The impact of climate change on soils and on their water management

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Abstract. Human activities result in changes in the global environment, sometimes with severe consequences for our future life. Changes in the gas composition of the atmosphere – partly due to CO_2 and 'greenhouse gases' emission – may lead to a rise in temperature with high spatial and temporal variability, to alterations in the global circulation processes, and to a serious rearrangement of atmospheric precipitation, increasing aridity in some locations. These modifications are reflected sensitively by ecosystems (natural vegetation and land use pattern) and by considerable alterations in soil formation and degradation processes, in soil properties and soil functions.

The potential impacts of the forecasted climate change reservoirs are briefly summarized in the present paper with special regard to soil water management, soil moisture regime and their influences on the main soil degradation processes. Based on this analysis, conclusions are drawn regarding the possibilities of sustainable soil moisture and the required measures of rational control: increasing water use efficiency; reducing evaporation, surface runoff, seepage and filtration losses; increasing water storage capacity and available moisture range of soils.

Key words: climate change, soil formation and degradation processes, infiltration, water storage capacity, soil moisture control

INTRODUCTION

Human activities are leading to changes in the global environment at virtually unprecedented rates, with potentially severe consequences to our future life. The study and solution of the problems of the predicted global environmental changes require urgent and efficient actions. This crucial task formulates a challenge for science: to describe, understand and control the interactive physical, chemical and biological processes that regulate the Total Earth System, the unique environment for life (Scharpenseel et al., 1990; Lal et al., 1994; Rounsevell & Loveland, 1994).

CLIMATE CHANGE AND ITS ENVIRONMENTAL CONSEQUENCES

In the last 150–200 years considerable changes have taken place in the *gas composition of the atmosphere* due to natural processes and human activities, such as increasing energy consumption, industrialization, intensive agriculture, urban and rural development. This may lead to a *rise in global temperature* and high spatial and temporal variability. The changing temperature regime would result in considerable changes in the *precipitation pattern.*

If, temperatures rise, as forecasted, an increasing number of mountain glaciers, the permafrost soil zone and the polar ice caps will melt. This would lead to changes in the water flow dynamics, including flood waves and surface runoff, resulting in a *rise of the eustatic sea level,* threatening low-lying, man-protected lands, settlements, agricultural areas, and extended seashores with low slope. Another consequence would be the further extension of salt-affected territories under the direct effect of sea water inundations or due to the rise of the sea level-connected water table of saline or brackish groundwater (Scharpenseel et al., 1990; Szabolcs, 1990; Várallyay, 1994).

A changing climate will result in considerable changes in *natural vegetation* and in *land use practice*s. These changes in turn result in a feedback effect on climate: modified albedo, surface roughness, micro-circulation processes, the heat and energy balance of the near-surface atmosphere, and the temperature and precipitation pattern considerably influence the field water cycle and soil formation/degradation processes.

The potential impacts of climate change are schematically summarized in Fig. 1 (Várallyay, 1998, 2002, 2007, 2009a; Harnos & Csete, 2008; Várallyay & Farkas, 2008).

IMPACT OF CLIMATE CHANGE ON SOIL PROCESSES

Climate change and its hydrological consequences may result in the significant modification of soil conditions. The impact analysis of *potential* future changes is rather difficult, due to the uncertainties in the forecast of global and long-term temperature and precipitation patterns (including their spatial and temporal variability) combined here with the changing hydrological cycle and the complex and integrated influences of natural vegetation and land use pattern (partly due to the changes in the socio-economic conditions). Consequently the long-term and global '*soil change prognosis'* can only be a rather rough, sometimes imaginative estimation and allows only for the drawing of general conclusions.

In the natural *soil formation processes* the pedogenic inertia will cause different time-lags and response rates for different soil types developed in various regions of our globe (Scharpenseel et al., 1990; Lal et al., 1994; Rounsevell & Loveland, 1994).

