A Chernozem Soil Water Regime Response to Predicted Climate Change Scenarios

Csilla FARKAS, Andrea HAGYÓ, Eszter HORVÁTH and György VÁRALLYAY

Research Institute for Soil Science and Agricultural Chemistry of the Hungarian Academy of Sciences (RISSAC), Budapest, Hungary

Abstract: Climate, hydrology and vegetation are closely linked at local, regional and global scales. The recent land use and plant production systems are adapted to the present climatic conditions. Thus, studies on the influence of possible climate change scenarios on the water and heat regimes of the soil-plant-atmosphere system are important in order to work out plant production strategies, adjusted to changed conditions. In this study the effect of two possible climate change scenarios on the soil water regime of a Chernozem soil was estimated for a Hungarian site. Soil water content dynamics simulated for different conventional and soil conserving soil tillage systems were evaluated, using the SWAP soil water balance simulation model. The combined effect of different soil tillage systems and climate scenarios was analysed. Climate scenarios were represented through the cumulative probability function of the annual precipitation sum. The SWAP model was calibrated against the measured in the representative soil profiles soil water content data. The site- and soil-specific parameters were set and kept constant during the scenario studies. According to the simulation results, increase in the average growing season temperature showed increase in climate induced soil drought sensitivity. The evaluated soil water content dynamics indicated more variable and less predictable soil water regime compared to the present climate. It was found that appropriate soil tillage systems that are combined with mulching and ensure soil loosening could reliably decrease water losses from the soil. From this aspect cultivator treatment created the most favourable for the plants soil conditions. It was concluded that soil conserving soil management systems, adapted to local conditions could contribute to soil moisture conservation and could increase the amount of plant available water under changing climatic conditions.

Keywords: climate change; SWAP; simulation modelling; soil moisture; soil tillage; Chernozem; soil water conservation; direct drilling

The increase in atmospheric CO_2, along with increase in other greenhouse gases, is believed to be changing the earth's energy balance (Haskett *et al.* 2000). There has been recent confirmation of anthropogenic changes in earth's climate related to this increase (IPCC 2001, 2007). Climate, hydrology and vegetation are closely linked at local, regional and global scales. Hence, climate and atmospheric composition are likely to have important effects on agriculture (Kovács & Dunkel 1997). Consequently, studies on the influence of possible climate change scenarios on the water balance of a stand are important.

Simulation models that are able to integrate the influence and relationship of different factors (Flachner *et al.* 2004) play an important role in

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studying the effect of different climate and atmospheric gas composition change scenarios on soil water regime and crop development. These studies, however, are affected by uncertainties, caused by several factors like climate variability, long-term changes in soil storage capacity and soil fertility, etc. (Sirotenko *et al.* 1997). It has been proved that water stress and drought are the most important limiting factors in crop productivity in the continental climate region under changed climatic conditions (Kovács & Dunkel 1997; Farkas *et al.* 2005). Štekauerová *et al.* (2006) called attention towards the importance of hydrolimits in agricultural production under varying circumstances.

The natural conditions in Hungary are generally favourable for rainfed biomass production. These conditions, however, show extremely high spatial and temporal variability and give sensitive reactions to various natural or human-induced stresses (Láng *et al.* 1983; Csete & Várallyay 2004). The agro-ecological potential is mainly limited by three soil factors: soil degradation processes (Szabolcs & Várallyay 1978; Várallyay 2000), extreme moisture regime (Várallyay 2004a) and unfavourable changes in the biogeochemical cycles of elements, especially of plant nutrients and environmental pollutants (Láng *et al.* 1983).

Considering the most relevant climate change scenarios for the Carpathian Basin, it can be stated, that in Hungary most probably water will be the determining (hopefully not limiting) factor of food security and environmental safety in the future. Consequently, the increase in water use efficiency will be one of the key issues of agricultural production, rural development and environment protection and the control of soil moisture regime will be an imperative task without any other alternatives (Várallyay 2004b, 2005). This calls attention towards further evaluation and spreading of sustainable, soil and moisture conserving soil management and land use systems that support elimination or moderation of extreme moisture situations. The reduction of risks and increase of yield stability is of primary importance and consists of three main elements: maintenance of water infiltration in the soil; increase of soil water storage in plant available form and drainage of the surplus amount of water from the soil profile and from the area (vertical and horizontal drainage). From this respect, it is very important to understand the combined effect of different soil management practices (Kroulík *et al.* 2007) and climate scenarios on hydraulic properties and soil water regime.

The objective of the current study was to quantify the impact of two recent climate change scenarios on the soil water balance and soil water content dynamics of a Chernozem soil of a Hungarian site under various soil management systems.

