Potential Impacts of Climate Change on Agro-ecosystems

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Summary

Human activities lead to changes in the global environment at virtually unprecedented rates, with potentially severe consequences to our future life. Changes in the gas composition of the atmosphere – as the consequence of CO_2, CH_4 and other "greenhouse gases" concentration rise – may lead to a rise of temperature with heterogeneous spatial and temporal distribution, to alterations in the global circulation processes, and to a serious rearrangement in atmospheric precipitation, in some places to increasing aridity. These modifications are reflected sensitively by ecosystems, manifested by the changes in natural vegetation and land use pattern with considerable alterations in soil processes and – consequently – in soil properties and soil functions.

Key words

climatic scenarios, soil formation processes, soil moisture regime, soil degradation processes, agro-ecosystems

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Introduction

Various anthropogenic activities have different positive or negative, predictable or surprising primary, secondary or tertiary impacts on the environment, including the "quality" (or at least tolerability) of human life. The study and solution of the problems of global environmental changes require urgent, well-coordinated and efficient actions. The three most important criteria of the quality of life are:

– secure supply with healthy and good quality food;
– availability of clean water;
– pleasant environment.

All three depend strongly on climate and weather conditions and are closely related to the sustainable management of natural resources, to rational land use and soil management and to landscape preservation (Várallyay, 2003). These crucial tasks formulate a challenge for science: to describe and understand the interactive physical, chemical and biological processes that regulate the Total Earth System, the unique environment for life (Committee on Global Change, 1988).

Climate change

In the last century considerable changes took 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. The CO_2 concentration, which was about 180–200 ppm after the last glaciation and 270 ppm in early industrial times rose up to the present 320–350 ppm, amounting to an approx. 25–30% increase during the last 100–120 years. Similar tendencies were registered for other main "greenhouse" gases (CH_4, NO_x, carbohalogenides) as well (Scharpenseel, 1990).

This may lead to a rise in global temperature with a rate of 0.1–0.8 °C per decade. The spatial and temporal patterns of temperature increases will be heterogeneous and are expected to be the greatest in the northern mid-continent region of North America and Eurasia. The various Global Circulation Models (GCMs) predict an increasing rate of temperature rise from the Equatorial to the Polar regions; and relatively higher temperature increase during summer, and lower during winter periods in both hemispheres. These predictions are still rather uncertain, because in addition to solar radiation the influences of circulation, changes in vapour content, cloudiness, albedo and surface roughness have to be evaluated more quantitatively (Rounsevell and Loveland, 1994; Scharpenseel et al., 1990).

The changing temperature regime pattern will be followed by considerable changes in precipitation characteristics: quantity of rain and snow, their spatial and temporal distribution pattern, rain intensity, etc. Their forecast is even more uncertain (IGBP, 1989). From the GCMs of the WMO World Climate Program it can be concluded that in the first period of the forecasted warming up the average global precipitation will decrease, with high spatial variability and considerable regional redistribution. But later these tendencies will be counterbalanced by the increasing evaporation from water surfaces, first of all from the World Oceans. The increasing evaporation leads to higher air humidity and – probably – more precipitation, again in more uneven spatial and temporal distribution, and with increasing frequency of heavy rainfalls and extreme weather events (droughts, storms, floods, etc.).

Consequences of climate change

Due to the increasing temperature an increasing part of the mountain glaciers, the permafrost soil zone and the Polar ice caps will melt. It leads to changes in the water flow dynamics, including flood waves and surface runoff. (Committee on Global Change, 1988). The melting of ice and the increasing volume of the warmer World Oceans will result in a rise of the eustatic sea level. Its magnitude is forecasted as 0.20-1.40 m by various authors (Szabolcs and Rédly, 1989; Várallyay, 1990a). This sea level rise threatens low-lying, man-protected lands, settlements, agricultural areas, and extended seashores with low slope. Another consequence will be the further extension of salt affected territories under the direct effect of temporal sea water inundations or due to the rise of the sea level-connected water table of saline or brackish groundwaters (Szabolcs and Rédly, 1989; Várallyay, 1994). The change of the sea level will also rise the erosion basis in the affected catchment area which may result in a non-significant reduction of the water erosion potential.

