Dual permeability soil water dynamics and water uptake by roots in irrigated potato fields

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Abstract A consistent picture of water movement and uptake by roots in a drip-irrigated potato field was obtained by combination of field experiments in the Bohemo-Moravian highland, the outputs of numerical simulation and the summary results of measurements and modelling made within the EU project FertOrgaNic (www.fertorganic.org).

The Valečov site (49°38'40" N, 14°30'25" E, 461 m a.s.l.) is a deep loamy Stagnosol developed on weathered paragneiss. Detailed measurements of soil moisture suction and weather conditions made it possible to arrive at improved estimates of some soil and root zone parameters for the dual permeability model (S1D_DUAL), valid at least for the first half of a particular growing season. A reasonably good agreement between the measured and the estimated soil hydraulic properties was obtained. The root zone depths obtained by measurements and by inverse simulation with S1D_DUAL are compared with an exponential boundary curve derived from FertOrgaNic field measurements on six field sites across Europe (including Valečov). The difficulty of optimising parameters of a simulation model when the measurements taken as criteria are diverging or conflicting is highlighted. It is suggested that an improved model should provide several parallel outputs to mimick several parallel measurements.

The results of Valečov measurements and S1D_DUAL simulations in terms of soil water pressure head fields are comparable with those achieved by simulations with the Daisy model. During dry spells, the measured suction head tend to be higher than the simulated ones. Various hypothetical causes of this phenomenon are discussed. The readings of tensiometers during and after rain or irrigation oscillated between the simulated pressure heads in the matrix and those in the preferential flow domain. Lateral flow from the macropores to the matrix domain quickly wetted the matrix after such percolation events. Irrigation facilitated deep seepage after rain events.

The transversal width of the root zone in a potato row is also briefly discussed. The fact that the root zone dimensions vary in time and from case to case leads us to a conclusion that several parallel soil moisture sensors are needed for adequate irrigation control. The sensors cannot adequately detect the time when the irrigation should be stopped.

Key words: *Modelling, S1D_DUAL, Daisy, FertOrgaNic DSS, sensors, drip irrigation*

Introduction

The root zone of soils is an arena of many important processes which affect in a substantial way the efficiency of agriculture and the quality of the environment, including all possible feedbacks and self-controlling mechanisms. It is therefore appropriate that these processes are studied and modelled in detail. Mutual interactions between plant roots on the one hand and soil water movement and retention on the other hand have been receiving attention of practitioners and scientists since very long ago. Numerous studies on retardation of plant growth due to insufficient water supply to their roots led to the concepts of wilting point (e.g., Briggs and Shantz, 1912), the critical point and its dependence on evaporation demand (e.g., Denmead and Shaw, 1962) and their generalisation in the form of water stress functions, such as that by Feddes et al. (1978). The threshold soil moisture below which potato starts to experience water stress has been studied many times. The results depend on circumstances such as soil, climate, potato variety, rooting depth, irrigation method and the depth at which the soil moisture is measured. The FAO 56 methodology (Allen et al., 1998) suggests that the allowable depletion of available water capacity of the root zone should not decrease below 35 %. Wright and Stark (1990) suggest an optimum range of soil water pressure heads for potato between -200 and -600 cm. A newer overview is provided, e.g., by Pereira and Shock (2006), who suggest, among other figures, a threshold of -300 cm for drip irrigation systems on silt loam soils in Oregon. The success of application of all these concepts heavily depends on the root zone dimensions (in particular, on its depth) and its development over the growing season. Moreover, recent studies (e.g., Parker et al., 1989) explicitly recognize that plants can indirectly abstract water even from the soil layers in which there are virtually no roots, due to capillary rise of water from these layers towards the root zone.

On the wet side of the soil moisture range, the presence of plant roots and their rhizosphere with their soil-structure forming power, as well as the temporary loosening of ploughed soils due to tillage, enhances the capacity of these soils to absorb water from rain, snowmelt or irrigation (e.g., Halabuk, 2006; Farkas et al., 2006). Water in many soils, if its pressure is close to atmospheric, seeps downwards via macropores of biological or mechanical origin and/or via preferential paths other than macropores, such as the more permeable and less dense patches of soil or the water fingers produced by hydraulic instability (e.g., Beven and Germann, 1982; for the state of the art, see Roulier and Schulin, 2006). Whatever are the origin and mechanisms of preferential flow, it always results in a faster penetration of water and solutes into deeper soil layers and towards deeper-lying roots, bypassing, to some extent, the roots in shallow layers. Sensors of soil moisture content or suction and soil solution samplers (such as suction cups or lysimeters) then receive more water from the surface and receive it quicker than if there were no preferential flow. Different sensors are affected differently, because of their different connectivity with the preferential flow network (Doležal, 2006a, 2006b). This observation also pertains to the sensors used for irrigation control. Their placement and the way in which their signal is interpreted must take the existence of preferential flow into account. Many aspects of preferential flow can be satisfactorily reproduced by dual porosity and dual permeability models, such as S1D_DUAL (Vogel et al., 2000; HYDRUS 2D/3D (Šimůnek et al., 1999) or MACRO (Jarvis, 1994). For an example, see Dušek et al. (2006).