MATERIAL AND METHODS

Experimental site

The investigation was carried out in the long-term soil tillage experiment of the Szent István University, established in 2002 (Birkás & Gyuricza 2004a). The Józsefmajor Experimental Station (altitude 110 m, latitude: 47°40’ N, longitude 19°40’ E) is located nearby Hatvan, Hungary, 60 km north-east from Budapest on the northern edge of the Carpathian basin. The year average temperature is 7.9°C, the annual and growing season precipitation amounts are 580 and 323 mm on average, respectively. The prevailing soil type is Calcic Chernozem, developed on loam and is moderately sensitive to soil compaction. The soil has a slightly acidic reaction (pH H_2O is 6.38 and pH KCl is 5.43); the sand, silt and clay contents of the upper 20 cm layer are 23%, 42% and 35%, respectively. The organic matter content is 3.2% and 2.5%; the total N, P_2O_5 and K_2O contents of the 0–20 and 20–40 cm layers are 0.13 and 0.082%; 270 and 214 ppm and 110 and 85 ppm, correspondingly. The experiment was set up on 13 × 150 m experimental plots with four replicates in a split-plot design. The tillage variants comprised mouldboard ploughing (P, 26–30 cm); disking (D, 16–20 cm); loosening + disking (L + D, L: 40–45 cm, D: 16–20 cm), two cultivator treatments (K1, 12–16 cm and K2, 16–20 cm) and direct drilling (NT) (Birkás & Gyuricza 2004b). Our studies concerned the NT, P and K2 treatments. The crop sequence – wheat–maize – during years 2001–2003 was improved by catch crops (mustard, rye and pea). In 2003 maize was the main crop grown.

Soil sampling, analyses and monitoring

In April 2003, disturbed samples and undisturbed soil cores of 100-cm^3 volume were collected from each tillage treatment in 3 replicates. Samples were taken from the layers of 0 to 5, 5 to 10, 15 to 20 and 45 to 50 cm, representing the soil surface, the cultivated layer, the pan and the non-tilled layers, respectively. Samples were wetted from bellow and further drained to water suctions, h, of 1, 2.5, 10, 32, 100 and 200 hPa using the hanging water column method (Várallyay 1973) and to 500, 2500 and 15850 hPa by the osmotic method (Várallyay 1973). The field capacity and the wilting point were defined as the water content, corresponding to water suctions of 100 and 15850 hPa, respectively. The residual water contents were estimated by fitting the van Genuchten analytical expression (van Genuchten 1980) to the measured soil water retention data, as described below. The water contents were then measured gravimetrically by drying the samples at 105°C until no changes in their weight was observed. Bulk density was calculated from dry soil weights (105°C, 48 h) and the volume of undisturbed samples. Soil texture was determined, using the pipette method. The method, suggested by Wösten *et al.* (1995) was used to estimate the saturated hydraulic conductivity of the soil matrix (Tóth *et al.* 2006). The main soil properties, determined for three different soil tillage systems are given in Table 1.

In each tillage treatment, 3T-System type capacitive probes (Szőllősi 2003) were installed up to 80 cm depth with 10 cm increment to ensure continuous measurement of soil temperature and soil water content. Measurements were performed four times a day from May 13 until September 11, 2003. Daily average values were used for the evaluation. Basic crop properties (sowing and harvesting dates, rooting depth, plant height) were monitored and recorded during the vegetation period.

Adaptation of the SWAP model to the study area

The SWAP model (Van Dam 2000) simulates the water flow in the unsaturated zone in relation to plant growth for the entire growing season. The model input data consists of meteorological, crop and soil data as well as initial and boundary conditions. The soil hydrophysical functions are introduced by the analytical expressions of van Genuchten and Mualem (van Genuchten 1980). The RETC computer program (van Genuchten 1980) was applied to quantify these parameters from the experimental data on soil water retention characteristics and saturated hydraulic conductivity. The analytical parameters of the soil hydraulic functions, fitted to the soil hydrophysical data are given in Table 2. The SWAP simulation model was parameterised, using soil and plant data, collected from the experimental sites (Farkas 2007). The simple crop subroutine of the model was applied for maize. Meteorological input data were set according to air temperature, wind speed, solar radiation, air

Table 1. Soil properties, determined in three soil tillage systems of the Hatvan experiment

Soil properties	Soil management systems					
	NT		P		K2	
	soil layer (m)					
	0.15–0.20	0.45–0.50	0.15–0.20	0.45–0.50	0.15–0.20	0.45–0.50
Bd (g/cm^3)	1.54	1.41	1.22	1.45	1.23	1.37
HUM (%)	3.40	2.53	3.42	2.53	3.45	2.53
Sand (%)	23.0	20.0	23.0	20.0	23.0	20.0
Silt (%)	42.0	43.4	42.0	43.4	42.0	43.4
Clay (%)	35.0	36.6	35.0	36.6	35.0	36.6
Ks (cm/day)	1.70	3.07	3.10	2.85	3.51	3.35
SWC (m^3/m^3)	0.44	0.42	0.52	0.37	0.49	0.44
FC (m^3/m^3)	0.38	0.35	0.33	0.35	0.36	0.36
WP (m^3/m^3)	0.20	0.20	0.16	0.17	0.17	0.18

NT – direct drilling; P – ploughing; K2 – cultivator treatment; Bd – bulk soil density; HUM – humus content; *Ks* – hydraulic conductivity at saturation; SWC – soil water content at saturation; FC – field capacity; WP – wilting point humidity and precipitation data, measured at the Hatvan meteorological station of the Hungarian Meteorological Service. Initial boundary conditions were set according to soil water contents, measured in the beginning of May. The upper boundary conditions were calculated by the model, using meteorological data. Free flux bottom boundary conditions were defined. The measured soil water content dynamics were used as reference data for model calibration. Model adaptation was achieved by tuning model parameters to obtain the smallest possible difference between the continuously measured and simulated by the model soil water content values. Standard errors were calculated from the measured and corresponding simulated soil water content and total soil water values by ordinary method using the Excel software.

