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Impact of expected climate change on soil water regime under different vegetation conditions

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Abstract: A mathematical model was applied for the Bükk Mountains (Hungary) to evaluate the effects of climate change on soil water balance elements and soil water regime. Model runs using SWAP model were performed for combinations of four distinctive soil types and three land use systems of arable land, grassland, and forest. The temporal variation of soil water regime under changing climatic conditions was examined considering no land cover change occurring in the future. The climate data consisted of the predictions of two regional climate models, the Swiss CLM and the Swedish RCA. The RCA results showed 45% to 50% and the CLM showed 5% to 14% higher future precipitation outlook compared to present conditions. Considering different land use types, the projected number of days with soil moisture deficit was the highest in forest ecosystems for both the upper 50 cm soil layer and the whole soil profile, which could be as high as 61% of days below optimal soil water content range. Our results showed increased water fluxes, especially in deep percolation in far future period and a strong influence of soil properties on the changes in the climate model results, indicating significant long–term effects of climate change on soil water regime.

Key words: climate change; land use; soil water regime; SWAP model

Introduction

The effects of climate change have been in the focus of many research efforts in recent years. Increase in annual mean temperature and changes in precipitation amounts in mid to high latitudes were observed since the start of the 20th century (Easterling et al. 2000). One of the major concerns in potential climate change is the changes in precipitation amounts and distribution that can alter soil water regime in the terrestrial subsurface affecting ecosystem functioning as well. Many studies predict changes in the amount and temporal variation of rainfall by 2100 (Stern 2007; Heinrich & Gobiet 2011; Kjellström et al. 2010); therefore soil water regime changes are inevitable (Trnka et al. 2013).

Water and carbon cycling, productivity of agricultural lands, mainly arable cropping systems, grasslands, and forests can be greatly affected by the altered rainfall and temperature (Olesen & Bindi 2002; Kurukulasuriya & Rosenthal 2003; Zachos et al. 2008). For instance, the hot and dry period in summer 2003 over Europe caused by a long lasting anticyclonic situation, which is one of the most studied extreme events, caused a Europe-wide drop in ecosystem productivity (Black et al. 2004; Moser et al. 2011).

The main aspects determining land use types or vegetation cover in a certain region are the agro–climatic conditions and land resources (Fischer et al. 2005). One of the most important and often most limiting resource for the vegetation is the water content in soil. However, plants also play a major role in forming the soil water regime. The interaction among vegetation and soil conditions highlights the importance of understanding possible changes in the atmosphere – plant – soil system forced by altered atmospheric conditions.

Grasslands and forests play a significant role in maintaining water retention capacity of the soil compared to cultivated lands (Fu et al. 2000). Forested areas are often in focus due to their role in soil erosion control and their carbon sequestration capacity. Their effect on water retention in the soil-plant system and on soil water regime (Lichner et al. 2013); however, has not been often studied in prospects of the climate change impacts. As water retention capacity and water regime of soils have strong impact on surface runoff generation

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and erosion processes, it is important to highlight their sensitivity to climate change.

Impact studies are essential ways to understand more deeply the studied process and estimate the potential effect of the changing climate. These studies are mostly based on a model, which describes a biophysical system. Model simulations are widely used and unique tools for risk assessment, planning of adaptation measures and scenario analyses to assess the combined effects of land use, agricultural practices, and climate change on soil and water quality (Even & Parkin 1996; Hanel et al. 2012; Mori et al. 2013; Nikodem et al. 2013; Jian et al. 2014). Process-based models, describing physical processes of the investigated system have the ability to simulate variables under altered future conditions, supposing that the current physical relations remain valid under changing conditions. The main input of these models is the meteorological data for the future. In order to estimate the meteorological conditions in the future climate model results could be used (IPCC 2007). However, direct use of Regional Climate Model (RCM) outputs is limited by systematic er-

