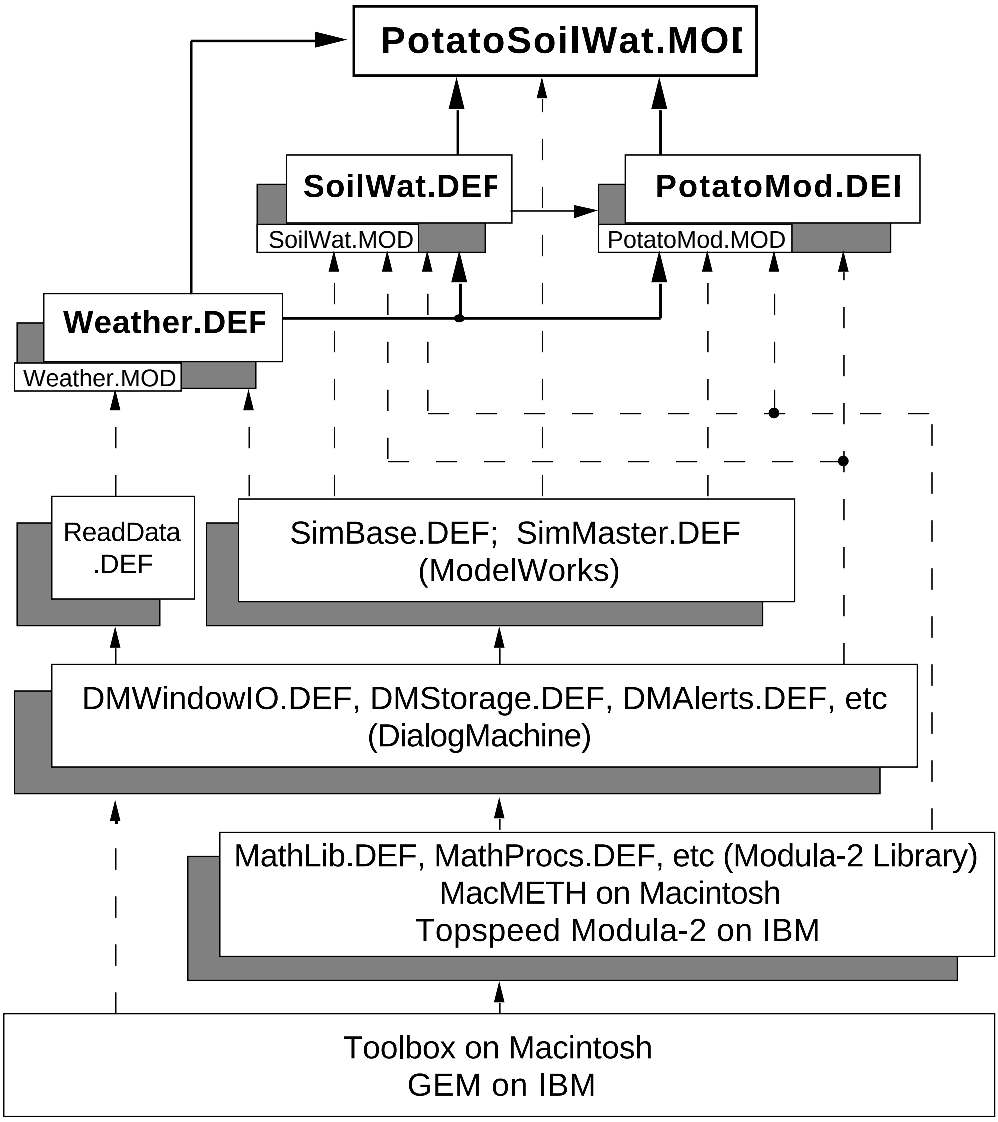

Fig. 4. Structure of the modules of the PotoatSoilWat model. Arrows indicate imports from other modules (solid lines were used inbetween (sub)models, broken lines stand for imports from library modules), boxes stand for single modules or a module library, underlying grey boxes represent the according implementation

modules (file extension .MOD). For reasons of simple graphical representation the pseudo model "PotModValid" (see Fig. 1) is omitted here.

Approximately 250 lines of the source code of the potato submodel (PotatoMod) contain actually executable instructions, whereby only approximately half of the lines define the model equations. The remaining code serves the instantiatiation of models and model objects such as state variables, parameters etc. About the same proportions hold for the soil water submodel (SoilWat), but only with a total of ca. 200 lines of executable source code.

3. PARAMETERIZATION and CALIBRATION

3.1 Parameterization and calibration in general

By the process of parameterization we understand the finding of values for parameters of general validity whereas calibration covers the action of fine tuning of only some selected parameters to a more restricted area. This means that only parameters typical for a particular pototo variety and planting condition have to be calibrated. Since the presented models are nonlinear models parameterization proves to be rather difficult, mainly because of the numerous local minima in the parameter space. Especially the potato growth model is 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 and 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. in prep.). On the other hand did we change only very few parameters of the soil water submodel. The reason was, that until recently we had only limited access to suitable soil data and considered the equations sufficiently well parameterized by the authors of the original models (BERKHOUT & VAN KEULEN, 1986; DRIESSEN, 1986; SCHROEDTER, 1985; STROOSNIJDER, 1982).

Tab. 2. Parameters of "PotatoMod" and "SoilWat" with information on parameterization.