Climate scenarios

In this study, two climate change scenarios, representing the IPCC SRES A2 and B2 scenarios for the period of 2071–2100 were used to evaluate their effect on soil water regime as compared to the present (reference – 1961–1990) climate. The A2 storyline and scenario family (Nakicenovic & Swart 2000; IPCC 2007) describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 storylines (Nakicenovic & Swart 2000; IPCC 2007). While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

In this study, the reference climate data and the climate scenarios consisted of downscaled from Hadley Centre model outputs to the nearest big city (Miskolc) (Bartholy *et al.* 2007) data on minimum, maximum and annual mean air temperature as well as precipitation for 30 years in daily resolution. Variability of meteorological properties within the reference period and the scenarios were represented by 3-3 selected years, corresponding to the main points (min, max and 50%) of the cumulative probability function of the yearly precipitation sum. Impact studies were performed for the selected 3 years by running the SWAP model with the reference and downscaled scenario weather data, using the previously calibrated model parameters. The soil and crop input data remained unchanged.

RESULTS AND DISCUSSION

Previous studies related to the Hatvan long-term tillage experiments proofed, that the soil hydraulic properties vary significantly among the tillage systems (Farkas 2004, 2007). The seasonal variability of these soil properties has also been proofed

Table 2. Parameters of the Mualem-van Genuchten functions, fitted to soil hydrophysical data, measured in different soil tillage systems of the Hatvan experiment

Soil layer (m)	Tillage system	Mualem-van Genuchten parameters				
		Θ_{SAT} (m^3/m^3)	Θ_{RES} (m^3/m^3)	α (cm^{-1})	n (–)	Ks (cm/day)
0.15–0.20	NT	0.418	0.001	0.0072	1.1472	1.70
	P	0.583	0.001	0.0738	1.0843	3.10
	K2	0.493	0.001	0.3791	1.0992	2.59
0.40–0.45	NT	0.415	0.001	0.0738	1.0843	3.07
	P	0.393	0.001	0.0148	1.1009	2.85
	K2	0.466	0.001	0.3757	1.0805	2.85

Θ_{SAT} – soil water content at saturation; Θ_{RES} – residual soil water content; α, n – fitting parameters of the van Genuchten analytical function; Ks – hydraulic conductivity at saturation; NT – direct drilling; P – ploughing; K2 – cultivator treatment