In Fig. 2, two examples are presented on the impact of four potential climate scenarios on two important soil processes as the *texture differentiation* in the soil profile and on the soil *organic matter cycle* (Brinkman & Brammer, 1990; Scharpenseel et al., 1990

The influence of climate change on *soil structure* (type, spatial arrangement and stability of soil aggregates) is a more complex process. The most important direct impact is the aggregate-destructing role of raindrops, surface runoff and filtrating water, especially during heavy rains, thunderstorms and even 'rain bombs', the increasing hazard, frequency and intensity of which are characteristic features of climate change. The indirect influences are caused by changes in the vegetation pattern and land use practices.

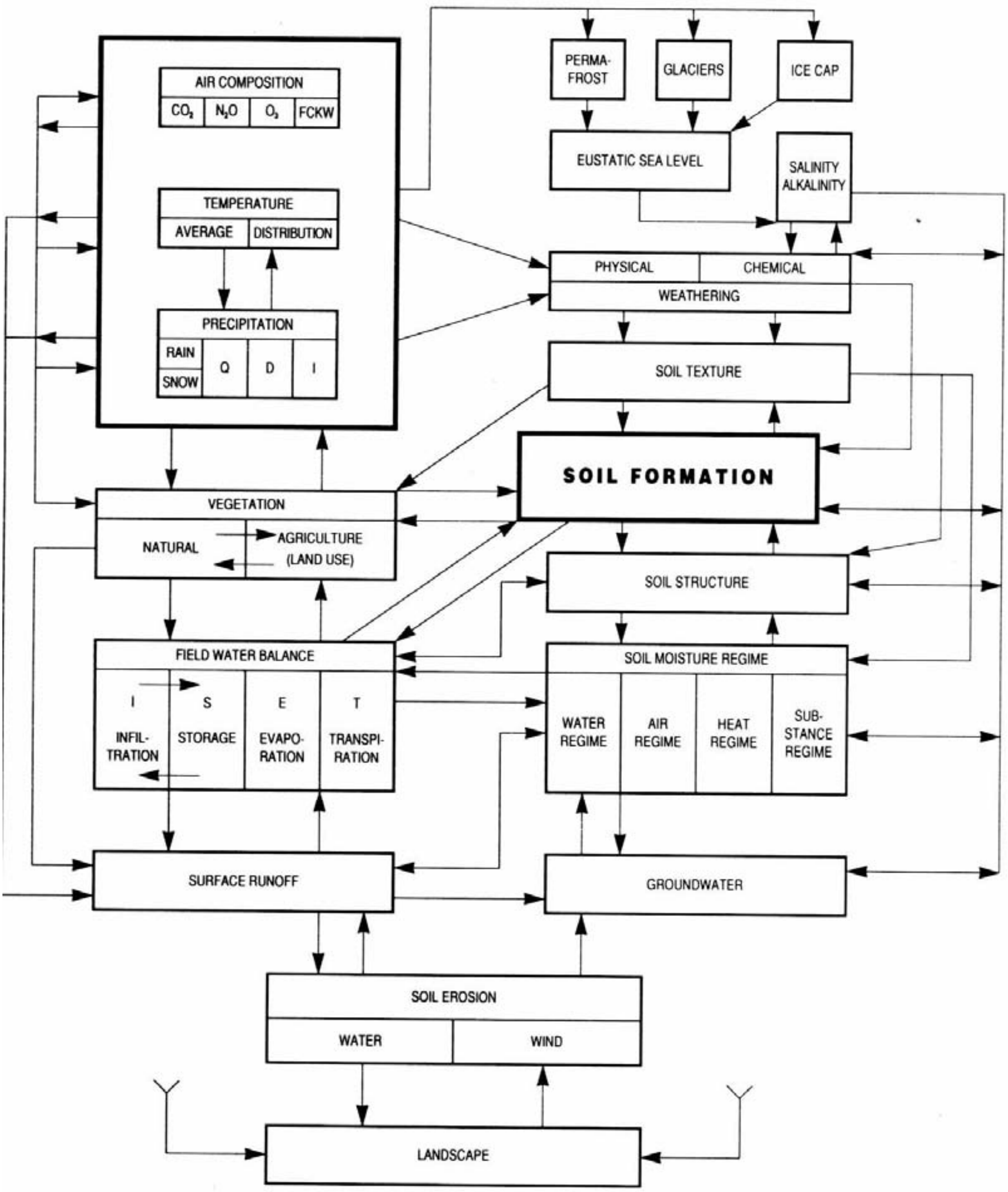


Figure 1. The potential consequences of climate changes on agro-ecosystems.

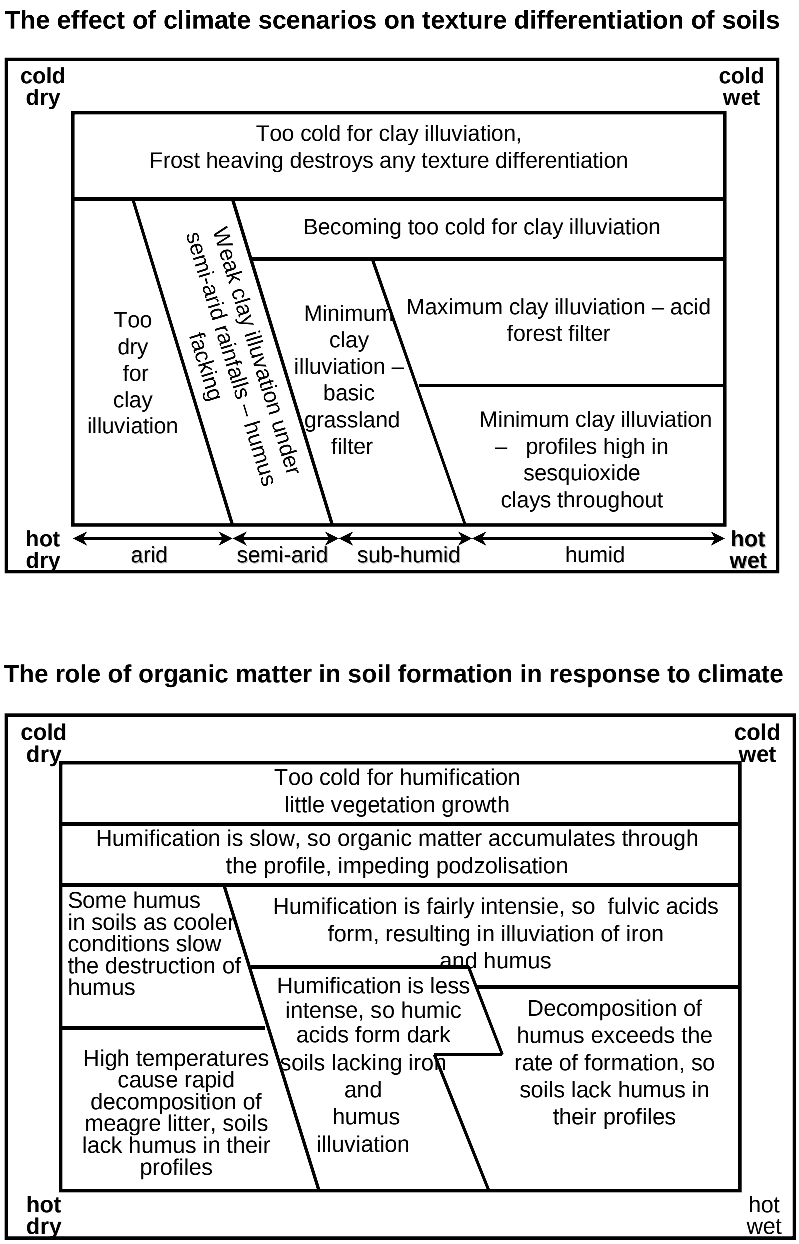
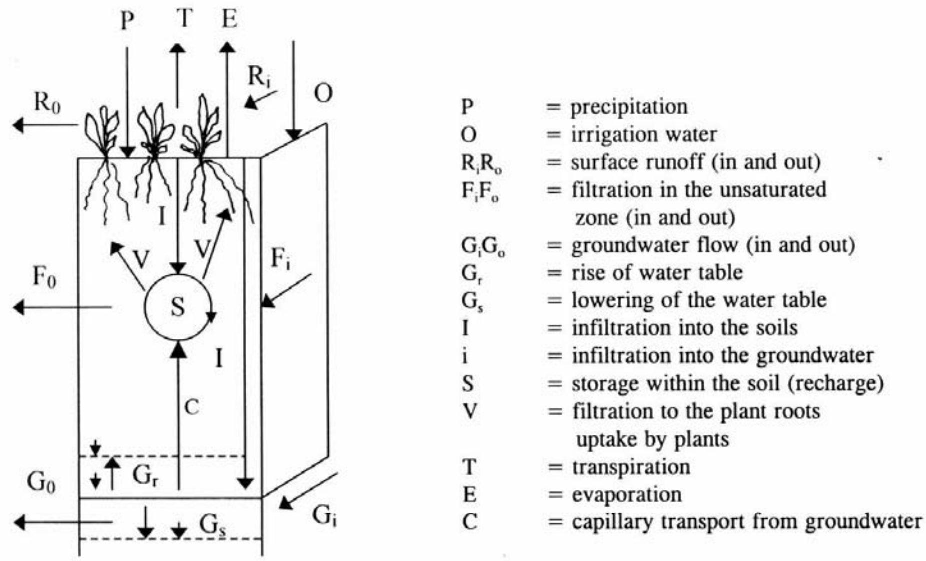