Process	Eq. no.	Parameter (Units)	Description	Orig. value	Method of estimation	Data source	Method of re-estimation	New value
POTATOMOD								
partitioning		K (g/pl)	Michaelis Menten half saturation	50.0	non-linear iteration	Johnson 86	optimisation	56.0
partitioning		μL (g pl^{-1} d^{-1})	max. growth rate of leaves	1.0	non-linear iteration	Johnson 86	optimisation	1.25
partitioning		μS (g pl^{-1} d^{-1})	max. growth rate of stems	6.0	non-linear iteration	Johnson 86	optimisation	30.0
partitioning		μR (g pl^{-1} d^{-1})	max. growth rate of roots	1.0	non-linear iteration	Johnson 86	optimisation	6.1
partitioning		μT (g pl^{-1} d^{-1})	max. growth rate of tubers	6.0	non-linear iteration	Johnson 86	optimisation	12.0
partitioning		tuberInitPA (pA)	start of tuber growth	200.0-225.0	field observations	Johnson 86	optimisation	100.0
partitioning		usage (%/100)	maximal usage of ass. pool	0.75	guessing	Johnson 86	original	0.75
partitioning		tuberInit (g/pl)	start weight of new tubers	0.5	field observations	Johnson 86	original	0.5
senescence		maxLeafPA (pA)	maximum leaf age	400.0	field observations	Johnson 86	original	600.0

Tab. 2. Parameters of "PotatoMod" and "SoilWat" with information on parameterization (continued)

senescence	maxPlantPA (pA)	maximum plant age	675.0-810	field observations	Johnson 86	original	1000.0
net assimilation	maxPotNetGR (g MJ^{-1} d^{-1})	maximum potential net growth rate	1.56	literature	Johnson 86, 87 Ng & Loomis 84	optimisation	1.83
net assimilation	lpAge1 (pA)	maximum leaf age of maxPotNetGR	160.0	literature	Johnson 86, 87 Ng & Loomis 84	optimisation	386.0
net assimilation	lpAge2 (pA)	minimum leaf age of maxPotNetGR	80.0	literature	Johnson 86, 87 Ng & Loomis 84	original	75.0
net assimilation	leafRecycle (%/100)	proportion of senescend leaves recycled	0.5	guessed	Johnson 86	original	0.5
net assimilation	averagePA (pA/d)	average phys. age increase per day	8.0	meteo data	Johnson 86	calibration data	7.0
net assimilation	specLA (m^2/g)	specific leaf area	0.023	field data	Johnson 86	calibration data	0.028
net assimilation	stemA (g/g)	stem to leaf area equivalent	0.0869	field data	Johnson 86	original	0.0869
emergence	pASeedCont (pA)	duration of assimilate contrib. from seed tuber	200.0	field data	Johnson 86	Bintje, unpubl.	120.0
emergence	propBefE (%/100)	proportion allocated before emergence	0.2	field data	Johnson 86	original	0.2
emergence	propAftE (%/100)	proportion allocated after emergence	0.6	field data & literature	Johnson 86	original	0.6
emergence	propInLeaf (%/100)	proportion allocated to leaves	0.2	field data & literature	Johnson 86	original	0.2

Tab. 2. Parameters of "PotatoMod" and "SoilWat" with information on parameterization (continued)

emergence	propInStem (%/100)	proportion allocated to stems	0.4	field data	Johnson 86	original	0.4
emergence	propInRoot (%/100)	proportion allocated to roots	0.4	field data	Johnson 86	original	0.4
emergence	effUtil (%/100)	eff. used proportion of ass. during emergence	0.4	field data	Johnson 86	original	0.4
ageing	minGrT (pA)	minimum growth temperature	7.0	literature	Johnson 86 Sands et al 79	Bintje, unpubl.	4.0
ageing	maxGrT (pA)	maximum growth temperature	30.0	literature	Johnson 86 Sands et al 79	Bintje, unpubl.	30.0
ageing	optGrT (pA)	optimal growth temperature	21.0	literature	Johnson 86 Sands et al 79	Bintje, unpubl.	20.0
planting	rowDist (m)	planting distance between rows	1.0	planting data	Johnson 86	husbandry data	0.75
planting	plantDist (m)	planting distance between plants in rows	0.3	planting data	Johnson 86	husbandry data	0.33
planting	seedWeight (g/pl)	seed weight per plant	0.60-0.80	planting data	Johnson 86	husbandry data	45.0
validation	tuberDWtoFW (g/g)	tuber dry to fresh weight conversion	5.0	field data	Johnson 86	husbandry data	5.0
SOILWAT							
soil water balance	soilNr (1..9)	number of soil				soil data	1

Tab. 2. Parameters of "PotatoMod" and "SoilWat" with information on parameterization (continued)

surface water storage	SROU (-)	surface roughness	soil data	20.0
capillarity	ZT (cm)	ground water table height	graphical estimation	100.0
soil water balance	RD (cm)	rooting depth	V'Keulen & Wolf 86	45.0
soil water balance	PRS (%)	proportion of stones	soil data	10.0
evapo-transpiration	ALB (-)	albedo	Schroedter 85	0.2
energy balance	LAT (°N)	latitude	husbandry data	56.0
energy balance	ALT (m)	altitude above sea level	husbandry data	24.0
surface water storage	SL (%)	slope of the field	husbandry data	0.0
surface water storage	DELT (°)	clod/furrow angle	husbandry data	0.524

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 and 1986 under "wet" (optimal) and "dry" (sheltered) conditions. We started with the parameters listed in the original publication (JOHNSON et al., 1986) for the varieties Russet Burbank and Norland and those we found for the variety Bintje under Swiss conditions (ROTH et al., in prep). 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. (1989).