The Fifth EU Framework Programme Project FertOrgaNic "Improved organic fertiliser management for high nitrogen and water use efficiency and reduced pollution in crop systems" (www.fertorganic.org), executed in 2003-2006, resulted, among other outputs, in a Decision Support System for controlling irrigation and nitrogen fertilisation of potato (Battilani, 2006a, 2006b), in a guidebook for using soil moisture sensors for the same purpose (Plauborg et al., 2006b), in a set of improved parameterisations of the Daisy model (Abrahamsen et al., 2006) and in an overall comparison of the improved potato growing technology (using drip irrigation, organic manures or amendments and the supplemental mineral nitrogen supply via drip irrigation, called fertigation) with conventional technologies (Plauborg et al., 2006a).

The objective of this paper is to build on these results and to compare some of them with the results of a dual-permeability model. It is demonstrated that the root zone depth and the soil hydraulic properties, appearing as parameters in the dual-permeability model, can be optimised by using measured data from a field experiment, and that the result can provide a reasonably realistic picture of the underlying processes. Conclusions of practical relevance are drawn.

Methods and materials

Three-year field experiments, aimed at exploration of potato (*Solanum tuberosum* L.) growing technologies on a European scale from the viewpoints of agronomic and economic efficiency, quality of tubers and nitrate leaching, were carried out in six different countries (Czechia, Denmark, Italy, Poland, Portugal and Slovakia) over three growing seasons 2003-2005 (two seasons only, namely 2003-2004, in Portugal) within the above-mentioned FertOrgaNic project. Experiments consisted of several treatments, which ideally differed only in terms of drip irrigation (yes or no), organic manures or amendments (yes or no) and fertigation (two different regimes or none). A more detailed description of experimental sites and the design of experiments can be found, for example, in Plauborg (2006a).

The potato plants were grown in elevated ridges. Drip irrigation lines were placed on the top of ridges and covered with a layer of soil about 3 to 8 cm thick. Agronomic and biometric measurements on the field sites were accompanied by an intensive programme of soil sampling, soil solution sampling and soil moisture content and suction measurements. Weather conditions were monitored in 10-minute intervals. In particular, the potato root zone depth and transversal width were inspected in the field several times during the growing season in a vertical cross-section made perpendicularly to the rows. These measurements were generalised (Battilani et al., 2006a, 2006b, 2007) by plotting the relative root zone depth $RZD_{rel} = RZD/RZD_{max}$ and the relative root zone width $RZW_{rel} = RZW/RZW_{max}$ against the accumulated thermal units ΣThU since emergence (°C d), and approximating the data points with boundary curves such that 85 % of points lay below the curves. The resulting average boundary curves, applicable to all sites, were:

$$RZD_{rel} = \min\left\{1,\ A_D + B_D \Big/ \left[1 + \exp\left(-\frac{\Sigma ThU + C_D}{D_D}\right)\right]\right\} \qquad (1)$$

$$RZW_{rel} = \min\left\{1,\ A_W + B_W \Big/ \left[1 + \exp\left(-\frac{\Sigma ThU + C_W}{D_W}\right)\right]\right\} \qquad (2)$$

where *RZD* and *RZW* (e.g., in cm) are the actual root zone depth and width, RZD_{max} and RZD_{max} (in the same units as *RZD* and *RZW*) are the maximum root zone depth and width and RZD_{rel} and RZD_{rel} (dimensionless) are the relative root zone depth and width, respectively. The optimised values of parameters in (1) and (2) were as follows: A_D = - 0.8109, A_W = -1.4401, B_D = 1.8138, B_W = 2.4417, C_D = 12.5232 °C d, C_W = 31.6550 °C d, D_D = 53.6654 °C d and D_W = 44.2301 °C d. The thermal units were calculated as follows:

$$\Sigma ThU = \sum_{i=1}^{n} ThU_i\ ; \quad ThU_i = \frac{P_i}{24}\left(11 \times T_{max,i} + 13 \times T_{min,i}\right) \qquad (3)$$

$$\begin{aligned} &P_i = 0 \quad \text{for} \quad T_{av,i} < 7\ °C \quad \text{for} \quad T_{av,i} > 30\ °C \\ &P_i = 1 - (21 - T_{av,i})^2 / (21 - 7)^2 \ \text{for}\ 7\ °C \le T_{av,i} < 21\ °C \\ &P_i = 1 - (T_{av,i} - 21)^2 / (30 - 21)^2 \ \text{for}\ 21\ °C \le T_{av,i} < 30\ °C \end{aligned} \qquad (4)$$

where *i* is the day number since emergence, *n* is the same number referring to the day for which ΣThU is caculated, $T_{max,i}$, $T_{min,i}$ and $T_{av,i}$ are the maximum, minimum and average air temperatures, respectively, on the *i*-th day, with $T_{av,i} = (T_{max,i} + T_{min,i})/2$, and P_i is the coefficient expressing the intensity of potato growth on the *i*-th day.