Figure 2. The effect of four potential climate scenarios on texture differentiation and organic matter regime.

IMPACT ON THE SOIL MOISTURE REGIME

The integral influence of climate–hydrology–vegetation–land use changes are reflected by the *field water balance* and *soil moisture regime* (Várallyay, 1990a,c; Farkas et al., 2008; Várallyay & Farkas, 2008). Their components and the potential impact of four plausible climate change scenarios on these factors are summarized in Fig. 3.



Factors	Cl			
	Cold, wet	Cold, dry	Hot, wet	Hot, dry
P	I	D	I	D
R	I	d,D	I	D
G	i	d	i	D
I	I	d	I	D
I	i	D	(i)	D
S	I	d	(I)	D
E	D	E	E	I
T	D	E	i	I
F	-	-	-	-
G_r	i	-	(I)	-
G_s	-	I	-	I

Figure 3. Components of the field water balance and soil moisture regime and the influence of four potential climate scenarios on these factors: i and I: slight and great increase; d and D: slight and strong decrease; E: no change (equilibrium).

As an example: The rise in **temperature**

– increases the potential E and T, if the plant canopy is not suffering from limited water supply due to climate or soil-induced drought, e.g. low precipitation or limited water storage capacity;

– decreases R, I, S and G, especially if accompanied by low precipitation;
– moderates the unfavourable hydrological consequences of frost and quick snowmelt (→ waterlogging hazard) giving more opportunity for water penetration.

The decrease in atmospheric *precipitatio*n will result in a decrease in

– water infiltration (I) and water storage (S) in the soil; and plants' water supply;
– surface runoff (R) in hilly lands with undulating surfaces, consequently water erosion hazard (but increasing the risk of wind erosion for dry surfaces);
– filtration losses and groundwater recharge (G); and will increase
– evaporation losses;
– the rate of transpiration (if the vegetation or crop canopy has not deteriorated due to water deficiency);
– drought sensitivity with its physiological, ecological and environmental consequences.