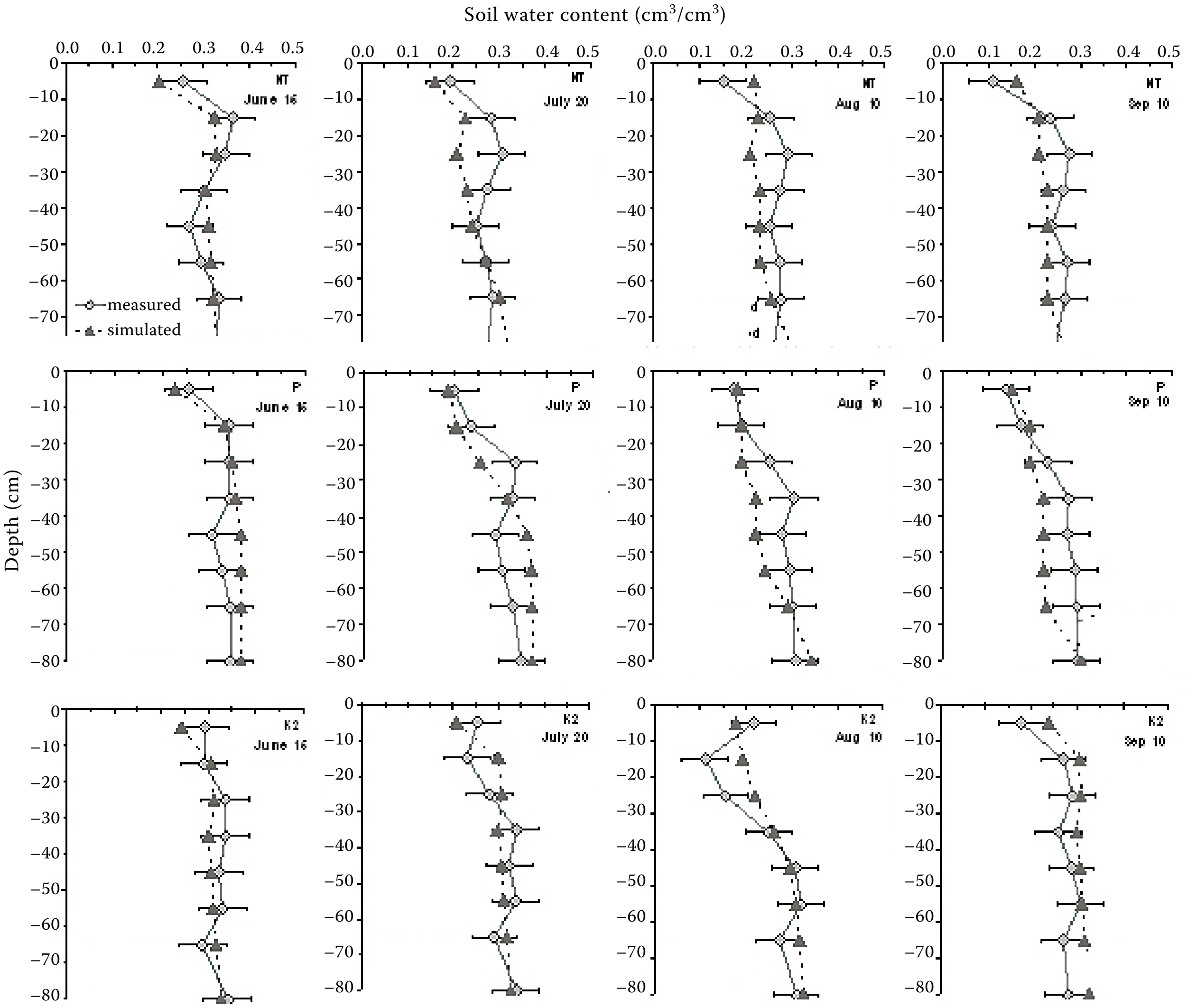

Figure 1. Soil water content profiles measured and simulated for direct drilling (NT), ploughing (P) and cultivator (K2) treatments for four selected dates (Hatvan 2003)

(Farkas 2004, 2007). Based on these results, the calibration of the SWAP simulation model to the study area was performed, considering the seasonal variability of soil hydraulic properties (Farkas 2004; Farkas & Majerčák 2007). Measured and simulated for the three different soil tillage systems soil water content profiles for four chosen dates are given in Figure 1. The shape of the soil water content profiles measured in different treatments (Figure 1) differed significantly in the cultivated topsoil layer. Standard errors of the model estimates in terms of average soil water contents for chosen layers (Θ, m^3/m^3) and total soil water of the 0–80 cm layer (TSW, mm) are presented in Table 3. The best fitting was obtained for the direct drilling (NT) system, where the smallest soil disturbance occurred. In general, good agreement between the measured and simulated TSW values was achieved, which indicates, that the soil water balance elements (evaporation, transpiration, leaching etc.) of the soil profiles could be simulated with reasonable precision. However, it was found, that the redistribution of water within the soil profile could not be described accurately for the whole simulation period. The reason for that could be the unsuitable characterisation of the hydrophysical characteristics in the deeper soil layers, especially of the saturated hydraulic conductivity values. This indicates that the vertical sampling resolution of the soil profile should be further refined and adjusted to the depth of the applied soil tillage system.

The main meteorological characteristics of the selected years, corresponding to the main relative frequencies (RF; 0.0, 0.5 and 1.0) of the cumulative

Table 3. Standard error (SE), measured and simulated characteristics of the soil water content and total amount of water, stored in the soil profile

Tillage system	Soil layer (cm)	Θ_{SIM} (m^3/m^3)	Θ_{MEAS} (m^3/m^3)	SE (m^3/m^3)	TSW_{SIM} (mm)	TSW_{MEAS} (mm)	SE (mm)
NT	0–80				210.88	219.19	12.82
	0–20	0.227	0.244	0.035			
	20–50	0.261	0.281	0.035			
	50–80	0.292	0.286	0.017			
P	0–80				227.21	206.49	14.45
	0–20	0.224	0.233	0.046			
	20–50	0.281	0.253	0.040			
	50–80	0.325	0.314	0.120			
K2	0–80				206.50	212.28	13.13
	0–20	0.229	0.195	0.051			
	20–50	0.277	0.249	0.040			
	50–80	0.301	0.300	0.013			

Θ_{SIM} – mean of the simulated soil water contents; Θ_{MEAS} – mean of the measured soil water contents; SE – standard error; TSW_{SIM} – total soil water, simulated for the upper 80 cm of the soil profile; TSW_{MEAS} – total soil water, measured in the upper 80 cm of the soil profile; NT – direct drilling; P – ploughing; K2 – cultivator treatment

probability functions of yearly precipitation sum (ΣP, mm) and annual mean temperature (T) of the reference period and two climate change scenarios are given in Table 4. The A2 and B2 scenarios did not differ significantly with respect to the mean annual sum of precipitation. Both the scenarios indicated much drier climate for the study area in the end of the century with average decrease in ΣP of about 70 mm. According to A2 and B2 scenarios, the annual mean temperature would increase by 5°C and 4°C, respectively. However, while the A2 scenario just indicated shifting of the cumulative probability functions of ΣP and T with respect of the axes towards more dry and warm climate, the B2 scenario also predicted increase in variation of climatic factors, which referred to increased occurrence of extremes.