The Czech site, Valečov, lies at 49°38'40" N, 14°30'25" E and 461 m a.s.l. near Havlíčkův Brod town. Description of the site and the experiments conducted on it can be also found in some previous papers (e.g., Doležal et al., 2005; Zumr et al., 2006). The soil type is deep Stagnosol on weathered paragneiss. The topsoil, about 25 to 30 cm thick, is quite fertile, due to a long history of previous intensive cultivation associated with regular application (about every fourth year) of farmyard manure. The subsoil is dense and less favourable to root growth. Nevertheless, some plant roots can be found in the subsoil, too. The soil is fairly heterogeneous due to heterogeneity of the parent rock. The movement of water in this soil after rain, snowmelt or irrigation is distinctly preferential, occurring via macropores of various types. The spacing between the potato ridges, between plants in the ridges and between drippers in drip lines were, respectively, 0.75 m, 0.35 m and 0.30 m. The tops of ridges lay approximately 20 cm higher than the bottoms of furrows between them. Groundwater table was absent, except for short periods (between few hours and few days) of waterlogging after intensive snowmelt or rain events. The results and discussion below refer mainly to the first half of the 2004 season and to two (out of the total of six) treatments, referred to as T2_1 (non-irrigated, pig manure applied in previous autumn, 120 kg mineral N ha^{-1} in spring before planting) and T5 (drip irrigation by 125 mm of water, pig slurry applied in spring before planting, 35 kg mineral N ha^{-1} supplied via fertigation).

The soil water pressure head was measured and recorder by tensiometers once per hour over most of the growing season. The sensing tips of tensiometers were placed at 45 cm and 75 cm below the average soil surface (i.e., 55 and 85 cm below the tops of ridges). The readings of tensiometers varied during the diurnal cycle, partly due to true diurnal variations of soil water pressure head but mainly due to temperature instability of the instruments. In order to remove this effect, the data presented below consist of readings taken at midnight of every day, when the measured pressure heads usually reached their diurnal maxima (i.e., the suction heads reached their diurnal minima).

Hydraulic properties of the soil in Valečov were measured repeatedly in the laboratory and in the field (Štekauerová et al., 2004; Doležal et al., 2004). Some measurements are still going on. The soil water retention curves were measured in the laboratory on small undisturbed core samples, using mainly the conventional pressure plate apparatuses. The saturated and unsaturated hydraulic conductivity was measured in the laboratory on small core samples and in the field, using pressure infiltrometers, borehole permeameters and suction infiltrometers. A primary conclusion from all these measurements is that the soil is considerably heterogeneous, to the extent that its hydraulic characteristics cannot be expressed by a single curve or a single set of parameters. Instead, whole families of curves and statistical distributions of parameters are needed to describe the site in a sufficient way.

Taking into account the difficulties inherent to measurements of both the root zone geometry and the soil hydraulic parameters, we found it meaningful to look for effective values of these parameters by optimising a comprehensive soil water and root water uptake model, comparing its outputs with measured data. The results presented below refer to two comprehensive simulation models of soil water flow and the root uptake, namely Daisy (Hansen et al., 1990; Abrahamsen and Hansen, 2000; http://www.dina.kvl.dk/~daisy/; Abrahamsen et al., 2006) and S1D_DUAL (Vogel et al., 2000).

Both models are one-dimensional and contain also solute and heat transport submodels (not used in this paper). Out of the two, Daisy is more comprehensive, capable of simulating the turnover of organic mater and nitrogen species, the crop growth and development, evapotranspiration and, to some extent, also the snow and frost phenomena, surface water and solute balance, interception, sowing, harvest, tillage, manure and fertiliser application, pesticide application and fate, irrigation and drainage. The preferential flow can be simulated in Daisy as a short-circuiting process which takes place when there is a sufficient water pressure anywhere in the soil or a sufficient depth of ponds on the soil surface. The meteorological time step in the Daisy model was one day, which may not have been enough for the simulation of rapid processes.

The Daisy model parameters relating to soil and crop were optimised by trial and error, in order to make the model outputs comparable with the comprehensive results of FertOrgaNic field experiments. A description and some results are reported in Abrahamsen et al. (2006) and Heidmann et al. (2006). The optimisation was focused on the potato crop growth and the nitrogen turnover. It was found that the hydraulic properties of the Valečov soil can be best expressed by a bimodal Brooks-Corey equation. The soil profile modelled was 130 cm thick and was composed of five horizons (for details, see Abrahamsen et al., 2006). The upper boundary condition was given by the evapotranspiration and the surface water balance submodules. The lower boundary condition was free drainage into deep groundwater. A long warm-up period (since 1991) created a suitable initial condition. The root zone depth dynamics was simulated as a part of the crop growth submodule.