These direct influences are modified with the impact of vegetation characteristics (type, density, dynamics, species composition, biomass production, litter and root characteristics). Man's influence is still more complex. Land use, cropping pattern, agrotechnics, amelioration (including water and wind erosion control, chemical reclamation, irrigation and drainage) and other activities sometimes radically modify the field water balance and its components. This fact offers possibilities for the elaboration of efficient measures for adaptation to the predicted climate change scenarios preventing, or at least moderating their unfavourable consequences (Láng, 2006; Várallyay, 2007; Birkás, 2008; Harnos & Csete, 2008).

An example: Application to the Carpathian Basin

The natural conditions of the Carpathian Basin are *generally favourable for rain-fed biomass production.* These conditions, however, show extremely high, irregular, and consequently hardly predictable spatial and temporal variability, often extremes, and react sensitively to various natural or human-induced stresses.

According to the meteorological/hydrological/ecological forecasts the risk, probability, frequency, duration and intensity of extreme meteorological (thunderstorms, high intensity rains, hail) and hydrological (floods, waterlogging, over-moistening vs. droughts) events will increase in the future and their unfavourable consequences (safety of biomass production for food, industrial raw material and alternative energy) will be increasingly serious, sometimes catastrophic. Consequently in the Carpathian Basin these irregular, hardly predictable extreme events, rather than long-term global tendencies, will be the most important climate change consequences!

Under such environmental conditions it is an important fact that in the Carpathian Basin *soil is found the largest potential natural water reservoir*. The 0–100 cm soil layer may store more than half of the average annual precipitation (500–600 mm). About 50% of it is 'available moisture content'. This favourable finding is quite contrary to the high and increasing number of "double-face' water stress situations. In many cases, however, this huge water storage capacity is not being used efficiently, because (Farkas et al., 2008; Várallyay & Farkas, 2008; Várallyay, 2009a) of the following:

– pore space is not „empty", it is filled up to a certain extent by a previous source of water (rain, melted snow, capillary transport from groundwater, irrigation etc.): *„filled bottle effect";*

– the infiltration of water into the soil is prevented by the frozen topsoil: *„frozen bottle effect”;*
– the infiltration is prevented or reduced by a nearly impermeable soil layer on, or near to the soil surface: *„closed bottle effect”;*
– the water retention of soil is poor and the infiltrated water is not stored in the soil, but only percolates through the soil profile: *„leaking bottle effect”*.

Under such conditions the risk reduction of climate change-induced extreme hydrological events and soil moisture stresses consists of the following three soil moisture management elements:

– reduction of evaporation, surface runoff and filtration losses;
– increase of the available moisture content of the soil: to help infiltration into the soil, increase the water storage capacity; reduce the immobile moisture content;
– improving of the vertical and horizontal drainage conditions of the soil profile or the given area (prevention of over-saturation and waterlogging).

The possibilities and potential methods (technologies) for an efficient soil moisture control are summarized in Table 1, indicating their – mostly positive – environmental impacts (Birkás, 2008; Várallyay & Farkas, 2008; Várallyay, 2009a).

Table 1. Elements and methods of soil moisture control with their environmental impacts.

Elements		Methods	Environ-mental impacts*
Reducing	Surface runoff	Increase in the duration of infiltration (moderation of slopes; terracing contour ploughing; establishment of permanent and dense vegetation cover; tillage; improvement of infiltration; soil conservation farming system)	1,1a 5a,8
	Evaporation	Helping infiltration (tillage, deep loosening) Prevention of runoff and seepage, water accumulation	2,4
	Feeding of ground-water by filtration losses	Increase in the water storage capacity of soil; moderation of cracking (soil reclamation); surface and subsurface water regulation	5b,7
	Rise of the water table	Minimization of filtration losses (↑); groundwater regulation (horizontal drainage)	2,3 5b,5c
Increas-ing	Infiltration	Minimization of surface runoff (tillage practices, deep loosening) (↑)	1,4,5a, 7
	Water storage in soil in available form	Increase in the water retention of soil; adequate cropping pattern (crop selection)	4,5b,7
Irrigation		Irrigation; groundwater table regulation	4,5c,7, 9,10
Surface / Subsurface } drainage		Surface / Subsurface } moisture control (drainage)	1,2,3,5c, 6,7, 11