The performance criteria we used was the sum of squares of deviations of the sum *Stem+Tuber* dry weights to measured data plus the 10 fold sum of squares from the differences between simulated and measured *LAI*. Three single simulation runs for all the given calibration data sets (i.e. 1984, 1986 wet, 1986 dry) allowed one performance function evaluation. All the parameters of the Michaelis-Menten type partitioning (*K*, *μLeaf*, etc) were identified by optimization. This approach appears reasonable since JOHNSON et al. (1986) have used a similar procedure to find values for these parameters and they have also used other values for each variety (Russet Burbank and Norland).

Obviously potato varieties differ especially in their partitioning scheme. Hence we adopted the partitioning parameters during emergence, such as *propInLeaf*, rather from the variety Russet Burbank than taking the values found for the varietiy Bintje. The longevity of leaves (*maxLeafPA*) of Maris Piper is variable but clearly longer than the 400 physiological age units given for Russet Burbank.

Growth processes in the JOHNSON model depend very sensitively on the value of the parameter *maxPotNetGR* which stands for real potential net growth. We concluded that the real potential net growth of european varieties must be calibrated for each othe variety and included the parameters *maxPotNetGR* and *lpAge1* in the set of parameters to be identified by optimization. After 147 iterations of the algorithm "Amoeba" we obtained the parameter values given in Tab. 2.

The specific leaf area *specLA* was directly determined from the available data (0.035). We took the average of all ratios of measured leaf dry matter versus leaf area except the last points of each calibration data set; the latter were discarded because of the obvious effects of senescence.

The water balance model was not further parameterized. From the soil data descriptions and water data we determined the soil type to be fine sandy loam. The parameters depending on the type of soil were all taken from the tables given by DRIESSEN (1986). One parameter was not easily available: *ZT* the height of the groundwater table. The examination of the different layers of the provided soil water data and pore space characteristics suggests the presence of a perched water table. These data and the graphical evaluation, especially the "dry" conditions, led us to set this value to 100 cm.

4. RESULTS

The outcome of the calibrated simulation model (i.e. the tuber dry matter *Tuber*, leaf area index *LAI* and the water in the root zone *WR*) was compared to the calibration data (Fig. 5-7). The simulated trajectories resemble qualitatively the calibration data provided by the workshop organizers. Tuber dry weight and the leaf area index are once over-estimated, once under-estimated and once very closely estimated. The simulated water content in the root zone is in two cases slightly too high, and in one case rather low when compared with the observations.

The figures 8 till 10 show the simulation results of the variables *Tuber*, *LAI* and *WR* plotted together with the corresponding validation data. Note that the latter were neither used to parameterize nor to calibrate the model. The simulated tuber dry mass follows the validation data considerably well, but the simulated leaf area index agrees less well with the provided measurements. For validation purposes the soil layers 1 to 3 were averaged and compared to the single layer of "SoilWat". The water in the root zone is clearly overestimated for the year 1985 but is not too far from the measurements of both treatements (wet and dry) in 1987. Towards the end of the season, many simulated trajectories tend to disagree more with the measurements than this is the case at the begin of the summer, e.g. tuber dry matter becomes flatter towards the end of the growing season, which is much less the case in the observed tuber dry matter (Fig. 5-10).

The measurements can be easily grouped into the following three types: a) 1984, 1985, b) 1986 wet, 1987 wet, and c) 1986 dry, 1987 dry. The first group a) shows very high leaf area indices values (≈6) which were never reached in any other situation. This effect becomes also visible in the leaf to stem ratio, which was in 1984 and 1985 ca. 1:2, compared with the smaller ratio of ca. 1:1 in the year 1986.