Figure 3 demonstrates the soil water content dynamics, simulated for the NT, P and K2 treatments for an extremely dry (1988) and an average (1990) year of the reference period corresponding to the present climate. Valuable differences between the soil water regimes of the three soil management systems could be observed. These differences in simulation results were indicated by soil tillage induced changes in soil hydraulic

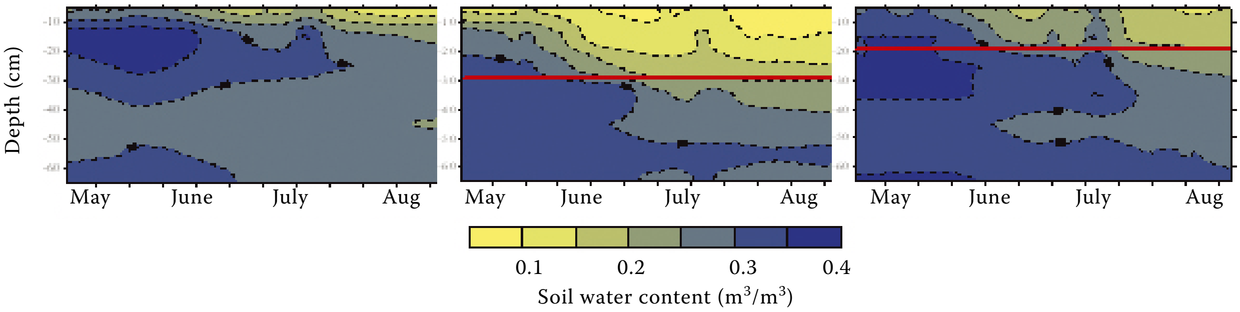

Figure 2. Spatial and temporal distribution of soil water content, measured in the direct drilling (NT), ploughing (P) and cultivator (K2) treatments (Hatvan 2003)

The red lines indicate the maximum depth of soil tillage applied.

Table 4. Mean values, coefficients of variation (*CV*) and representative values of annual mean temperature (T) and precipitation sum (ΣP) derived from the cumulative probability functions used for the simulation experiments

	Reference period REF (1961–1990)		Climate change scenarios			
			A2 (2071–2100)		B2 (2071–2100)	
	T (°C)	ΣP (mm)	T (°C)	ΣP (mm)	T (°C)	ΣP (m)
Statistics, calculated from data of 30 years						
Mean	11.8	466.1	16.8	396.5	15.7	395.8
CV (%)	0.4	21.2	0.4	21.1	0.4	29.9
Representative years, used for comparison of climate scenarios (Figures 3, 4)						
RF ≈ 0.0	13.3	233	17.4	183	13.6	183
RF ≈ 0.5	12.6	483	17.5	376	15.7	390
RF ≈ 1.0	9.7	584	14.5	520	13.3	597
Representative years, used for comparison of soil tillage systems (Figure 2)						
RF ≈ 0.10 (1988)	9.2	239				
RF ≈ 0.55 (1990)	10.9	488				
RF ≈ 1.00 (1961)	11.8	584				

T – annual mean temperature; ΣP – annual sum of precipitation; *CV* – coefficient of variation; RF – relative frequencies derived from the cumulative probability functions of T and ΣP

properties. Soil water content values, measured by the capacitive soil moisture probes installed in different soil management systems showed similar differences in soil water regimes (Figure 2), which verified, that the model outputs were trustworthy. According to the simulation results, the most even distribution of water within the soil profile occurred in the NT system, which remained dry during the vegetation period. In the ploughing treatment (P), the effect of plough pan could clearly be detected. This compacted layer constrained the infiltration of water in the deeper soil layers, which could lead to increased evaporation losses and extremely dry soil conditions during the summer period. Concerning the cultivator treatment (K2), precipitation water could penetrate in the soil until the beginning of summer, increasing the soil water storage below the tillage depth, and raising