* Referring numbers: See below

Favourable environmental effects		Unfavourable environmental effects
Prevention, elimination, limitation or moderation of:		
1. water erosion 1a. sedimentation 2. secondary salinization, alkalization 3. peat formation, waterlogging, over moistening 4. drought sensitivity, cracking	Plant nutrient losses by: 5.a. surface runoff (→ surface waters eutrophication) 5 b. leaching (→ subsurface waters) 5.c. immobilization 6. formation of phytotoxic compounds 7. 'biological degradation' 8. flood hazard	9. overmoistening, water-logging, peat and swamp formation, secondary salinization/alkalization 10. leaching of plant nutrients 11. drought sensitivity

IMPACT OF CLIMATE CHANGE ON SOIL FERTILITY AND SOIL DEGRADATION PROCESSES

Climate change may have stronger or weaker, permanent or periodical, favourable or unfavourable, harmful (sometimes catastrophic), primary (direct) or secondary (indirect) impact on soil processes. Among these processes soil moisture regime plays a distinguished role. It determines the water supply of plants, influences the air and heat regimes, biological activity and plant nutrient status of soil. In most cases it determines the agro-ecological potential, the biomass production of various natural and agro-ecosystems and the hazard of soil and/or water pollution (Fig. 4.).

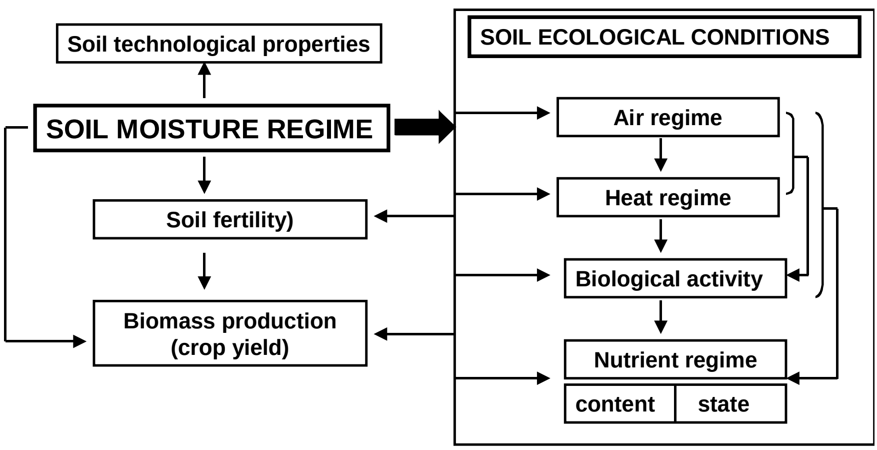


Figure 4. The relationships between soil moisture regime, other soil ecological conditions and soil fertility.

In Fig. 5 the potential impact of four main plausible climate scenarios on the most important soil degradation process are summarized, indicating their determining natural and anthropogenic factors (Szabolcs, 1990; Várallyay, 1990b, 1994, 2002).

Soil degradation processes	Soil	Climatic scenarias					Causative factors	
		Cold and Dry	Cold and Wet	Hot and Dry	Hot and Wet		Natural	Antrop
Soil erosion by water	E	4	1	4	1		1,2,3	9,10,11,12
Soil erosion by wind	D	3	4	2	4		3	9,10,11,12
Acidification	A	3	1	4	1		2,4	13,15
Salinization/Alkalization	S	2	4	1	4		5,6,8	14
Physical degradation	P	3	2	2	1		-	10,12
Extreme moisture regime (water logging)	M	4	1	4	2		5,6,7	11,12,14
Biological degradation	B	3	2	2	1		-	11,16
Unfavourable nutrient regime	N	3	2	2	1		(2,6)	13
Soil pollution (toxicity)	T	4	3	3	4		-	16