The S1D_DUAL model is based on solving, in parallel, two Richards equations, one for the matrix domain and the other one for the preferential flow (PF) domain, coupled together by a term which expresses the rate of water transfer between the two domains (Gerke and van Genuchten, 1993a, 1993b). For S1D_DUAL, the simulated soil profile was composed of three horizons: 0-10 cm (a loose and more permeable soil, like that in the potato ridges), 10–35 cm (the less loose part of the topsoil and the topsoil-subsoil transitional zone), and 35-100 cm (subsoil). Initial estimates of the model input parameters related to soil hydraulic properties were mainly derived from the results of laboratory measurements. Some of these parameters, and also the scaling factors (defined, e.g., by Vogel et al., 1991), the volumetric fraction of PF-domain and the inter-domain transfer coefficient, were optimised by inverse simulation for the non-irrigated treatment, using the Levenberg-Marquardt algorithm (Doherty et al., 1995). The objective function to be minimised was the sum of squares of differences between the simulated pressure heads and those measured by two reference tensiometers (one at 45 cm and another on at 75 cm). An atmospheric boundary condition was defined at the top of the flow domain and the free-drainage boundary condition was applied to its bottom. The initial condition was based on measured soil water pressure heads on the starting date. The meteorological time step was 10 minutes.

The S1D_DUAL model allows the roots to take up water from the matrix domain only. The code also allows for a gradual enlargement or shrinkage of the root zone. The simulated period was therefore split into five subperiods and the root zone depth was optimised (within feasible constraints) for each subperiod separately (for the non-irrigated treatment only). Otherwise the shape of the root water uptake function was the same for all periods: rectangular in the core of the root zone, decreasing linearly from maximum to zero in the very top few centimetres and decaying exponentially to zero at the bottom of the root zone. The water stress response function proposed by Feddes et al. (1978) was used, allowing for optimum root water uptake at pressure heads higher than -350 cm at high transpiration rates, higher than -600 cm at low transpiration rates and higher than an intermediate threshold at intermediate transpiration rates. For pressure heads lower (more negative) than the threshold, the root water uptake was supposed to decrease linearly with decreasing pressure head, becoming zero at -12000 cm, the wilting point. The parameters of the water stress response function were not subject to optimisation.

The evapotranspiration inputs for S1D_DUAL were obtained from the FAO 56 combination equation (Allen et al., 1998) with 10-minute weather data. The dual crop coefficient approach was adopted and the water stress of plants was taken into account. The daily long-wave radiation estimates were disaggregated as in Zavadil & Doležal (2005). This was essential, because the processes in the preferential flow zone are very rapid. In order to simulate them realistically, one must make sure that the time resolution of all inputs (such as rain, irrigation and evapotranspiration) is high enough (cf. Vogel, 2007).

The simulation results presented here embrace only a first part of the 2004 growing season (21 May to 18 July 2004), which more or less coincides with the period of root zone deepening. Similar S1D_DUAL simulation results were presented by Zumr et al. (2006). They differed from what is presented here in three main aspects:

- the assumed root zone depth was larger and was not allowed to vary,
- evapotranspiration was taken as constant over particular days (from midnight to midnight),
- the irrigated treatment (T5) was not simulated.

Results and discussion

The soil parameters used in the final predictive S1D_DUAL simulations are summarised in Table 1 and in the following text. The parameterisation used is due to van Genuchten. Here, θ_r and θ_s are the residual and the saturated moisture contents, respectively, α and n are the shape parameters of the retention curve equation and K_s is the saturated hydraulic conductivity. Of the parameters listed in Table 1, only the saturated hydraulic conductivities of both domains

Table 1 The final set of S1D_DUAL soil parameters (see the text for explanation)

Layer (cm)	Matrix					Preferential flow (PF) domain				
	θ_r	θ_s	α (cm^{-1})	n	K_s ($cm\ d^{-1}$)	θ_r	θ_s	α (cm^{-1})	n	K_s ($cm\ d^{-1}$)
0-10	0.07	0.390	0.022	1.16	20					
10-35	0.07	0.440	0.035	1.12	18	0.07	0.30	0.1	2.5	2500
35-100	0.07	0.443	0.020	1.11	3					

and all parameters of the preferential flow domain were optimised. The other parameters in Table 1 were derived from measurements.

The optimised matrix scaling factors for the surface level (0 cm) and the bottom of the profile (100 cm), respectively, were A_h = 1.13 and 0.92 for the pressure head, A_k = 1 and 0.69 for the hydraulic conductivity, and A_θ = 0.88 and 2.25 for the volumetric moisture content. Within the soil profile they were assumed to vary in a linear manner. The optimised PF-domain volume was 7 % at all depths, which is in accordance with field and laboratory observations (suggesting a range from 5% to 12%). The optimised inter-domain transfer coefficient was 0.01 $cm^{-1}\ d^{-1}$. The optimised root zone depths are presented graphically in Figs 3 and 4 below. The optimisation was done for the T2_1 treatment only and the same set of parameters was then used for simulation of the T5 treatment.

The soil hydraulic conductivity near saturation *K*(-2 cm) (at pressure head – 2 cm), measured by tension infiltrometers over several years, seasons and depths, varied within broad limits between 1 and 30 cm d^{-1}. The van Genuchten parameterisation given in Table 1 and the optimised scaling factors indicated above lead to the estimates *K*(-2 cm) = 19.76 cm d^{-1} at 0 cm and *K*(-2 cm) = 2.22 cm d^{-1} at 75 cm depth, which is in a reasonable agreement with the measurements.