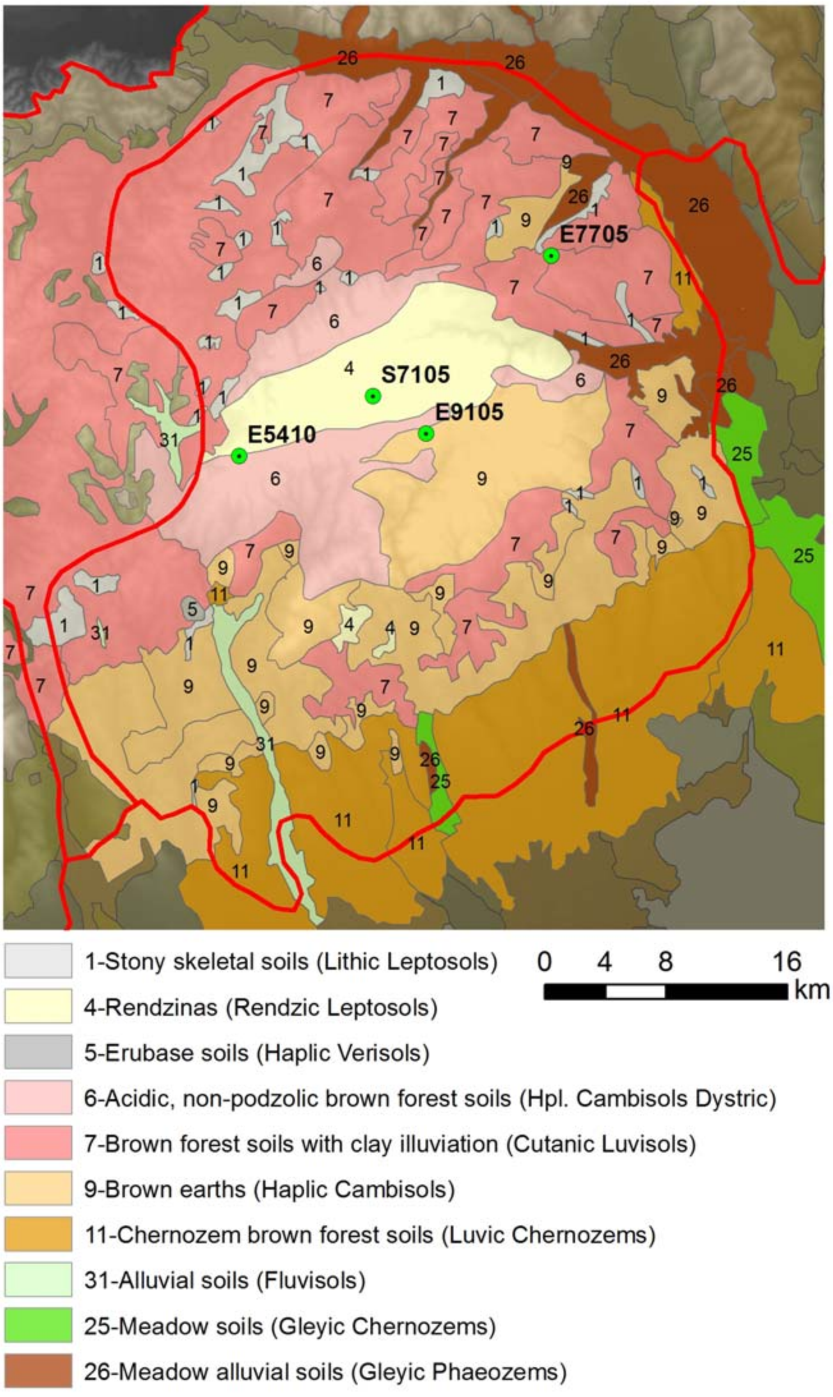

Fig. 1. Location of study sites and soil types in the area.

Table 1. Measured soil properties and the calculated van Genuchten–Mualem parameters of the four reference soil profiles. OM stands for organic matter content.

Soil profile ID	Soil type	Depth	OM	Sand	Silt	Clay	Bd	WC_R	WC_S	alpha	n	K_s
			Measured soil properties					van Genuchten – Mualem parameters				
		cm	%				g cm^{-3}	v%		cm^{-1}	–	cm day^{-1}
E5410	Haplic. Cambisol Dystric	0–120	5.5	45	39	15	1.14	1.7	45.0	0.0080	1.563	59.3
E7705	Cutanic Luvisol	0–4	7.5	32	37	31	1.46	5.3	44.8	0.0188	1.164	9.3
E7705		4–29	1.6	28	36	36	1.46	4.3	44.9	0.0359	1.172	66.5
E7705		29–79	0.7	28	31	41	1.23	4.2	53.7	0.0320	1.198	86.2
E7705		79–129	0.2	38	29	33	1.36	4.2	48.7	0.0242	1.192	79.7
E7705		129–150	0.2	33	31	36	1.28	4.5	51.4	0.0088	1.223	80.3
E9105	Haplic Cambisol	2–12	6.4	20	61	19	1.38	2.0	41.3	0.0053	1.66	19.0
E9105		12–40	2.6	19	50	31	1.49	3.2	41.6	0.0084	1.502	6.1
S7105	Rendzic Leptosol	0–25	5.5	5	72	23	1.3	4.5	47.4	0.0059	1.615	20.8
S7105		25–55	3.5	4	61	35	n.a.	0.0	48.0	0.0087	1.488	10.7

rors inherently present in the simulation results due to uncertainties in parameterization and model structure (Varis et al. 2004; Christensen et al. 2008). Fortunately, these systematic errors are quite stable in time (Maraun 2012), thus the errors are not causing problems if only the expected changes are examined. However, problems may arise when such data are to be used for climate change related impact study, which generally requires realistic daily meteorological data.