The changing climate will result in considerable changes in the natural vegetation and in land use practices (Greenland and Szabolcs, 1993; IGBP, 1989; Lal et al., 1994; Mayr et al., 1994). The great vegetation zones will move into the direction of the Poles, with a predicted rate of 25–200 km/100 years. Vegetation – in many cases – cannot tolerate and follow this „velocity" and it leads to considerable changes in the species distribution, dynamics, diversity and production capacity of various ecosystems, consequently, in their ecosystem functions. Land use practices will follow or modify the natural changes, depending on environmental and socio-economic conditions (Greenland and Szabolcs, 1993; Lal et al., 1994; Mayr et al., 1994).

Changes in the vegetation or land use pattern result in a feedback effect on climate, modifying albedo, surface roughness, micro-circulation processes, the heat and energy balance of the near-surface atmosphere, the characteristics of both temperature and precipitation. Vegetation

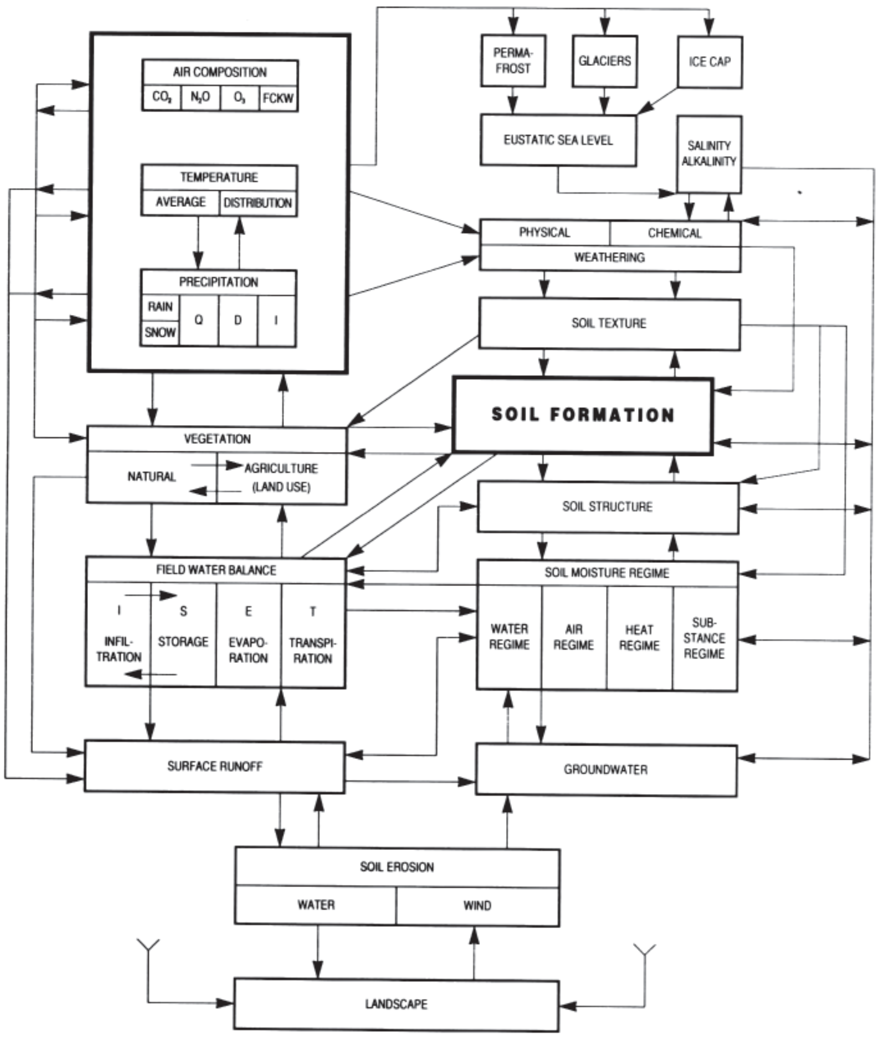


Figure 1.
The potential consequences of climate changes on agro-ecosystems

changes will considerably influence the field water cycle and soil formation processes (Lal et al., 1994).

Influences of climate change on soils and soil processes

Climate changes and their consequences will result in significant alterations in soil conditions (Brinkman and Brammer, 1990; Greenland and Szabolcs, 1994; Lal et al., 1994; Rounsevell and Loveland, 1994; Scharpenseel et al., 1990; Tinker and Ingram, 1994). These impacts and their relationships are summarized in Figure 1 (Várallyay, 1990a,b, 1994, 1998, 2002, 2005). The figure clearly indicates why the quantitative evaluation of the impact of any climate change on the soil conditions and soil processes is so difficult and far from being satisfactory. The uncertainties in the long-term global temperature and precipitation forecasts are combined here with the complex, integrated influences of changing vegetation and land use pattern and the changing hydrological cycle (partly due to the changes in socio-economic conditions). Consequently, the global soil change prognosis can only by a rough, qualitative – semi-quantitative estimation and allows only some rather general conclusions.