1 Strong 2 Medium 3 Slight 4 No or negligible

CAUSATIVE FACTORS:

Natural

1. Undulating surfaces
2. Parent rock
3. Lack of permanent and dense vegetation
4. Litter decomposition
5. Low-lying lands
6. Improper drainage
7. High water table (non saline)
8. High water table (saline)

Antropogeneous

9. Deforestation
10. Overgrazing
11. Irrational land use
12. Improper tillage practices
13. Irrational fertilizer application
14. Improper irrigation
15. Acid deposition
16. Chemical soil pollution

Figure 5. The influence of four main climatic scenarios on the main soil degradation processes, and their natural and anthropogenic causative factors.

The primary and secondary impacts of climatic change on various soil degradation processes are as follows:

a) Soil erosion. There are no linear relationships between mean annual precipitation, surface runoff and the rate of denudation/erosion. The rate, type and extension of *soil erosion* depends on the combined influences of climate (primarily the quantity and intensity of rainfall), relief, vegetation (type, continuity, density), and soil erodability characteristics. The main influences of potential climate changes on soil erosion are as follows:

– higher precipitation, especially intensive rainfalls and thunderstorms, may result in an increasing rate of erosion ($\rightarrow$ higher runoff), if it is not balanced by the increasing soil conservation effect of more dense and permanent vegetation due to better water supply;
– lower precipitation generally reduces the rate of erosion, but it can be counterbalanced by the poorer vegetation due to moisture limitations;
– lower precipitation may intensify wind erosion.

b) Acidification. Decreasing precipitation may reduce downward filtration and leaching. Climate determines the dominant vegetation types, their productivity, the decomposition rate of their litter deposits, and influences soil reaction in this indirect way.

c) Salinization/sodification. A consequence of the expected global 'warming' is the rise of eustatic sea level: increase of inundated territories (especially in the densely populated delta regions and river valleys), and the areas under the influence of sea water intrusion.

Higher precipitation ($\rightarrow$ increasing rate of downward filtration $\rightarrow$ leaching) will reduce, lower precipitation and higher temperature will intensify salinization/ sodification processes: higher rate of evapo(transpi)ration $\rightarrow$ increasing capillary transport of water and solutes from the groundwater to the root zone + no or negligible leaching. This salt accumulation, however, can be balanced by the sink of groundwater table (due to the negative water balance: $G_o > G_i + ET$) in low-lying, poorly drained, depressed lowlands (evaporative basins, i.e. the Carpathian lowlands) where the main salt source is the shallow saline/brackish groundwater.

Similar tendencies are expected for the leaching or accumulation of carbonates, which may lead to the formation of compact carbonate accumulation (petrocalcic) horizons.

d) Structure destruction, compaction. The most important direct impact is the aggregate-destructing role of raindrops, surface runoff and filtrating water (see earlier). The indirect influences act through the vegetation pattern and land use practices.

e) Biological degradation. Temperature, precipitation and vegetation changes considerably influence biological soil processes, but few data are available on these consequences.

f) Unfavourable changes in the biogeochemical cycles of plant nutrients and pollutants. These processes are closely connected with the soil moisture regime and with the abiotic and biotic transformation phenomena (fixation, immobilization – release, mobilization; changes in solubility and redox status, etc.). High precipitation increases leaching, filtration losses ($\rightarrow$ potential groundwater „pollution") and reductive processes. Low precipitation ($\rightarrow$ dry conditions) may reduce the solubility, mobility and availability of available elements and compounds.

CONCLUSIONS

Due to many uncertainties in 'global' climate changes (direction, rate, seasonal and geographical distribution) and in the prediction of their environmental, ecological, economical and even social consequences, more detailed, integrated multidisciplinary studies are required to give an exact scientific basis for the adaptation or mitigation of the unfavourable consequences of climate change, following the 'old slogan': 'Think globally and act locally!'