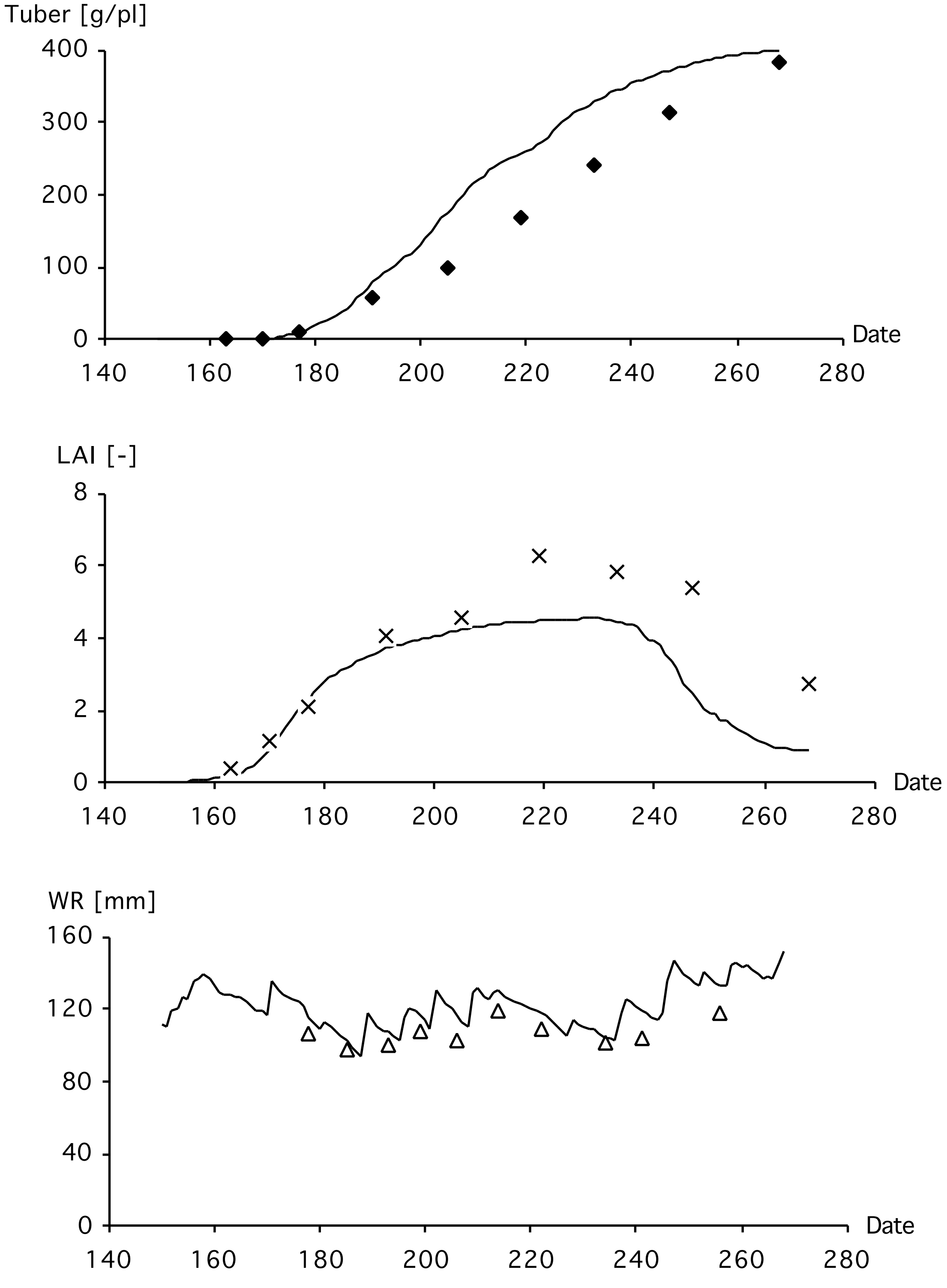

Fig. 5. Calibration data 84: variety Maris Piper grown near Invergowrie in 1984 under potential conditions (symbols denote observations, lines are simulated).