These general influences are modified with the impact of vegetation characteristics (type, density, dynamics, species composition, biomass production, litter and root characteristics), and depend greatly on the type, intensity, spatial and temporal distribution of atmospheric precipitation. 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 soil processes. In areas under agricultural utilization the influence of a global climatic change on the soil process is considerably affected through these human actions (Bradbury and Powlson, 1994; Greenland and Szabolcs, 1993; Lal et al., 1994; Mayr et al., 1994).

Soil processes and soil properties

In the soil formation processes pedogenic inertia will cause different time-lags and response rates for different soil types. Soil changes will be more rapid and profound in the younger or less weathered sediments of the glaciated or desert fringe region of the Northern Hemisphere and slower or less profound on the stable, continental shields of the equatorial region (Scharpenseel et al., 1990).

If temperature increases, a warming up of the Northern Eurasian and North American permafrost plains with their loamy to silty sediments, all the shallow, imperfectly to poorly drained soils of the tundra and the Northern boreal forest biomass, will be radically changed by the melting of huge amounts of ice. The peat soil of the polar and boreal zones will shrink and slowly disappear due to the increased rates of decomposition of the organic matter. The podzolized soils of the tundra and boreal forests, which are derived from (peri)glacial sands and coarse crystalline rocks will turn into more acid and more leached variants.

If precipitation increases, the heavy textured soils of present day tundra, boreal/and humid temperate regions (some Luvisols, Podzoluvisols) will develop gleyic features in their topsoil, turning them into pseudogleyic/stagnic variants (Brinkman and Brammer, 1990; Lal et al., 1994; Scharpenseel et al., 1990).

In Figure 2 two examples are illustrated on the impact of four potential climate scenarios on the texture differentiation in the soil profile and on the soil organic matter cycle.

The influence of climatic change on soil structure (type, spatial arrangement and stability of soil aggregates) is a more complex process with numerous direct and indirect impacts. The most important direct impact is the aggregate-destructing role of raindrops, surface runoff and filtrating water. The rate of structure damage depends on the intensity of the destroying factor and the stability of soil aggregates against these actions. The indirect influences act through the vegetation pattern and land use practices. The consequence of vegetation changes on soil structure can be both favourable (tundra → forest; forest → grassland) and unfavourable (desertification, waterlogging, salinity-alkalinity). The same is true for land use. The impact of over-grazing, irrational land use, misguided agricultural utilization (cropping pattern, crop rotation) and improper agrotechnics (heavy machinery, over-tillage, over-irrigation) is unfavourable, practically non-reversible and hardly correctable. However, rational land use, proper agrotechnics and amelioration practices may help the maintenance or restoration of good soil structure (Várallyay, 1990a).

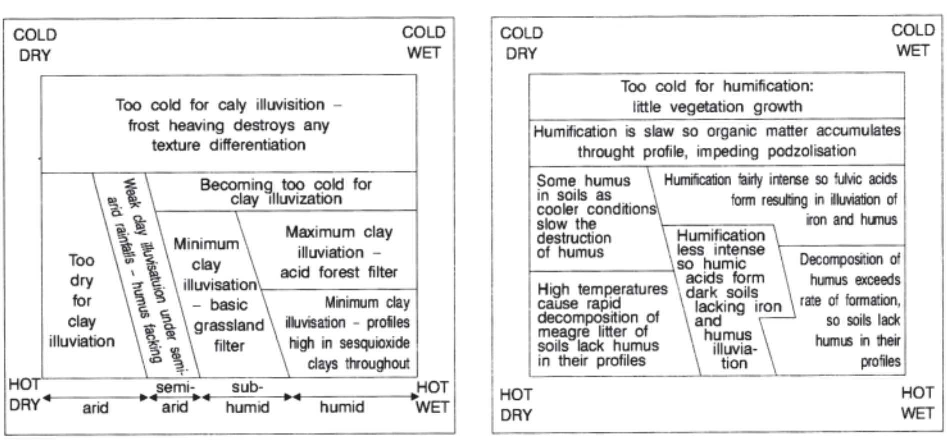
Moisture regime

The integral impact of climatic–hydrologic–vegetation–land use changes are reflected by the field water balance and soil moisture regime (Várallyay, 1990a,c). Their components and the potential impact of 4 plausible climate change scenarios on these factors are summarized in Figure 3.