Figs. 1 to 8 display how the soil water pressure heads at particular depths varied, according to the field tensiometric measurements (at 45 and 75 cm only) and the two models (Daisy and S1D_DUAL). Note that the horizontal scales in all graphs are linear in terms of time (calendar date, day after planting *DAP* and day after emergence *DAE*) but nonlinear in terms of the cumulative thermal units *ΣThU.* All depths in the graphs refer to the average soil surface, which is defined as the middle level between the tops of ridges and bottoms of furrows. Empty circles in Figs. 3 and 4 refer to the reference tensiometers, with respect to which the S1D_DUAL parameters were optimised. The other tensiometers are represented by full thin lines only. There were no reference tensiometers in the irrigated treatment T5. The full circles (Daisy) pertain to soil matrix, because the Daisy model does not calculate pressure heads in macropores. The Daisy model simulation compares reasonably well with the measured pressure heads, except for dry spells, large depths and large percolation events. The S1D_DUAL results are represented by two lines, one for the soil matrix and the other one for the preferential flow domain.

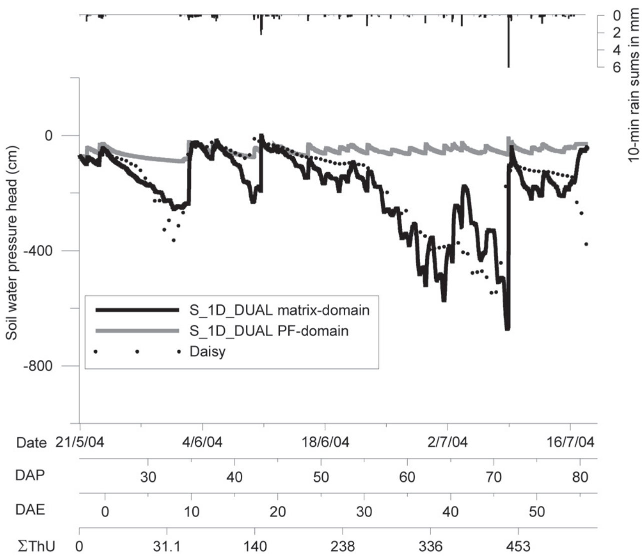

Fig. 1 Soil water pressure heads at 20 cm depth for the non-irrigated treatment (T2_1) in Valečov during the first part of 2004 season, simulated by S1D_DUAL (both in the matrix and the preferential flow (PF) domain) and Daisy (in the matrix only). DAP and DAE are the days after planting and emergence, respectively. ΣThU (°C d) are accumulated thermal units since emergence. The upper graph presents 10-minute rain sums.

Several conclusions can be drawn from Figs. 1 and 2:

a) There is a considerable spread of readings among parallel tensiometers. This is due to a genuine heterogeneity of the soil matrix but also due to the preferential flow (mainly via macropores) which induces additional heterogeneity of soil moisture and pressure head fields measured by sensors of usual size (Doležal et al, 2006a, 2006b).

b) On average, the pressure heads measured during dry spells tend to be lower (i.e., the suction heads tend to be higher) than the simulated ones. This can be explained by a non-representative selection of reference tensiometers (used for optimisation) or by the (hypothetical) presence of potato roots below the declared bottom of the root zone. The latter explanation is improbable for the conditions of the Valečov site. A third hypothesis is that the physical evaporation from greater depths, driven by barometric variations, is facilitated by the presence of open macropores (cf. Scotter and Raats, 1968; Massman, 2006).

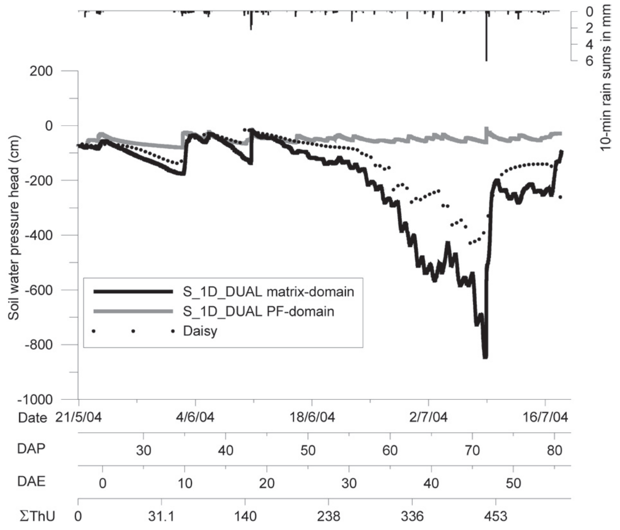

Fig. 2 The same as Fig 1, non-irrigated treatment (T2_1), depth 30 cm.

