Working Paper and Preprint
90/3

SOILS ON A WARMER EARTH: THE TROPICAL REGIONS

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International Workshop on Effects of Climatic Change on Soil Processes
UNEP-Nairobi, 12-14 February, 1990

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SOILS ON A WARMER EARTH: THE TROPICAL REGIONS

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I INTRODUCTION

The greenhouse function of the earth's atmosphere can be described as the trapping of part of the thermal emission from the earth's surface, because of the presence of a number of gases. The most important greenhouse gases are water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and chlorofluorocarbons (CFC's). The greenhouse function is an essential part of the life support system of planet Earth. In its absence there would be no life as we know it, because mean global annual temperatures would be minus 18°C. An enhanced greenhouse function of the atmosphere, caused by anthropogenic increase of the above greenhouse gases, is commonly known as the GreenHouse Effect (GHE), or the Arrhenius Effect after its first postulator in 1896.

A definite increase since 1850 has been measured in the atmospheric concentration of CO_2 (from 290 to 345 ppm) and CH_4 (from 0.85 to 1.7 ppm). This has coincided with a trend to global warming of about 0.5°C (global mean annual near-surface temperature) in the period 1880-1990 (Hansen et al., 1981 and 1987). Part of this gradual increase, viz 0.2°C, has recently been ascribed to "urban warming" at some key observation points (Karl et al., 1988). The series of temperature measurements may also be misleading due to changes in the methods of ocean surface temperature measurements in the past hundred years (for instance a change-over from "bucket" to "engine" measurement of ocean surface temperature). Long-term measurements in parts of Europe (Scandinavia, Holland) show no increase at all or even a slight decrease in local temperatures over the period considered. At global level there is a peculiar interruption in the period 1940-1975 when a slight downward trend occurred. This may well be caused by changed solar activity (sun spots) as already mentioned in chapter 1; during the period concerned many researchers speculated on the imminence of a new ice age.

Notwithstanding the observed increase in atmospheric CO_2 and CH_4, the rise in global temperatures over the past 100 years is slow and irregular and even non-significant statistically; it would be "noise" rather than a "signal". Hansen et al. (1988) estimated that only by the mid-nineties a definite signal on temperature rise from the combined effect of all anthropogenic greenhouse gases can be expected.

II CLIMATIC CHANGE MODELS

There is little doubt that anthropogenic greenhouse gases will increase substantially in the forthcoming 50-100 years. A doubling of the atmospheric pre-industrial CO_2 content to about 580 ppm by the year 2050 is not unlikely. Therefore, atmospheric scientists and climate modellers have combined the 0.5°C over-all temperature rise in the past 100 years, uncertain as it may be, with the measured atmospheric CO_2 rise of 55 ppm in the same period, using algorithms of atmospheric processes, to make projections of future climates. A doubling of the atmospheric CO_2 has been taken as scenario for the development of a number of General climatic Circulation Models (GCM's, see Table 1 for the results of five of them). The temperature rises predicted by these models varies between 2.8 and 5.2°C worldwide. However, there is much discrepancy between the various modelling results. Even the present-day climate is not simulated satisfactorily (Mitchell, 1989). The scientists concerned use varying estimates of the influence of feedback mechanisms by oceans (surface phenomena and deep water upwellings), by cloudiness, by ice-coverage, by land cover and land use, by soils, etc. Terms used in these respect are: "negative feedback" = mitigation of the GHE, and "positive feedback" = strengthening of the GHE.

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Table 1. Global Mean Changes in Five Recent CO_2-Doubling Studies

Study	Source	Surface Temperature Change, K	Precipitation Change, %
GISS	Hansen et al. (1984)	4.2	11.0
NCAR	Washington and Meehl (1984)	4.0	7.1
GFDL	Wetherald and Manabe (1986)	4.0	8.7
UKMO	Wilson and Mitchell (1987a)	5.2	15.0
OSU	Schlesinger and Zhao (1987)	2.8	7.8