REFERENCES

Birkás, M. 2008. Environmentally-sound adaptable tillage. Akadémiai Kiadó. Budapest. 351 pp.

Brinkman, R., & Brammer, H. 1990. The influence of a changing climate in soil properties. In: *Trans. 14th ISSS Congress, Kyoto,* 1990. V. pp. 283–287.

Farkas, Cs. et al. 2008. A chernozem soil water regime response to predicted climate change scenarios. *Soil and Water Research.* **3** (Special Issue, 1), 558–567.

Harnos, Zs. & Csete, L. (eds.) 2008. Climate change: environment–risk–society. Research results. (In Hungarian) Szaktudás Kiadó Ház. Budapest. 380 pp.

Lal, R. et al. (eds.) 1994. *Soil Processes and Greenhouse Effect.* CRC Lewis Publishers, Boca Raton. 440 pp.

Láng, I. 2006. Global climate change: Hungarian impacts and reactions.. In*: Summarization of the VAHAVA Project*, coordinated by the Ministry of Environmental Protection and Rural Development and the Hungarian Academy of Sciences, Budapest. (In Hungarian)

Rounsevell, M. D. A. & Loveland, R. J. (eds.) 1994. *Soil Responses to Climate Change.* NATO ASI Series I: Global Environmental Change. Vol. 23. Springer-Verlag. London. 312 pp.

Scharpenseel, H. W., Schomaker, M. & Ayoub, A. (eds.) 1990. *Soils on a Warmer Earth.* Elsevier, Amsterdam, 274 pp.

Szabolcs, I. 1990. Impact of climatic change on soil attributes. Influence on salinization and alkalinization. In: Scharpenseel, H. W., Schomaker, M. & Ayoub, A. (eds.) *Soils on a Warmer Earth.* Elsevier. Amsterdam pp. 61–69.

Várallyay, Gy. 1990a. Influences of climate changes on soil moisture regime, texture and erosion. In: Scharpenseel, H. W., Schomaker, M. & Ayoub, A. (eds.) *Soils on a Warmer Earth.* 39–49. Elsevier, Amsterdam.

Várallyay, Gy. 1990b. Consequences of climate induced change in soil degradation processes. In: *Trans. 14th ISSS Congress, Kyoto.* V. pp. 265–270.

Várallyay, Gy. 1990c. Potential impact of climate change on soil moisture regime and soil degradation processes. In: *Proc. Int. Sem. Future Research Trends in MAB,* Tokyo, Japan, 20-29 Aug, 1990, pp. 256–267.

Várallyay, Gy. 1994. Climate change, soil salinity and alkalinity. In: Sounsevell, M. D. A. & Loveland, R. J. (eds.) *Soil Responses to Climate Change.* NATO ASI Series. Vol. **23**, pp. 3–11. Springer-Verlag, London.

Várallyay, Gy. 1998. Climate change and soil processes. In: *Proc. Int. Conf. on 'Agriculture and forestry – adaptability to climate change'.* Acad. Sci. and Art, Zagreb, Croatia. pp. 5–16.

Várallyay, Gy. 2002. Climate change and soil processes. *Időjárás.* **106** (3–4), 113–121.

Várallyay, Gy., 2007. Potential impacts of climate change on agro-ecosystems. *Agriculturae Conspectus Scientificus*. **72** (1), 1–8.
Várallyay, Gy., 2009. The impact of climate change on soils and on their water management. Abstract Volume. Symposium and 3rd Training Course 'Climate change: challenge for training of applied plant scientist. Impact of climate change on crop production'. 'Agrisafe' (Martonvásár, 7–11 Sept, 2009). Agricultural Research Institute of HAS, Martonvásár. pp. 6–15.
Várallyay, Gy. & Farkas, Cs. 2008. Impact of climate change on soils in Hungary. In: *Climate change: environment–risk–society. Research results.* (In Hungarian) (Eds.: Harnos, Zs. & Csete, L.) Szaktudás Kiadó Ház. Budapest. pp. 91–129.