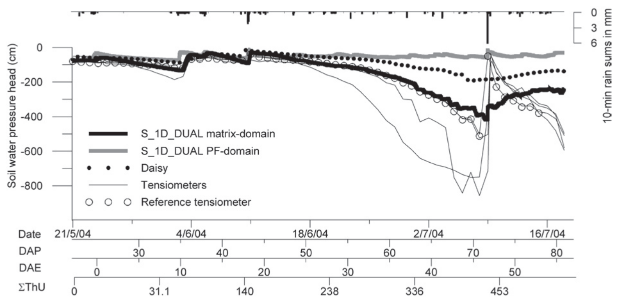

Fig. 3 Soil water pressure heads at 45 cm depth for the non-irrigated treatment (T2_1) in Valečov during the first part of 2004 season, measured by tensiometers and simulated by S1D_DUAL (both in the matrix and the preferential flow (PF) domain) and Daisy (in the matrix only). *DAP* and *DAE* are the days after planting and emergence, respectively. *ΣThU* (°C d) are accumulated thermal units since emergence. The upper graph presents 10-minute rain sums.

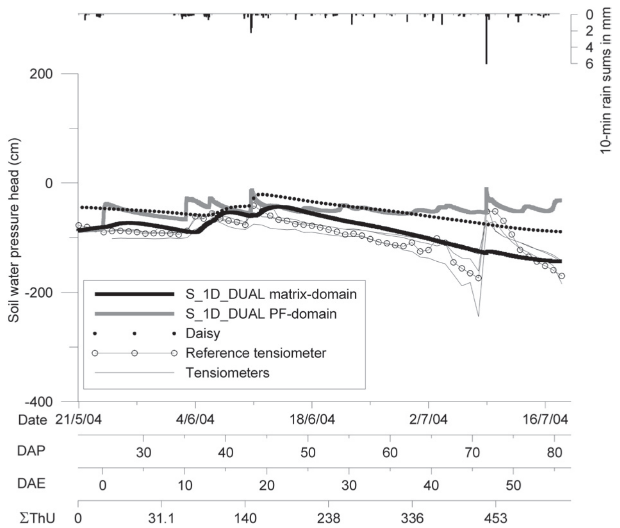

Fig. 4 The same as Fig. 3, non-irrigated treatment (T2_1), depth 75 cm.

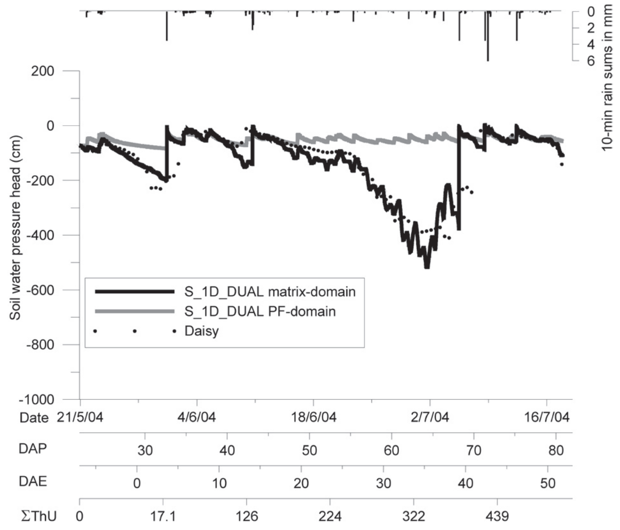

Fig. 5 The same as Fig. 1, irrigated treatment (T5), depth 20 cm. The upper graph presents 10-minute rain and irrigation sums.

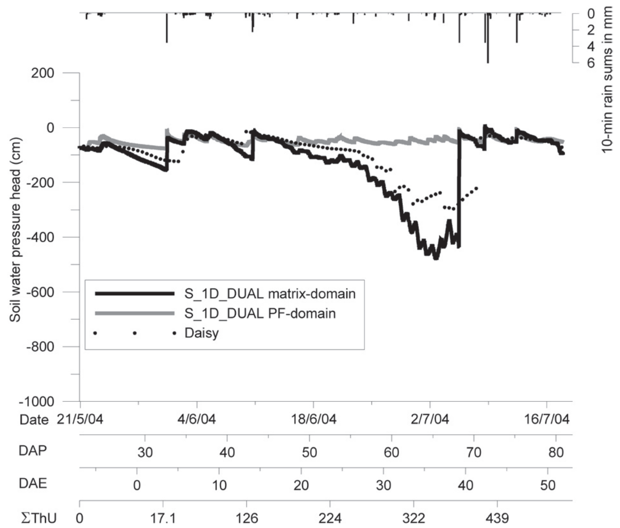

Fig. 6 The same as Fig. 2, irrigated treatment (T5), depth 30 cm. The upper graph presents 10-minute rain and irrigation sums.

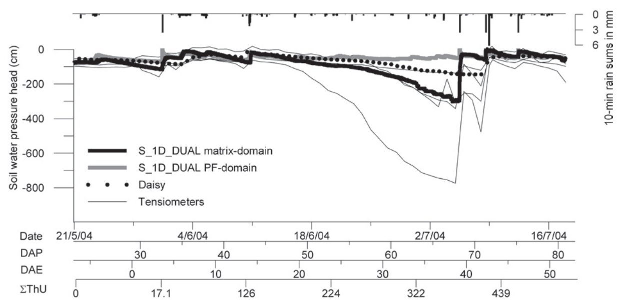

Fig. 7 The same as Fig. 3, irrigated treatment (T5), depth 45 cm. The upper graph presents 10-minute rain and irrigation sums.