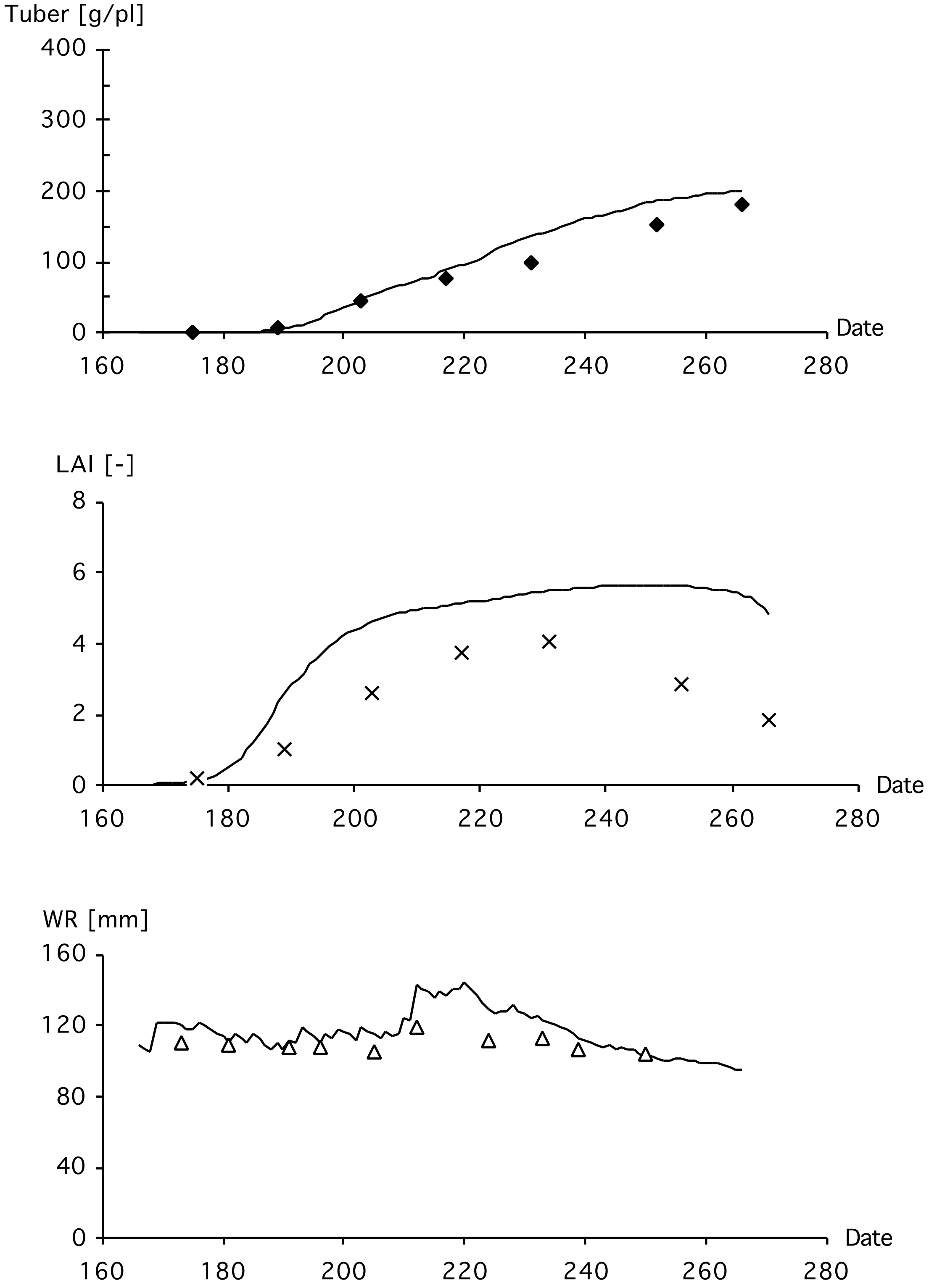

Fig. 6. Calibration data 86W: variety Maris Piper grown near Invergowrie in 1986 under potential conditions (symbols denote observations, lines are simulated).

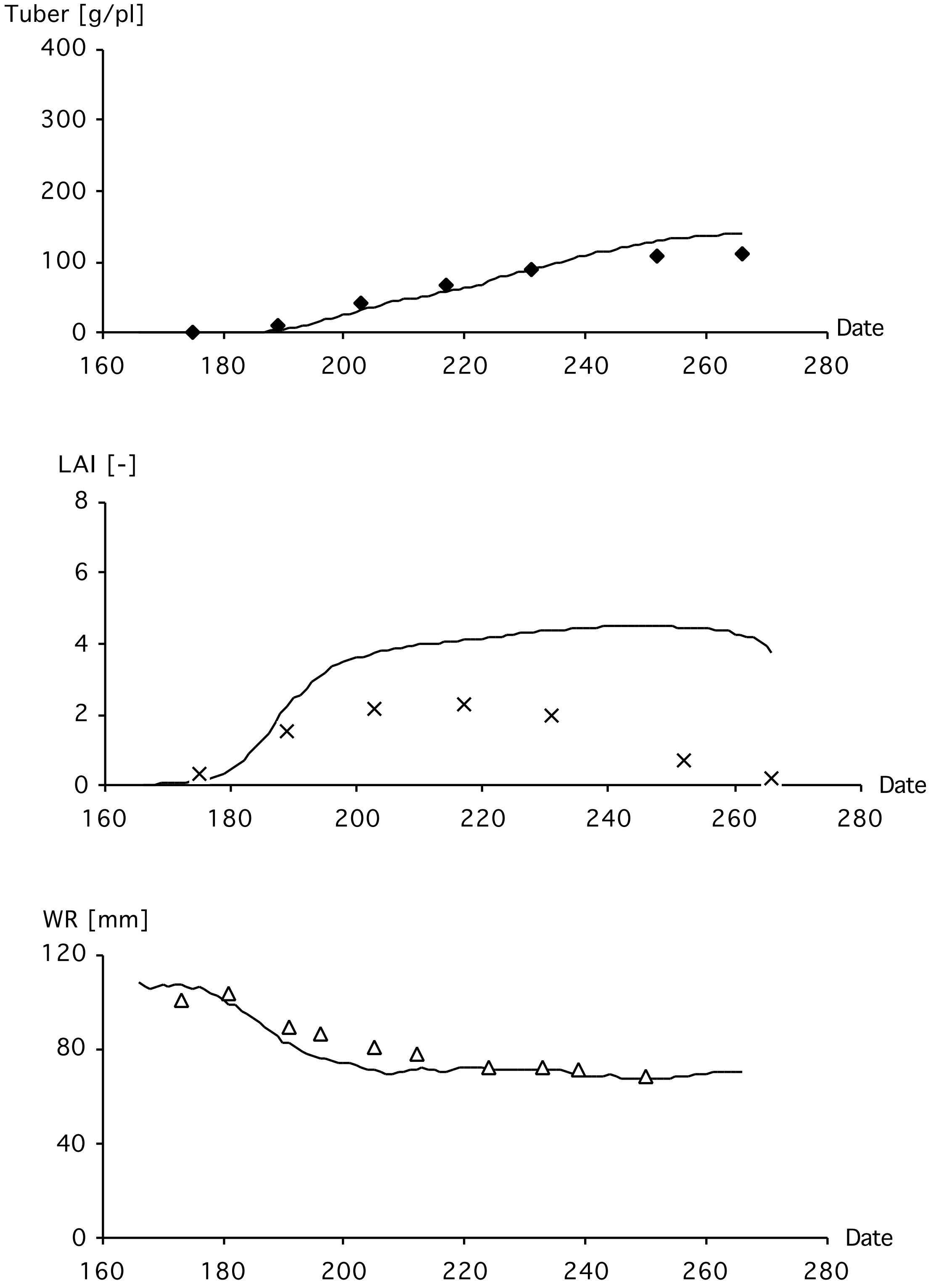

Fig. 7. Calibration data 86D: variety Maris Piper grown near Invergowrie in 1986 under "drought" conditions (symbols denote observations, lines are simulated).