Such data may be unusable for impact studies, which typically need unbiased climate data as the models are sensitive to biases in the driving meteorological data (Baigorria et al. 2007; Teutschbein & Seibert 2010). The assumption that systematic errors in the past are equally propagated to the future (Maraun 2012) allows for using various bias correction methods (Ines & Hansen 2006; Li et al. 2010; Piani et al. 2010; White & Toumi 2013). Because of the well recognized importance of such corrections, in this study we paid special attention to this issue. We used weather data from the FORESEE (Open Database **FOR** Climat**E** Change-Related Impact **S**tudies in C**E**ntral **E**urope) database, which contains bias corrected RCM data.

In the present study, a model-based evaluation of the effects of the projected climate change on water balance elements and water regime of the soil-plant system for different soil types in the mountainous Bükk area of the Carpathians was carried out. The Bükk area is an important study area due to its mountainous soil characteristics, which has presently limited studies available. This region can also provide valuable information for projected climate change effects in areas where uncertainties in climate model predictions are relatively high.

Material and methods

Site description

The Bükk Mountains are situated in Northern Hungary (midpoint 48°05′ N, 20°30′ E) and have two main parts: the uplifted Central Part of the Mountains (highest point at 959 m above Bsl) built up from limestone (called Bükk karst Plateau) and the surrounding hilly regions built up mainly from shale and sandstone. For the present study, four soil survey sites were chosen in the area (Fig. 1). Measured data were used for soil properties retrieved from a soil survey database for the chosen sites. Each selected site has different soil types, which were selected to provide a better representation of the investigated system as a whole.

The karst surface is a part of the Bükk National Park protected area, covered by forest and grasslands. At this location, under a thin silt loam or silty clay loam surface layer, the limestone appears in the subsurface, resulting shallow soils with extreme water regime (Rendzic Leptosols, site ID S7105). Hence, the shallow soil saturates very fast during rainfall events, but dries rapidly due to evapotranspiration and percolation to limestone and karst systems, as there is no water supply from deeper layers. The edges of the Plateau and the higher regions are covered by brown forest soils (Cutanic Luvisols – site ID E7705 and Cambisols, site IDs E9105 (Haplic Cambisols), E5410 (Hpl. Cambisols Dystric)), with clay loam or silt loam surface layer (Table 1). The current land cover is grassland within a spontaneous shrubbing area for the S7105 site and forest for the other three.

Model description

The SWAP (Soil–Water–Atmosphere–Plant) simulation model (version 2.2; van Dam 2000), developed in Wageningen UR, the Netherlands, was selected to simulate water movement in the soil. The SWAP model is a mathematical model that calculates soil water balance elements (evaporation, transpiration, deep percolation, surface runoff, interception etc.), integrated at daily time step. It employs the Richards' equation (Richards 1931; Feddes et al. 1978) to calculate the soil water movement in the soil matrix. The soil hydraulic functions are described by the analytical expressions of van Genuchten (1980) and Mualem (1976) or in table format from measured values. Root water extraction at various depths of the root zone was calculated from potential transpiration, root length density, and possible reductions due to wet, dry or saline conditions (van Dam 2000). At the lower boundary of the soil profile, different kind of boundary conditions can be specified, including free drainage or zero flux at the bottom of the profile, pressure head of bottom compartment or given groundwater level (van Dam 2000). The model input data requirements were (i) soil profile data; (ii) weather data, and iii) vegetation data.

Model setup – Soil profile data

Soil profile data for the four selected sites recorded in the Soil conservation Information and Monitoring System (SIMS; Várallyay 2009) were used. The van Genuchten–Mualem parameters, characterizing the soil hydraulic functions (the soil water retention curve and the soil hydraulic conductivity function) were obtained using the RETC (RETention Curve) software (van Genuchten et al. 1991). The calculations were performed based on measured water contents at pF values of 0, 2.5, 4.2 and 6.2 (data not shown) for each layer of each soil profiles.

Detailed soil data and the van Genuchten parameters for the four soil profiles selected are given in Table 1. Where WC_R and WC_S stand for the residual and saturated soil water contents, respectively, α and n are the van Genuchten parameters and K_s is the saturated hydraulic conductivity. The α parameter of the soil hydraulic conductivity function was set to –1.

Weather data

Weather data requirements of the SWAP model include daily minimum and maximum temperature, solar radiation (SR, W m^{-2}), vapor pressure (VP, kPa), precipitation (P, mm), wind (u, m s^{-1}) or optionally potential evapotranspiration. In this study, we used available weather data for the study sites and used the SWAP model to calculate potential evapotranspiration.