An increase in *precipitation* will be followed by an increase of:

- surface runoff (R) in hilly lands with undulating surfaces and without permanent and dense vegetation, if the infiltration rate, permeability and water storage capacity of the soil are limited;
- infiltration (I) and water storage (S) within the soil if they are not limited, in flat lands;
- groundwater recharge (G) if the soil has good vertical drainage and permeability is not limited, especially in low-lying areas;
- evaporation (E), if infiltration is limited;
- transpiration (T) in the case of well-developed plant canopies.

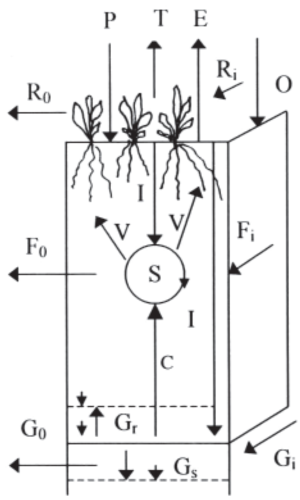
The decrease in precipitation results in adverse changes.



The effect of climate on texture differentiation in soils

The role of organic matter in soil formation in response to climate

Figure 2.
The effect of four potential climate scenarios on texture differentiation and organic matter (from IGBP Report No. 5., 1989)



P = precipitation
O = irrigation water
R_iR_o = surface runoff (in and out)
F_iF_o = filtration in the unsaturated zone (in and out)
G_iG_o = groundwater flow (in and out)
G_r = rise of water table
G_s = lowering of the water table
I = infiltration into the soils
i = infiltration into the groundwater
S = storage within the soil (recharge)
V = filtration to the plant roots uptake by plants
T = transpiration
E = evaporation
C = capillary transport from groundwater

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)

The rise in *temperature*

- increases the potential E and T, if the plant canopy is not suffering from limited water supply due to climatic or soil-induced drought, e.g. low precipitation or limited water storage capacity;
- decreases R, I, S and G, especially if it is accompanied by low precipitation;
- decreases the intensity (depth) of permafrost; it will modify the geographical boundaries of permafrost, opening possibilities for increasing water storage and water movement, biological activity and soil formation processes within the unfrozen part of the soil.

The decrease in temperature will result in adverse changes.

Soil degradation processes

Soil degradation is usually a complex process in which several features of soil deterioration can be recognized. Soil degradation may lead to the loss of land or soil; limitations in normal soil functions; decrease in soil fertility and „productive capacity" (Greenland and Szabolcs, 1993; Oldeman et al., 1991). Soil degradation may be the result of natural factors and/or human activities.

The main soil degradation processes are:

- soil erosion by water or wind;
- acidification development of extreme soil
- salinization/sodification reaction (and its consequences)
- physical degradation (structure destruction; compaction);
- extreme moisture regime (aeration problems, overmoistening, waterlogging, drought-sensitivity);
- biological degradation (decrease of biodiversity, the species spectra and biological activity);
- unfavourable changes in the nutrient regime (leaching, abiotic and biotic immobilization, etc.);
- decrease in buffering capacity; soil pollution, toxicity.

For the assessment of soil degradation a world-wide project was initiated by UNEP. In the framework of GLASOD (Global Assessment of SOil Degradation) a map was prepared in the scale of 1:10,000,000 on the present status and potential future development of the various human-induced soil degradation processes. The project was coordinated by ISRIC, Wageningen, The Netherlands (Oldeman et al., 1991).

Soil degradation processes	Soil	Climatic scenarias: Cold and Dry	Cold and Wet	Hot and Dry	Hot and Wet	Causative factors: 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 4. The influence of four main climatic scenarios on the main soil degradation processes, and their natural and anthropogenic causative factors

In Figure 4 an attempt was made to show the potential impacts of the four basic climatic scenarios on the main soil degradation processes. In the Figure their main natural and human causative factors were summarized, as well.

The direct and indirect, primary and secondary impacts of climatic change on various soil degradation processes can be summarized briefly, 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 starting point of a comprehensive erosion-risk assessment can be the rate of surface runoff or the sediment losses in the various major river basins.