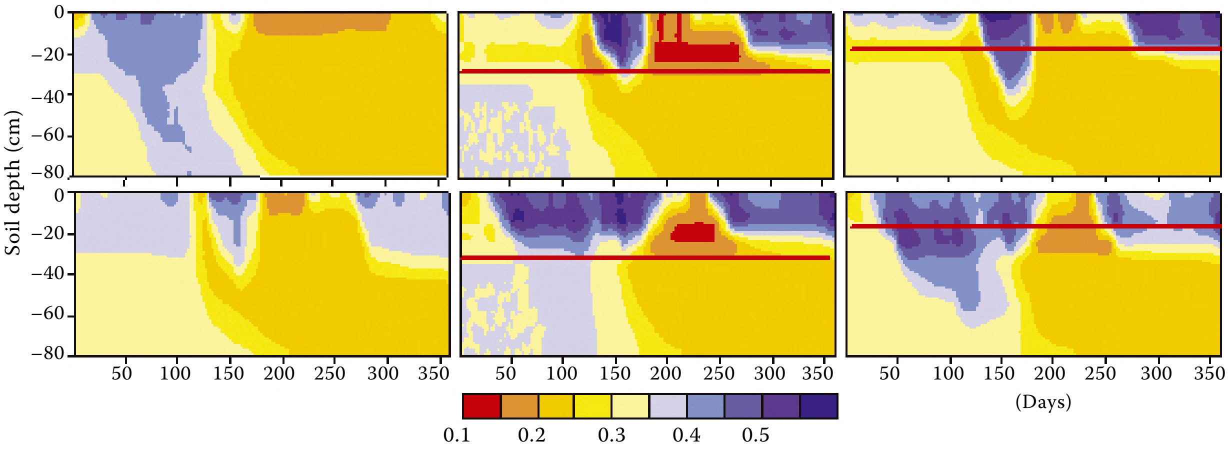

Figure 3. Spatial and temporal distribution of soil water content, simulated in the direct drilling (NT), ploughing (P) and cultivator (K2) treatments for two years of the reference (REF) period with extremely little (1988) and average (1990) amount of annual precipitation (ΣP)

The red lines indicate the maximum depth of soil tillage applied.

Table 5. Minimum, maximum and mean values of soil water content (m^3/m^3), simulated for the representative years of the A2 scenario for three different soil management systems

	Soil layer (m)								
	0.0–0.2			0.2–0.4			0.4–0.8		
	tillage systems								
	NT	P	K2	NT	P	K2	NT	P	K2
Θ (m^3/m^3) for RF 0.0	ΣP = 183 mm								
Min	0.19	0.15	0.16	0.24	0.20	0.23	0.24	0.20	0.23
Max	0.44	0.50	0.48	0.34	0.31	0.35	0.34	0.35	0.34
Mean	0.26	0.27	0.27	0.27	0.23	0.26	0.28	0.28	0.27
Θ (m^3/m^3) for RF 0.5	ΣP = 375 mm								
Min	0.18	0.15	0.17	0.24	0.20	0.22	0.24	0.20	0.22
Max	0.44	0.52	0.49	0.45	0.38	0.45	0.38	0.32	0.33
Mean	0.28	0.27	0.27	0.29	0.24	0.26	0.28	0.24	0.26
Θ (m^3/m^3) for RF 1.0	ΣP = 520 mm								
Min	0.18	0.15	0.16	0.24	0.21	0.23	0.24	0.20	0.23
Max	0.44	0.52	0.49	0.44	0.41	0.42	0.42	0.37	0.42
Mean	0.32	0.32	0.33	0.30	0.26	0.29	0.30	0.28	0.30

NT – direct drilling; P – ploughing; K2 – cultivator treatment; ΣP – annual sum of precipitation; RF – relative frequencies derived from the cumulative probability functions of ΣP

the amount of plant available water during the dry summer periods.

Comparing the soil water regimes, simulated for the two different years of the reference period, a huge variation in both, soil water content values and length of extremely dry periods could be observed in all the tillage systems.

The estimated variation in soil water contents of the K2 tillage system for years that correspond to different relative frequencies (RF) is given in Figure 4. Considerable differences between the soil water regimes, corresponding to various probability levels of different scenarios were found. According to the modelling results, longer and more harmful dry periods compared to the present conditions could be expected by the end of this century. In case of average years of the A2 and B2 scenarios, precipitation water could not penetrate below the 0.2 m soil layer and the subsoil remained dry during the majority of the study period. This calls further attention towards soil conserving soil management systems that contribute to the infiltration of autumn and winter precipitation to deeper soil layers and maintain soil water retention and storage until the dry summer periods.

Evaluating the soil moisture content distribution of REF, A2 and B2 cases for years with relative frequency values (RF) close to 1.0 (Figure 4, the lower 3 pictures) it was found, that the uneven distribution of precipitation and the higher air temperature values could not be compensated neither with higher amount of water, reaching the soil surface nor with soil water conserving tillage systems. Thus, the annual precipitation (ΣP) for the RF = 1.0 case of the reference period (583 mm) was less, than for the B2 scenario (597 mm) but the soil water regimes of the two years were dissimilar. The dry period was much longer in the case of B2 scenario, because of less frequent but more intensive rainfalls in springtime and absence of rainy periods during the summer and autumn periods.