Daily air temperature and precipitation data representing the present and future climate were derived from the 1/6 × 1/6 degree resolution FORESEE database. The FORESEE database (http://nimbus.elte.hu/FORESEE/, developed at the Department of Meteorology, Eötvös Loránd University Hungary) is based on the model results of the ENSEMBLES (http://ensembles-eu.metoffice.com/) project and contains bias-corrected climatological data (Dobor et al. 2012). It also provides continuous dataset for the period from 1951 to 2100, characterizing climate variables by one common reference dataset for the past (1951–2009) and eight different climate model runs for the future (2010–2100) considering A1B (balanced energy use among the energy sources) emission scenario (IPCC 2000).

In order to decrease processing time, two of the ten climate models were selected for the present water balance studies. The choice was based on the highest and lowest average change in precipitation and temperature they are predicting, using climatic diagrams (thermopluviograms) for the years of 2021–2050 (near future) and 2071–2100 (far future) time periods (not shown). Note that an earlier study using the climate model outputs showing the least extreme changes suggested only moderate changes in soil water regime (Gelybó et al. 2012). In order to further explore the uncertainty range of simulated impacts of climate change on soil water regime it is important to include extreme model results in the study. Using this approach, we do not explore the full uncertainty range of the results of the impact study but we can retrieve an estimation of this uncertainty. We chose the CLM and the RCA regional climate models (driven by the HadCM3Q0 and the ECHAM5 global climate models respectively), as they were the ones projecting the largest deviation from the present climate in the study area. The CLM and the RCA models are the regional climate models of the ETHZ (Swiss Federal Institute for Technology Zurich) and of the SMHI (Swedish Meteorological and Hydrological Institute), respectively.

Table 2. Summary of expected averages of annual mean temperature and precipitation total for the investigated periods.

Climate input	Mean Temp. (C)	Mean Precip. (mm)
REF	10.7	760
CLM_near	13.8	923
CLM_far	15.6	864
RCA_near	12.6	1202
RCA_far	14.8	1195

The annual average temperature and precipitation characterizing the investigated time periods presented in Table 2. In this study CLM model results represent the "drying" scenario, which for the Carpathian areas suggests decrease in precipitation. The RCA results represent the "wet" scenario where increase in precipitation is projected.

Considering the topography of the region it is important to correct meteorological data for slope and exposure of the site. We used the MT–CLIM mountain climate simulator (Numerical Terradynamic Simulation Group, University of Montana; Thornton and Running, 1999) to derive corrected meteorological variables required by the SWAP model. Because there was no exact wind data available for the study sites, wind speed was assumed and kept at constant 3.0 m s^{-1}. For the simulations, data in the closest FORESEE pixel were considered in representing daily meteorological conditions in the vicinity of the selected soil profile of the SIMS database. Meteorological variables were estimated from daily minimum and maximum temperature and precipitation data at the FORESEE pixel as base site with regard to the geographical characteristics of the mountain site such as elevation, latitude, aspect, and slope. Elevation of the base site was obtained as spatial average through the corresponding FORESEE pixel. Geographical characteristics of the mountain site and the base were retrieved from a 10 m horizontal resolution digital elevation model, came from digitized 1:10,000 topographic maps of the region.

Vegetation data

The simple crop routine of SWAP was applied. The crop parameters are shown in Table 3.

Initial and boundary conditions

Initial conditions in the model were set to field capacity in the soil profile for each soil types. The reasoning behind this was that the capillary pores usually saturated with water during autumn and stay saturated till the beginning of next year, thus, the water content of the soil corresponds to field capacity. Each 30 year simulation periods starts January 1. The error caused by this assumption in the initial conditions tends to disappear rather quickly during the model runs, so any incorrectness in the initial conditions most likely did not influence the 30-year model run results.

The upper boundary conditions, i.e. daily water and heat fluxes entering the soil surface during the simulation period, were calculated by the model from meteorological driving variables. Considering the slope conditions, water ponding on the soil surface was not allowed. Thus, the

Table 3. SWAP model crop parameters for various land use systems.