The main influences of potential climatic changes on soil erosion are as follows (Lal et al., 1994; Várallyay, 1990a):

- higher precipitation may result in an increasing rate of erosion (→ higher runoff), if it is not balanced by the increasing soil conservation influences of better vegetation due to better water supply;
- lower precipitation generally reduces the rate of erosion, but it can be counterbalanced by the less intensive soil conservation influence of poor vegetation due to the non-adequate water supply for plants; this can be the consequence of increasing temperature, as well;
- lower precipitation (or higher temperature) may intensify wind erosion;
- increasing temperature may reduce the erosion hazard moderating the permafrost influence (limited infiltration rate and water storage capacity of the soil); but may considerably increase the erosion-risk reducing the snow:rain ratio in the cold regions and in high mountains.

b) Acidification

Increasing precipitation may intensify downward filtration and leaching, consequently may help acidification. Climate determines the dominant vegetation types, their productivity, the chemical character and decomposition of their litter deposits, and influences the development of soil reaction in this way (Brinkman and Brammer, 1990; Scharpenseel et al., 1990).

c) Salinization/sodification.

One of the well-pronounced consequences of the forecasted global "warming up" is the rise of eustatic sea level, as it was discussed earlier. In addition to this influence higher precipitation (→ increasing rate of downward filtration → leaching) will reduce, lower precipitation and higher temperature will intensify salinization/sodification processes: higher rate of evapo(transpi)ration → increasing upward capillary transport of water and water-soluble salts from the groundwater to the root zone + no or negligible leaching (Szabolcs, 1990; Várallyay, 1994).

Similar tendencies characterize the leaching and accumulation of carbonates, which may lead to the formation of compact and impervious hardpans, petrocalcic horizons.

The situation is quite different in areas in which the main salt source is the shallow, saline or brackish groundwater and the main reason of salinization/sodification is the capillary transport of salts from the groundwater to the overlying horizons or even to the active root zone. In such cases the sinking of the groundwater table due to increasing aridity will reduce the capillary transport and it may counterbalance or even decrease the risk of salinization/sodification.

d) Structure destruction, compaction

The most important direct impact is the aggregate-destructing role of raindrops, surface runoff and filtrating water. The rate of structure damage depends on the intensity of the destroying factor and the stability of soil aggregates against these actions.

The indirect influences act through the vegetation pattern and land use practices. The consequence of vegetation changes on soil structure can be both favourable (tundra → forest; forest → grassland) and unfavourable (desertification, waterlogging, salinity-alkalinity). The impact of over-grazing, irrational land use, misguided agricultural utilization (cropping pattern, crop rotation) and improper agrotechnics (heavy machinery, over-tillage, over-irrigation) is unfavourable, practically non-reversible and hardly correctable. On the contrary, rational land use, proper agrotechnics and amelioration practices may help the maintenance or restoration of good soil structure (Várallyay, 1990a).

e) Biological degradation, decline in biodiversity.

Temperature, precipitation and vegetation changes all considerably influence biological soil processes, but only a few data are available on these consequences (Arnold et al., 1990; Bradbury and Powlson, 1994; Davidson, 1994; Greenland and Szabolcs, 1993; Lal et al., 1994; Tinker and Ingram, 1994).

f) Unfavourable changes in the biogeochemical cycles and the plant nutrient regime.

One part of these changes is connected with changes in the soil moisture regime (the ratio between downward and upward water movement in the unsaturated zone; leaching – accumulation), another part is related to the abiotic and biotic transformation phenomena (fixation, immobilization – release, mobilization; changes in solubility and redox status; etc.) in the chemical-biological cycles of various elements (Bradbury and Powlson, 1994; Scharpenseel et al., 1990). High precipitation helps leaching, filtration losses (→ potential groundwater „pollution") and reductive processes; low precipitation → dry conditions may reduce the solubility, consequently mobility and availability of less soluble compounds.

Conclusions

Due to the many uncertainties in "global" climate changes (direction, rate, seasonal and geographical distribution) and – consequently – in the prediction of their environmental, ecological, economical and even social consequences more detailed, integrated multidisciplinary studies are required on the quantification of the existing facts and processes in the air–water–soil–geological deposits–plant continuum, for a more actual environmental forecast and for the preparedness of a rational control of Earth processes under various potential climate scenarios. Such an integrated multidisciplinary national program was initiated and implemented in Hungary by the Hungarian Academy of Sciences (Prof. Dr. I. Láng): VAHAVA (Láng, 2006). The main results of the project were and will be published soon and can be efficiently applicable for regions under similar physiographic conditions.

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