For all the three periods studied (REF, A2 and B2), the soil water regime of the NT treatment was found to be more equilibrated, compared to the K2 and P ones (Table 5). Hence, precipitation water could penetrate to deeper layers in all the cases, causing a wilder wetting front with somewhat less soil water content in average. In the NT treatment, the soil did not dry out that much as in the P and K2 treatments. However, the wilting point in the

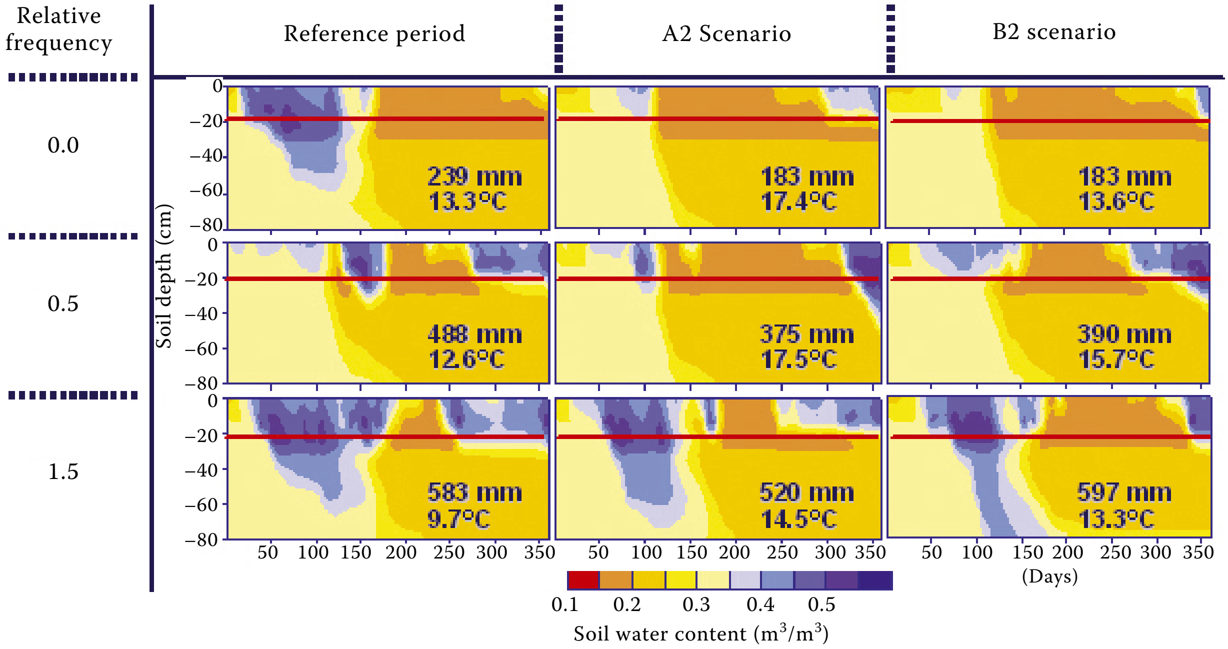

Figure 4. Spatial and temporal distribution of soil water content simulated in the cultivator (K2) treatment for years, corresponding to three different relative frequencies (RF) of the precipitation sum (ΣP) of the reference period (REF) and A2 and B2 climate change scenarios; ΣP (mm) and mean annual temperature (T, °C) are indicated

The red lines indicate the maximum depth of soil tillage applied.

NT treatment (0.20 m^3/m^3) was higher, than in the other two soil management systems (Table 1), so this higher water content could occur because the plant could not extract it. This indicates that the water use efficiency of the corps was most probably better in the P and K2 treatments. The soil water regime of ploughed plots, however, reflected the harmful effect of existing plough pan. This thin compacted layer limited the penetration of water below the 0.2 m layer causing extremely moist and dry soil conditions during rainy and dry periods, respectively. Therefore, the evaporation losses in the P treatment were most probably higher compared to the K2 treatment.

CONCLUSIONS

According to the climate change scenarios studied in this paper, more dry and warm climate compared to the present one could be expected by the end of the century for the Carpathian Basin. The simulation results, accomplished using soil hydrophysical data from three soil management systems of a long-term tillage experiment indicated that appropriate soil tillage systems that are combined with mulching and ensure soil loosening could reliably decrease water losses from the soil. From this aspect the cultivator treatments created the most favourable for the plants soil conditions.

We concluded that soil conserving soil management systems, adapted to local conditions could increase soil moisture conservation and the amount of plant available water under changing climatic conditions.

References

Bartholy J., Pongrácz R., Gelybó Gy. (2007): Regional climate change expected in Hungary for 2071–2100. Applied Ecology and Environmental Research, **5**: 1–17.

Birkás M., Gyuricza Cs. (2004a): Tillage–Climate Change–Technology. Szent István Egyetem, MKK Földműveléstani Tanszék, Gödöllő. (in Hungarian)

Birkás M., Gyuricza Cs. (2004b): Interrelations between elements of the agro-ecosystem in a soil tillage trial. AGRO-21 Füzetek, **37**: 97–110.

Csete L., Várallyay Gy. (eds) (2004): Agroecology – Environmental interactions of agro-ecosystems and possibilities of their control. AGRO-21 Füzetek, **37**: 217.