Parameter			Land use		
Code	Description	Unit	Grass	Forest	Arable
LCC	Length of the crop cycle	days	365	365	147
KDIF	Extinction coeff. for diffuse visible light	–	0.60	0.73	0.60
KDIR	Extinction coeff. for direct visible light	–	0.75	0.73	0.75
HLIM1	Pressure head below which roots start to extract water from the soil	cm	–2.5	0.0	0.0
HLIM2U	Pressure head below which roots start to extract water optimally from the upper soil layer	cm	–10.0	–1.0	–1.0
HLIM2L	as HLIM2U, but for all soil layers	cm	–10.0	–1.0	–1.0
HLIM3H	Pressure head, below which roots cannot extract water optimally any more, if high atm. Demand	cm	–1000.0	–700.0	–800.0
HLIM3L	Pressure head, below which roots cannot extract water optimally any more, if low atm. Demand	cm	–10000.0	–1000.0	–1500.0
HLIM4	Pressure head below which no water uptake by roots is possible	cm	–36000.0	–16000.0	–20000.0
GCTB	Leaf Area Index (LAI, ha/ha) as a function of crop development stage (CDS, -)	CDS	LAI	LAI	LAI
		0.00	3.0	5.6	0.2
		0.69		6.0	
		0.83		8.0	
		1.00	3.0		4.0
		1.50		8.0	
		1.67		6.0	
		2.00	3.0	5.6	0.5
CHTB	Crop height (CH, m) as a function of crop development stage (CDS, -)	CDS	CH	CH	CH
		0.0	0.1	35	0.1
		1.0	0.1	35	0.8
		2.0	0.1	35	0.8
SCTB	Soil cover fraction (SC, -) as a function of crop development stage (CDS, -)	CDS	SC	SC	SC
		0.0	0.8	1.0	0.0
		1.0	0.8	1.0	0.8
		2.0	0.8	1.0	0.7
RDTB	Rooting depth (RD, cm) as a function of crop development stage (CDS, -)	CDS	RD		
		0.0	15.0	200.0	10.0
		1.0	15.0	200.0	130.0
		2.0	15.0	200.0	130.0

amount of water that could not infiltrate in the soil assumed to leave as surface runoff.

The lower boundary conditions consist of daily water fluxes at the bottom of the soil profile. In case of all profiles, free drainage lower boundary conditions were set, as this is typical for well–drained forest soils of mountainous areas.

Evaluation of the results

We supposed that physically based soil hydrological models incorporating the existing knowledge on physical processes are able to describe the impact of climate, as a main driving force on soil hydrology.

Soil water balance elements were examined on daily time steps for 30–year long subperiods. The 1981–2010 period was selected to characterize the present state of local climate (reference period, REF), the 2021–2050 period was considered as near future (RCA_near and CLM_near), and the 2071–2100 period as far future (RCA_far and CLM_far). In these time periods, model results were examined and compared in case of 3 land cover types of arable (A), grass (G), and forest (F) over four different soil types.

Climate change can have a significant effect on soil hydrology, where available water for plant use can be altered. In this study, we tried to rank land use-soil type combinations according to their sensitivity to climate change. We defined that favorable effect of land use types are related to the ecosystem service of the soil to provide water to plants. According to this criterion any change in soil hydrology is favorable if it means more plant available water, and unfavorable if it leads to less water for plant uptake.

All the water regime characteristics used during the evaluation were presented as relative values compared to the reference ones, e.g. the water balance characteristics calculated for the present climate. Using such an approach, systematic errors occurring could be avoided.

For evaluation of soil water regime the following metrics were used (given in cm, as annual sums): expected gross and net rainfall (RAIN), potential evapotranspiration (PET_{pot}); actual evapotranspiration (ET); potential evaporation (from soil surface, EVS_{pot}); actual evaporation (EVS_{act}); potential transpiration (root water uptake or plant demand); TRA_{pot}); actual transpiration (TRA_{act}); deep percolation (amount of water leaving the entire profile; $FLUX_{bot}$). Among the soil water regime, we did not investigate water runoff in details because we mainly focused on soil water flux processes. The model parameters were set to have an elevated land surface where water could not accumulate. In this study, we present all investigated soil hydrological parameters as averages of the SWAP results governed by the two climate model outputs also indicating the higher and lower uncertainty of the estimates.

To characterize climate-induced changes in soil water regime we selected several indicators, which were calculated for the upper 50 cm soil layer and for the whole soil profile as weighted averages of the indicator values corresponding to the different soil layers. Critical soil water contents (CWC), below which the plants cannot extract water from the soil optimally, correspond to water potentials of 10^{-3} cm of water column (w.c.) (grass and winter wheat) and -10^{-4} cm (forest). Field capacity (FC) was defined as the volumetric water content at water potential of –336 cm. Based on the simulated soil water contents (SWC) at daily resolution, we calculated the number of days with relatively dry (CWC $\geq$ SWC), wet (SWC $>$ FC), and optimal soil water (CWC $<$ SWC $\leq$ FC) status for the present and future climate conditions.

Results and discussion

Changes in climatic factors

The most important factors of the predicted climate change are the change in temperature and precipitation. Atmospheric and subsurface increase in temperature can directly influence soil water balance.

In this study we examined the effect of climate change on water regime of forest soils in the Bükk Mountains (Hungary) in case of different land use types. The Carpathians are situated in one of the most uncertain geographical areas in Europe regarding the future climate. The European region can anticipate an increase in annual precipitation totals in the northern parts of Europe and a decrease in southern parts (Christensen & Christensen 2007), while the Carpathian region might experience no precipitation change on the annual basis. This projection, however, is associated with high uncertainties and seasonal variations (Giorgi & Lionello 2008; Bartholy et al. 2011).