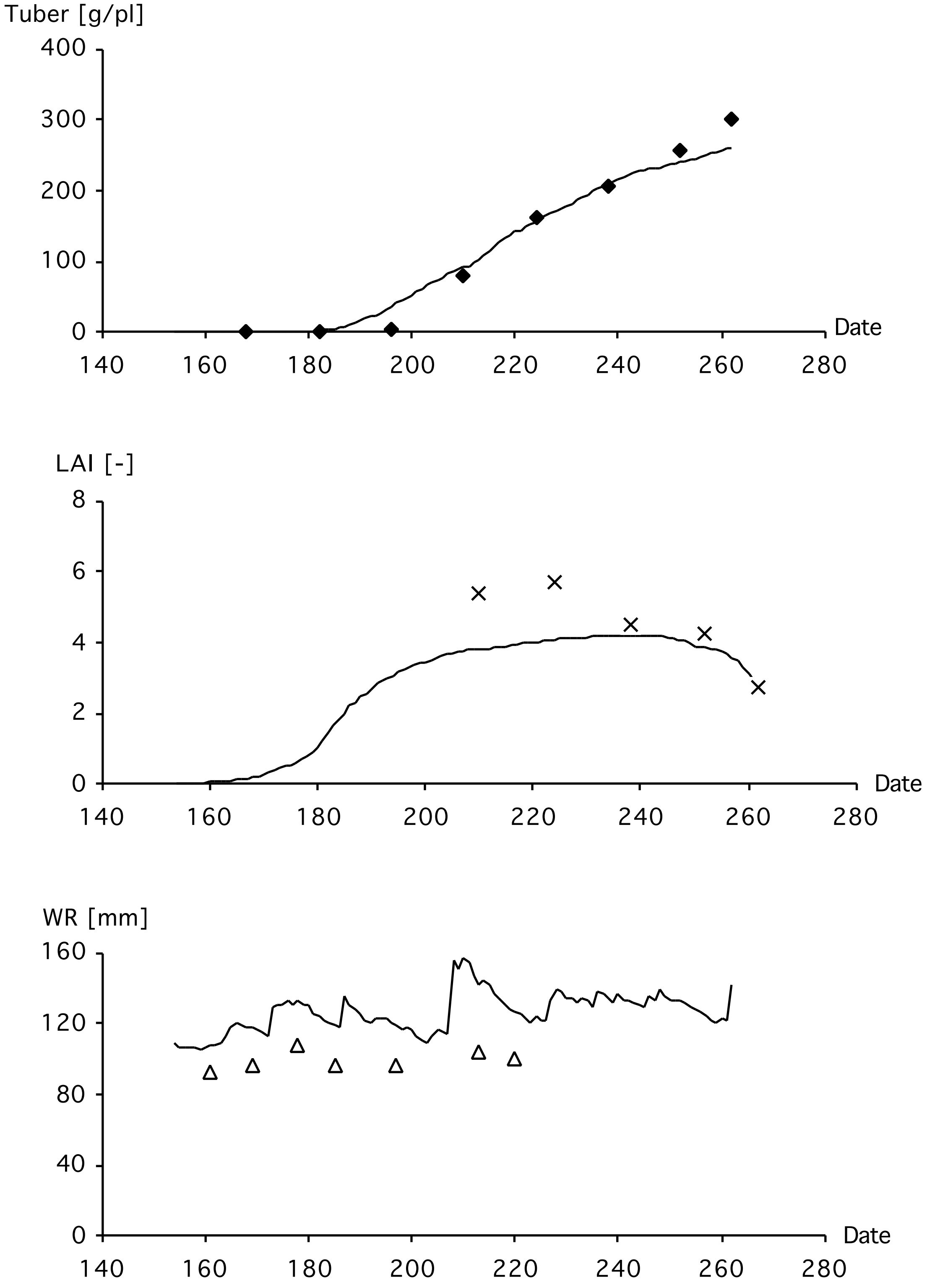

Fig. 8 Validation data 85: variety Maris Piper grown near Invergowrie in 1985 under potential conditions (symbols denote observations, lines are simulated).