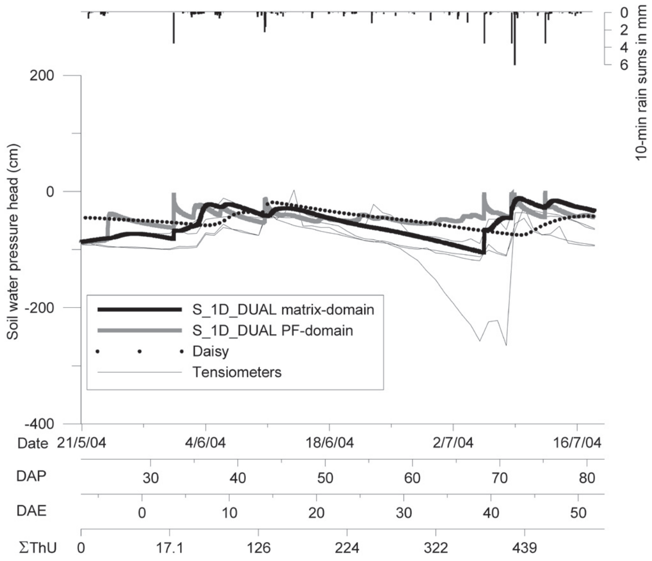

Fig. 8 The same as Fig. 4, irrigated treatment (T5), depth 75 cm. The upper graph presents 10-minute rain and irrigation sums.

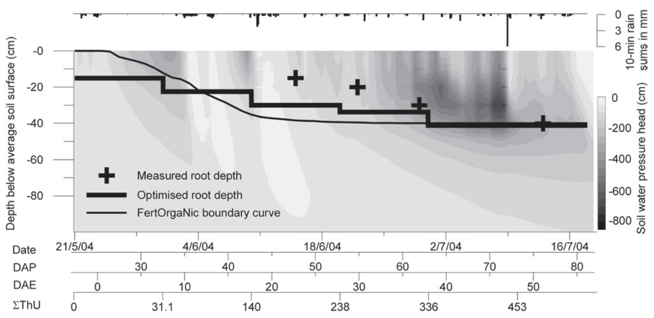

Fig. 9 Root depth dynamics for the non-irrigated treatment (T2_1) in Valečov during the first part of 2004 season, according to measurement, S1D_DUAL optimisation and the FertOrganic boundary curve. The graph also shows a map of the soil water pressure head variation in space and time. DAP and DAE are the days after planting and emergence, respectively. ΣThU (°C d) are accumulated thermal units since emergence. The upper graph presents 10-minute rain sums.

c) Putting aside the inaccuracy of simulation, one can discern a general trend, namely that the actual readings of tensiometers oscillate between the simulated pressure heads in the matrix and those in the preferential flow domain. The matrix pressure heads are measured by the tensiometers in the periods of drought or mild rains. After ample rains, the measured pressure heads frequently increase above the levels of simulated matrix pressure heads. In extreme cases, when the preferential flow domain becomes, for a while, nearly saturated, the tensiometric readings copy the pressure heads in this domain. This happened, for example, in both treatments on 8-9 July after a swarm of rainstorms (as already noticed by Zumr et al., 2006) and, partially, in the irrigated treatment T5 (Fig. 2) after a 10 mm irrigation on 5 July. Lateral flow from the macropores to the matrix domain after such events quickly wets the matrix.

The root zone depth measured in the field in Valečov is compared in Figs. 9 and 10 with the prediction resulting from (1) and with the step-wise pattern of root zone deepening obtained by S1D_DUAL optimisation. The values obtained from (1) were reduced by 10 cm in order to make them related to the average soil surface, because the development of (1) by Battilani et al., 2006a, 200b, 2007) was based on the depth measurements related to the tops of the ridges. The root zone depths assumed by the Daisy model (not shown) are similar to those adopted for S1D_DUAL, except that the former were represented by a continuous piecewise straight line and their terminal value was 50 cm. Figs. 9 and 10 also display ten-minute rain sums measured by the automatic weather station (in Fig. 10 also irrigation sums) and, the main thing, the spatio-temporal variation of soil water pressure head in the matrix domain. In Fig. 9, which pertains to the non-irrigated treatment T2_1, we see that several short dry and rainy spells followed each other by the start of the season. Later on, simultaneous root uptake and mild rains almost balanced each other. Finally the abstraction prevailed and the pressure heads decreased below the threshold of water stress. The stress persisted for about two weeks until ample rains on 8 and 9 July put an end to it for a while (a further period of severe stress came in August).