According to our results based on the FORESEE database, changes in climate conditions in the near and far future projected by the CLM model show increase in the range of 4–12% in the amount of rainfall, while the RCA scenario predicts a much substantial increase in rain amount with approximately 44–45% compared to the REF period (Table 4). This result is not contradicting with previous projections for the region. A regional climate model (RCM) mini-ensemble experiment, carried out using 4 different RCMs for the 2021–2050 and 2071–2100 period (Krüzselyi et al. 2011), suggested precipitation increase in the winter period and decrease in spring and summer seasons by the end of the 21th century for the Carpathian Basin, while the annual totals are likely to slightly decrease (Krüzselyi et al. 2011). However, considering the uncertainty of this 4-member ensemble, no change or even small increase can also occur in total annual precipitation (Krüzselyi et al. 2011). These findings are also supported by observed past trends in annual precipitation. Based on the interpolated, homogenized surface database of the Hungarian Meteorological Service, observed trends of annual precipitation amount show a decrease with uneven spatial distribution for Hungary since 1901, where the biggest decrease occurred in spring (Lakatos & Bihari 2011). We have chosen our study site in this transitional area in consideration of soil profiles characteristically representative of the Bükk mountainous areas.

When the precipitation amount and consequently soil properties deviate from the usual, plant growth is being affected (Olesen & Bindi 2002). It has been reported that with warmer climate the growing season can get longer and has already been supported by observation (Tucker et al. 2001). With the increased length of the growing season, new environmental risks can be forming. The longer growing season can change in agricultural management practice of using different crop types, and/or multiple cropping. However, this new system can also have negative impact on soil quality e.g. inorganic nitrogen build up from in additional fertilizer use in the agricultural soil systems that would increase the risk of nitrogen leaching (Olesen & Bindi 2002).

The effect of climate change – Water balance elements

Some of the most important components of soil water balance include precipitation, runoff, evaporation, transpiration, and drainage. Different types of plants need different amount of water that essentially extracted by its roots from soil moisture (Monteith 1965). From the plant's perspective, the main water balance components are the evaporation, transpiration and deep percolation, which determine the amount of water available for plant uptake, therefore these water fluxes are distinctively examined in the present study. As it can be expected, with the projected increase in precipitation amounts, intensity of water fluxes increase; however, according to the SWAP model results, the components of the water balance do not increase proportionally. We examined the suggested changes in case of the four different soil types and three land use combinations.

As it can be expected, potential water fluxes (occurring under theoretical ideal conditions of unlimited water supply) barely differ among sites. These fluxes are basically determined by atmospheric boundary conditions, mostly temperatures, which are the same in case of all sites. Therefore we focused on actual water fluxes, which are determined by the actual weather parameters and reflect the differences among hydraulic propertied of the examined soil types.

Amongst the investigated water balance elements, the biggest relative change is predicted in deep percolation, which is projected to increase for both future periods (2021–2050 and 2071–2100) and all land use types with somewhat larger values in far future (Fig. 2a). The least pronounced relative change is expected in the case of arable soil type, where 169% (± 28%) to 186% (± 36%) increase in water flux is expected at the study sites for near future and 175% (± 38%) to 204% (± 66%) change for far future (Fig. 2a). The largest increase in relative deep percolation is the most probable in forest soil types with 280% (± 59%) to 298% (± 66%) increase in for near future and 341% (± 93%) to 395% (± 149%) change for far future periods (Fig. 2a). For arable vegetation, both the near and far future changes in deep percolation are fairly similar, suggesting that bottom flux in cultivated soils are less sensitive to changes in precipitation. In all soil types under grass vegetation the rate of deep percolation has approximately doubled in the near future, which further increased in the far future period.

The increasing water flux downwards (deep percolation) can accelerate the process of leaching in the profiles. In case of forest soils, the more intensive leaching in long term may result in complete depletion of base cation and decrease in pH values in soils (Krug & Frink 1983). For example, Farkas et al. (2013) found that not only sediment loss can be expected by increasing precipitation amount, but also important nutrients leaching as well. On arable lands, the intensity of surface evaporation varies with the cultivation method and vegetation period of the crop. The evaporation and/or transpiration rate (outgoing flux on the top of the soil profile) may reach or exceed the infiltration rate (incoming flux on the top of the soil profile) during certain period of the year, reducing the flux of percolating water in the profile (outgoing flux on the bottom of the soil profile).

Actual evaporation data show similar future trends for both arable and forest types of vegetation with model results in the closest agreement in case of forest (Fig. 2b). In case of grass, the average simulated change in actual evaporation is somewhat close to the REF data in the far future, suggesting moderate changes; however, this tendency is preceded with elevated evaporation values at near future (Fig. 2b). When the different soil types are being compared to each other under same vegetation type, the actual evaporation values have similar trends under arable and forest soil types. Under grass vegetation the E5410 and E7705 soil profiles have a slight decrease in far future actual transpiration values, while the E9105 and S7105 showed increased values compared to the REF period (Fig. 2b).