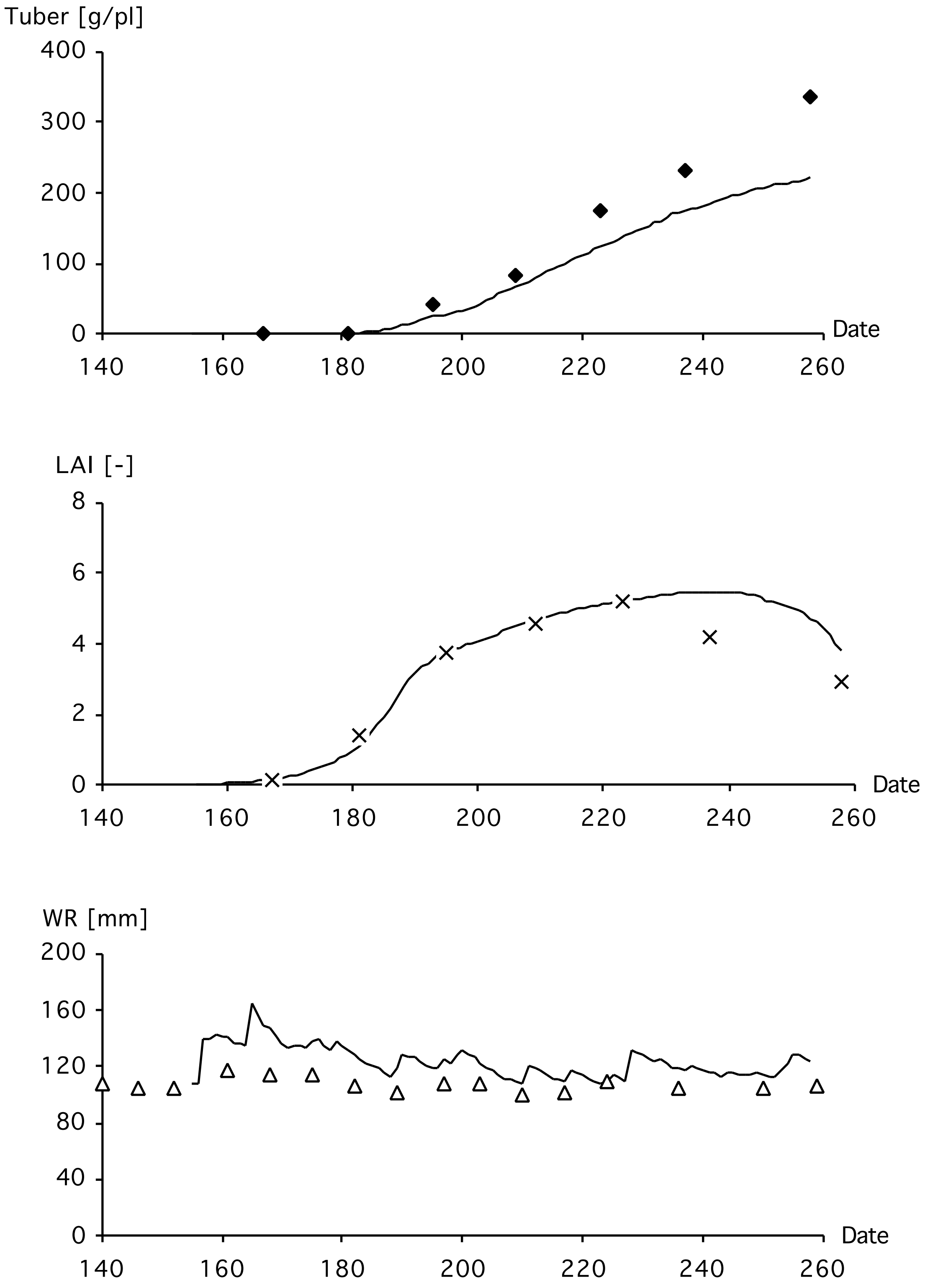

Fig. 9. Validation data 87W: variety Maris Piper grown near Invergowrie in 1987 under potential conditions (symbols denote observations, lines are simulated).