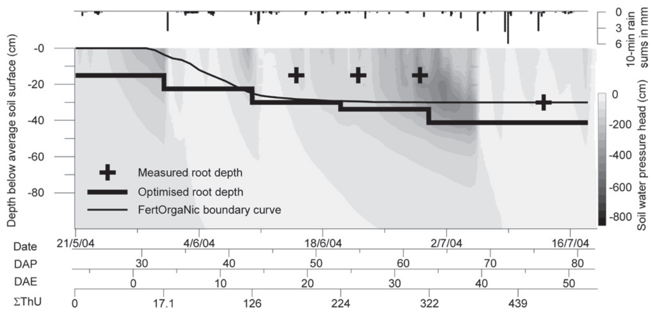

Fig. 10 The same as Fig. 3 for the irrigated treatment (T5). The upper graph presents 10-minute rain and irrigation sums.

During each dry spell, the soil below the bottom of the root zone also tended to dry out. This could be explained by the capillary rise towards the root zone (Parker et al., 1989) and by the gravity-driven unsaturated seepage. It must be noted, however, that the pressure head maps in Figs. 9 and 10 are results of S1D_DUAL simulation and not of measurements. The pressure head map of the irrigated treatment T5 (Fig. 10) shows a similar picture as Fig. 9, except that the effect or rain is enhanced by the influence of irrigation. In this treatment, very little plant stress occurred. On the other hand, it is evident that irrigation prepared the way for the following deep seepage after ample rains of 8 and 9 July. The measured root zone depths (as well as those calculated from (1), for which the measured terminal depth RZD_{max} was an input) were shallower in the irrigated treatment T5 than in the non-irrigated treatment T2_1. The explanation is that the plant roots in the irrigated treatment could not penetrate a slightly overwetted and anoxic layer at the bottom of the topsoil, an inadvertent consequence of the pig slurry application and incorporation. No importance is attached in this respect to a slightly better availability of topsoil moisture (i.e., a weaker push for plant roots to go deeper) in T5. The S1D_DUAL-optimised root depths in Fig. 10 are, of course, the same as in Fig. 9, because they were optimised for the non-irrigated treatment.

The width of the root zone, taken transversally to potato rows, was also measured. It could not be taken into account in simulations because the models used were one-dimensional. Nevertheless, it is important to notice that Battilani et al. (2006a, 2006b, 2007) assumed the maximum root zone width RZW_{max} in (2) to be equal to the row spacing. In reality, this need not necessarily be the case, especially when the furrows between rows are compacted (they were so in the Czech experiments). Allowing for the actual width of the root zone is important when the irrigation is scheduled on the base of root zone water balance (less water is needed if the root zone is narrower) but also when the irrigation is controlled by soil moisture sensors. In the latter case, the situation is even more complex because the success of irrigation depends on the proper account of the mutual position of the drip lines, the sensors and the plants. The size of the root zone in the third dimension, parallel to rows, could also be investigated, but the experience (Battilani, 2006a, 2006b, 2007) suggests that the potato roots occupy the whole space between adjacent potato plants very soon (shortly after the emergence).

Conclusion

In this paper, we made an attempt to explore and express, in terms of soil water pressure, potato rooting depth and plant water stress, what happens in a structured ploughed soil under a potato stand. The results are, of course, only partial. The following main conclusions can be made:

a) The empirical boundary curve of root zone growth expressed by (1) is in a reasonable accordance with the S1_DUAL optimised root zone depth variation derived from the soil water pressure head measurements. It is realistic to expect that the other empirical equations contained in the FertOrgaNic Decision Support System (Battilani et al., 2006a, 2006b) are similarly trustable.

b) While it is relatively easy (although not always trivial) to optimise parameters of a simulation model when the objective function relates to a single feature (such as a single curve of pressure head vs. time), the optimisation becomes more difficult if it is multi-objective (such as the parameterisation of Daisy in the FertOrgaNic project) and may be virtually impossible when one attempts to make a single model output similar to multiple, mutually diverging or conflicting measurements (such as the curves of pressure head vs. time measured by several parallel tensiometers in Figs. 3, 4, 7 and 8). This dilemma can be solved by a model capable of producing several random realisations (Doležal et al., 2006a).

c) The main argument against the use of soil moisture sensors for automatic or semiautomatic irrigation control is that the root zone dimensions vary in time and from case to case (the "case" may refer to soil, climate, season, tillage etc.). This pertains, in particular, to row crops, such as potato. More detailed experimental research and modelling is needed in order to optimise the placement of sensors with respect to ridges, plants and drippers. Several parallel sensors are needed. They should be placed at different depths and their signals should be evaluated differently at different crop development stages. The sensors can be used to indicate a suitable time when the irrigation should start, because at that instant there is usually no preferential flow. However, the sensors cannot detect the time when the irrigation should be stopped, because their reaction to preferential water percolation is variable and, to some extent, unpredictable.

Further progress in this field can be achieved if a 2D or 3D simulation model is used, the optimisation comprises several seasons, the variability of soil hydraulic parameters in time is allowed for and the concept of multiple model outputs as outlined above is applied. It is also essential that the time resolution of inputs and of the simulation model itself is high enough, because the processes in the preferential flow zone are very rapid.

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