Actual transpiration in general shows an increase in near future; however, the relative change became less pronounced when far future is being considered (Fig. 2c). Compared to REF data, the largest increase in actual transpiration is shown under forest vegetation in case of all soil types, while the arable type of vegetation can even experience a decrease in transpiration values in the far future period (Fig. 2c). This can be due to the area of the canopy and leaves, which can increase the additional surface, consequently enhancing

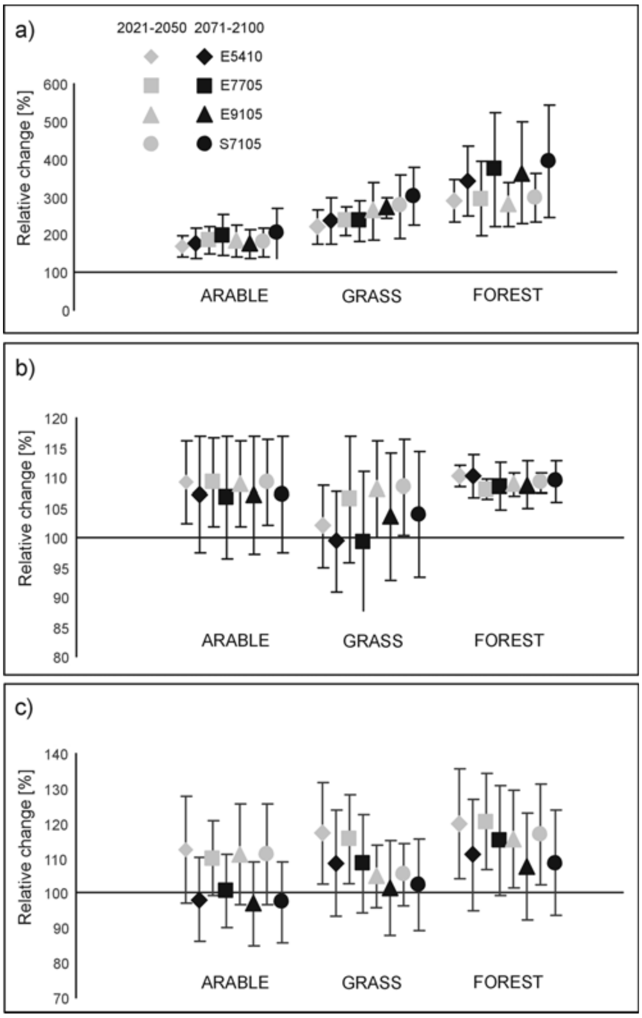

Fig. 2. Projected overall near and far future changes in a) deep percolation, b) evaporation and c) transpiration in relevance to REF data. TRA_{act} – actual transpiration (%); EVS_{act} – actual evaporation (%); $Flux_{bot}$ – amount of water, leaching downward from the soil profile (%). Error bars represent SD values.

transpiration (Kelliher et al. 1993). The figure also reveals that there are substantial differences among soil profiles. Under grass vegetation the E5410 and E7705 soil profiles showed increase in far future transpiration values; however, the E9105 and S7105 showed similar values as the REF period (Fig. 2c). These changes most probably can be attributed to the soil particle size distribution, as the E5410 and E7705 soil profiles have higher percent of sand particles (45% sand, 39% silt and 32% sand, 33% silt in average for the whole profile, respectively) compared to E9105 and S7105 where the silt and clay content are higher (20% sand, 55% silt and 4% sand, 66% silt, respectively). Soils with different particle size distribution have different hydraulic properties as well, such as hydraulic conductivity, which is higher for a sandy soil than a silty or clayey one (Rawls et al. 1982).

Table 4 presents results governed by the two climate models separately, but averaged across soil types. In case of simulations governed by the RCM data, due to extensive precipitation increase, an overall intensification in all main fluxes of water balance elements

Table 4. Relative changes in the yearly sums of the water balance elements (in % compared to the REF period), calculated for various climate scenario and land use combinations and averaged over the different soil types. For definition of water balance elements see text.