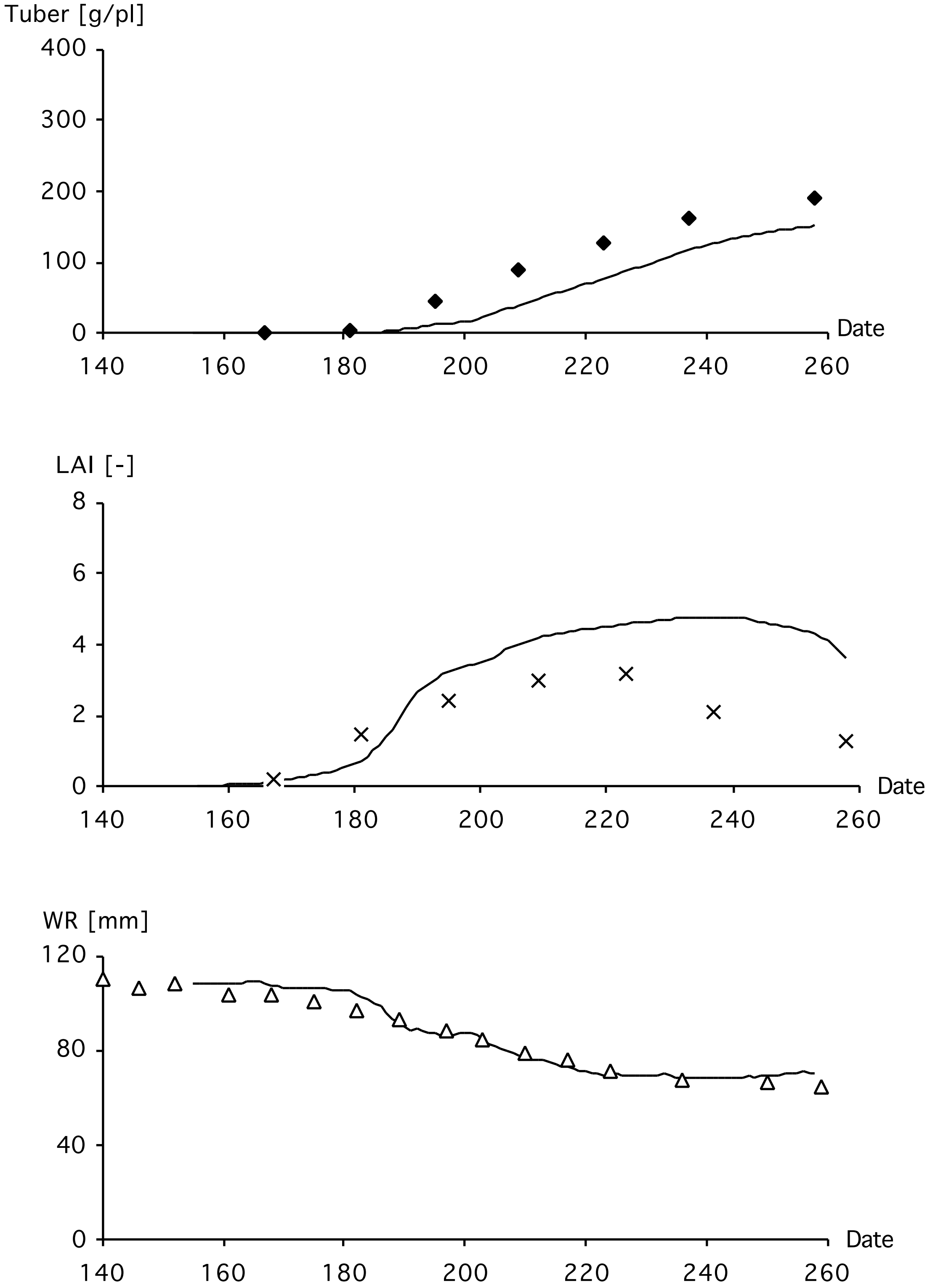

Fig. 10. Validation data 87D: variety Maris Piper grown near Invergowrie in 1984 under "drought" conditions (symbols denote observations, lines are simulated).

5. DISCUSSION and CONCLUSIONS

Many other promising models beside the others presented at the workshop could have been of interest for our purposes (e.g. crop growth models: RACSKO & SEMENOV, 1991; GUTIERREZ et al., 1984; NG & LOOMIS, 1984; soil water effects: LHOMME, 1991; VAN GENUCHTEN & NIELSEN, 1985; RITCHIE, 1972). But these models would have demanded much more work for adaptation, or they include more details than necessary for our goals. Especially for the soil water models any alternative would have demanded big efforts for parameterization with not easily obtainable data. The workshop confirmed once more the important amount of efforts which are necessary for model construction, adaptations, parameterization, calibration, validation etc. The approach of taking as much as possible from a already well adapted and parameterized models seems therfore necessary to hold tight time scales.

Despite the coarse model structure of the studied potato growth model, the simulated behavior resembles the provided data series considerably well. Towards the end of the growing season the model behaves less realistically. One possible explanation is that the modelled phenology depends mainly on fixed parameters, to be expressed in physiological time. Secondly, once ocurred, discrepancies between model and measurements, tend in general to accumulate than to cancel each other out. Thirdly physiological effects of the conditioning during early growth or other adaptive phenomena are neglected in this simple potato growth model. The fact that the simulated results by PotatoSoilWat fit the measured data badly towards the end of the growing season, is in seed potato production of minor importance, since seed potatoes are normally harvested much earlier than these discrepancies could become dominant.

For instance, the specific leaf area of the measured data fluctuates considerably, wheras in the model, it is assumed to be constant. On the other hand differences of the leaf area indices which are greater than about 4 have no major impact on the model behavior. The light interception ratio reaches 86 % at a leaf area index of about four. This is the reason why tuber growth (and growth of other crop organs) is in most cases fairly close to the observed tuber dry matter increase. Nevertheless, the big differencies 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 are remarkably consistent: For instance are the deviations between simulated and observed water in the root zone consistent with a too high or too low leaf area index; the latter should cause a too large or too little soil water loss via transpiration.

The model which was presented during the workshop did not contain any vertical water movements. Hence it failed mostly under the so called "dry" conditions. In this context it seems also remarkable that the obtained yield of potatoes grown under shelters was higher than 60% (dry weight) of the tubers grown under potential conditions. We concluded that something like a perched water table must have been present. Our decision to add a routine for capillary rise and percolation seems to be correct, since the simulations can now no longer be considered worse for "dry" conditions than for "wet".

Since the soil water model was assembled from already existing models, some physical aspects tend to be modelled in more details than this is the case for the other submodel. Yet, thanks to this fact, does the soil water balance model produce in general the necessary outputs with a high accuracy.

We believe that the equations and parameter settings must be kept identical for all situations (years, water regimes) to which the model ought to be applied; only the initial conditions and the input variables (weather and soil) should be left open for modification. The changing of equations or parameters according to potential or drought conditions could of course lead to an improved fit between simulated and provided data sets; but such an approach would hamper severely the generality and applicability of the model to exactly such rather unusual conditions.

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

Last but not least do we wish to congratulate the organizers for the success of this «First International Potato Modelling Workshop». We have appreciated the organizer's effort to bring a stimulating working environment to fruition; before, during and after the workshop, it was fun to participate. Thanks!

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SYSTEMS ECOLOGY ETHZ, INSTITUTE OF TERRESTRIAL ECOLOGY
GRABENSTRASSE 3, CH-8952 SCHLIEREN/ZURICH, SWITZERLAND