Farkas Cs. (2004): Effect of soil tillage on soil properties and soil water regime. In: Birkás M, Gyuricza Cs. (eds): Soil Management – Tillage Effects – Soil Water. Szent István University, Gödöllő, 61–81. (in Hungarian with English summary)

Farkas Cs. (2007): Extension of the validity of a soil water balance simulation model for intensively tilled soils with time-dependent soil physical properties. [HNSF Project Report No. 042996.] RISSAC HAS, Budapest.

Farkas Cs., Majerčák J. (2007): Soil water storage under conventional and soil conserving tillage practices. In: Németh T., Koós S. (eds): Role of Soil, Plant and Water Analysis in Multifunctional Agriculture. Abstracts of the ISSPA Conf., June 11–15, 2007, Budapest, RISSAC HAS, Budapest, 175.

Farkas Cs., Randriamampianina R., Majercak J. (2005): Modelling impacts of different climate change scenarios on soil water regime of a Mollisol. Cereal Research Communications, **33**: 185–188.

Flachner Zs., Fonyó Gy., Koncsos L. (2004): Dynamic modelling for water retention based floodplain management at Bodrogköz. Hungary. In: Verhoeven J.T.A., Turner R.E. (eds): Proc. 7th INTERCOL Int. Wetland Conf., 2004, Utrecht University, Utrecht. (CD-ROM)

Haskett J.D., Pachepsky Y.A., Acock B. (2000): Effect of climate and atmospheric change on soybean water stress: a study of Iowa. Ecological Modelling, **135**: 265–277.

IPCC (2001): Climate Change. 3rd Assessment Report. Cambridge University Press, New York.

IPCC (2007): Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., Miller H.L. (eds)). Cambridge University Press, Cambridge, New York.

Kovács G., Dunkel Z. (1997): Expectable results of the climate change on the Hungarian arable land. In: Dunkel Z. (ed.): Climate Changes and their Consequences. Proc. Meteorológiai Tudományos Napok, November 20–21, 1997, Budapest, Hungarian Meteorological Service, Budapest, 181–193. (in Hungarian)

Kroulík M., Hůla J., Šindelář R., Illek F. (2007): Water infiltration into soil related to the soil tillage intensity. Soil and Water Research, **2**: 15–24.

Láng I., Csete L., Harnos Zs. (1983): Agro-ecological Potential of Hungarian Agriculture. Mezőgazdasági Kiadó, Budapest. (in Hungarian)

Nakicenovic N., Swart R. (eds) (2000): IPCC Special Report on Emissions Scenarios. Cambridge University Press. Available at: http://www.grida.no/climate/ipcc/emission/index.htm.

Sirotenko O.D., Abashina H.V., Pavlova V.N. (1997): Sensitivity of the Russian agriculture to changes in climate, CO2 and tropospheric onzone concentration and soil fertility. Climate Change, **36**: 217–732.

Štekauerová V., Nagy V., Kotorová D. (2006): Soil water regime of agricultural field and forest ecosystem. Biologia, **61** (Suppl. 19): S300–S304.

Szabolcs I., Várallyay Gy. (1978): Limiting factors of soil fertility in Hungary. Agrokémia és Talajtan, **27**: 181–202.

Szőllősi I. (2003): Relationship between the soil penetration resistance and soil water content, measured on a loamy soil using 3T SYSTEM equipment. Agrokémia és Talajtan, **52**: 263–274.

Tóth B., Makó A., Rajkai K., Marth P. (2006): Study the estimation possibilities of soil hydraulic conductivity. Cereal Research Communications, **34**: 327–330.

Van Dam J. (2000): Field-scale water flow and solute transport. [Ph.D. Thesis.] Wageningen University.

van Genuchten M.Th. (1980): A closed-form equation for predicting the hydraulic conductivity of unsaturated soil. Soil Science Society of America Journal, **44**: 892–898.

Várallyay Gy. (1973): A new apparatus for the determination of soil moisture potential in the low suction range. Agrokémia és Talajtan, **22**: 1–22.

Várallyay Gy. (2000): Risk assessment and prevention of soil degradation processes in Hungary. In: Cottam M.P., Harvey D.W., Pape R.P., Tait J. (eds): Foresight and Precaution, Balkema, Rotterdam, 563–567.

Várallyay Gy. (2004a): Soil as a fundamental medium of agro-ecosystems. AGRO-21 Füzetek, **37**: 50–70. (in Hungarian)

Várallyay Gy. (2004b): Agro-ecology and water management. AGRO-21 Füzetek, **37**: 33–49. (in Hungarian)

Várallyay Gy. (2005): Water storage of Hungarian soils. Agrokémia és Talajtan, **54**: 1–8. (in Hungarian)

Wösten J.H., Finke P.A., Jansen M.J. (1995): Comparison of class and continuous pedotransfer functions to generate soil hydraulic characteristics. Geoderma, **66**: 227–237.

Corresponding author:

Dr. Csilla Farkas, Research Institute for Soil Science and Agricultural Chemistry of the Hungarian Academy of Sciences (RISSAC), Herman Ottó str. 15, Budapest, 1022 Hungary
tel.: + 36 1 2243652; fax: + 36 1 2243640; e-mail: csilla@rissac.hu