Climate dataset	Land use	$Rain_{gr}$	TRA_{pot}	TRA_{act}	EVS_{pot}	EVS_{act}	$Flux_{bot}$
		%	%	%	%	%	%
CLM_near	arable	112	104	93	104	102	155
	forest	112	107	102	104	108	268
	grass	112	109	98	99	96	216
CLM_far	arable	104	108	82	109	97	150
	forest	104	117	94	108	106	285
	grass	104	118	90	104	89	240
RCA_near	arable	145	99	118	100	117	234
	forest	145	99	131	100	111	427
	grass	145	103	120	95	112	354
RCA_far	arable	144	107	104	106	117	257
	forest	144	111	124	105	114	598
	grass	144	113	117	101	109	360

can be expected (Table 4). However, in case of CLM data the direction and degree of changes do not show such an agreement. Deep percolation is still indicated to increase, while the change in evaporation is only moderate in all the cases: the CLM results predicted only small precipitation increase, e.g. EVS_{act} is projected to slightly increase in forest but decline in grasslands (93% of the reference period) and arable land (97% of REF) in the far future (Table 4). Apparently, transpiration – strongly influenced by both soil and plant conditions – is the water flux that is most influenced by the expected precipitation amounts; in case of the CLM results it declines in all three land use types in the far future compared to REF (data not shown). The water potentials of plant leaves depend on water potentials of bulk soils, and change in transpiration values can induce a stress in the plants that negatively influence photosynthetic capacities (Sharkey 1984).

Soil water regime

The estimation of future soil water contents showed that most of the days were within the optimal soil water content range except in case of the E7705 site under arable conditions, where days above critical water content (51–75%) preceded the number of optimal days (16–32%); however, under forest and grass vegetation, these ratios are more favorable with 27–43% and 29–60%, respectively (data not shown). Site E7705 has the highest hydraulic conductivity measured below the root zone (> 66.5 cm d^{-1}), which highly influences water flow through the soil matrix. At the same time E7705 has the highest clay content (36%). Based on the amount of days in the optimal moisture range, the best condition was found at the E9105 site with at least 58% of days were within the critical margins for the first 50 cm soil depth. For the far future period, model results show an increase compared to the near future in the number of dry days, where the critical water content has not been met (Table 5). In general, the RCA 'wet' projections have substantially less dry days and more CWC days than CLM models, which represent the lower precipitation increase scenario in the study, which resulted in higher numbers of optimal days in most RCA simulations.

The number of days with optimal soil water content is drastically decreasing in case of arable lands and increasing in case of forests in the future projections (Table 5). This implies the favorable effect of forests in regulating soil water regime, although, grasslands also show increasing number of optimal days in the future periods as possible vegetation type. For the agricultural cultivation perspective, the arable land use type is the least suitable for future land type at the study area based on soil water characteristics.

In general, number of dry days is the highest in forest ecosystems regarding both the upper 50 cm soil layer as well as the whole soil profile (data not shown). The lowest number of dry days is projected in case of arable lands, with grasslands in between the two in both models and periods. A similar tendency was observed in case of wet days, but with less agreement in case of different climate model outputs (Table 5). However, only with one exception, model runs provided the lowest number of wet days in forests, highest in arable, and grasslands in the middle. Number of optimal days is less consistent but overall the lowest in forests regardless of climate model run or period.

Conclusions

According to the climate model results used in this study, more precipitation could be expected in the short term, while decrease in the rain amount (but still an increase compared to the reference period) was projected on the long term in the Carpathian Basin. Our results showed intensified water fluxes in case of the wet scenario, and a strong influence of soil properties on the changes.

Table 5. Relative frequency (in percentage) of days when the upper 50 cm of the soil and the whole soil profile are in dry, wet or at water conditions close to the optimal SWC.

		Upper 50 cm layer				Whole soil profile			
Climate Scenario	Land use	Dry days (%)	Wet days (%)	Days with optimal soil water content (%)	Average soil water content (v%)	Dry days (%)	Wet days (%)	Days with optimal soil water content (%)	Average soil water content (v%)
REF	arable	22	1	81	24	22	1	80	24
	forest	49	4	50	20	53	1	50	19
	grass	38	7	59	22	30	6	68	22
CLM_near	arable	24	16	60	26	23	15	62	26
	forest	36	10	54	23	36	6	58	22
	grass	28	4	68	25	21	11	68	25
CLM_far	arable	29	14	57	25	27	13	60	25
	forest	43	9	48	21	45	5	50	21
	grass	37	10	53	23	29	10	61	24
RCA_near	arable	12	20	68	29	11	19	70	29
	forest	21	14	65	25	21	11	68	25
	grass	14	15	71	28	10	16	74	28
RCA_far	arable	17	20	64	28	16	18	66	28
	forest	28	14	59	25	28	10	62	24
	grass	20	15	65	27	16	15	69	27

Decrease in precipitation is associated with less volume of percolating rainwater in the soil profile and consequently less intensive leaching process. The contiguous forest vegetation cover inhibits the surface evaporation; however the water consumption of forests can cause greater volume of water loss in the soil. In dry periods on cultivated lands the rate of evapotranspiration may exceed the precipitation during significant intervals of the year, and may result intensive precipitation of transported elements in the subsurface layers, which in long term may lead to limited vertical movement of water in the soil profile.

We conclude that the effect of climate change on soil water regime and water balance is basically determined by soil type and vegetation cover and more research is required to further explore the interactions between soil, land cover, and climatic factors.

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