GISS:	Goddard Institute for Space Studies (Hansen et al., 1984). Seasonal data on a 7.83° latitude x 10° longitude grid: mean surface air temperature and precipitation anomalies for ($2xCO_2$ - $1xCO_2$).
GFDL:	Geophysical Fluid Dynamics Laboratory (Wetherald and Manabe, 1986). A 4.5° x 7.5° grid: mean surface air temperature and precipitation anomalies for ($2xCO_2$ - $1xCO_2$).
NCAR:	National Center for Atmospheric Research (Washington and Meehl, 1984). Seasonal data on a 4.5° x 7.5° grid: mean surface air temperature and precipitation anomalies for ($2xCO_2$ - $1xCO_2$).
OSU:	Oregon State University (Schlesinger et al., 1985). Seasonal data on a 4° x 5° grid: mean surface air temperature and precipitation anomalies for ($2xCO_2$ - $1xCO_2$).
UKMO:	UK Meteorological Office (Wilson and Mitchell, 1987a). Monthly data on a 5° x 7.5° grid: mean surface air temperature and precipitation for control run ($1xCO_2$) and perturbed run ($2xCO_2$).

from: Hulme and Mitchell, 1989.

Most models are of the "steady state" type, which simulate up till a new equilibrium situation after a sudden increase of atmospheric CO_2 from 300 ppm to 600 ppm. Models of the "transient response" type which include a year-by-year cumulative time path, with due account of temporal-lag effects (such as delayed ocean warming) as well as short term effects (such as increasing plant assimilation), are more complicated than steady state models. Comprehensive reviews of the GCM results and their drawbacks have been given by Dickinson (1986) and Mitchell (1989).

All GCMs predict a much stronger temperature rise at higher latitudes in the respective summers than near the equator. The maximum steady-state responses at CO_2 doubling are upward from 5°C annual mean surface air warming for the high latitudes, but only 2°C for the equatorial regions.

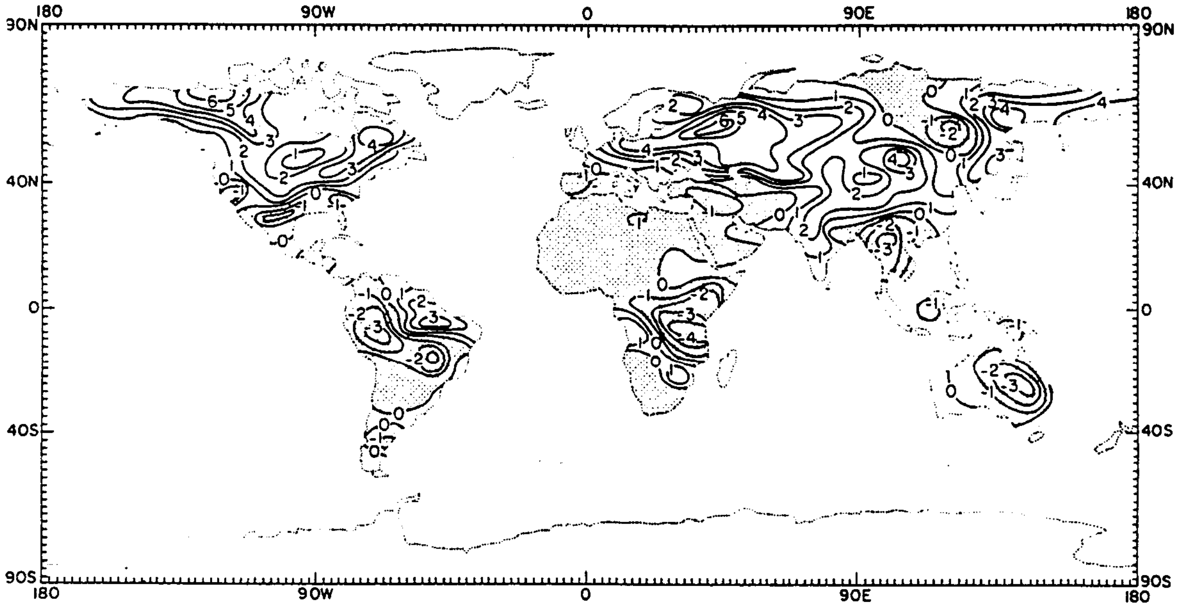
The latest models, presumably including not only CO_2 doubling but also the longer and stronger action of increases of trace gases such as methane and nitrous oxide, are said to predict a global rise in temperature of 5°C, with increases up to 12°C in polar regions (Press, 1989). The magnitude of such a change would be comparable to the change from a glacial to an interglacial period in the Pleistocene. On the other hand, within the Intergovernmental Panel on Climate Change (IPCC) a consensus emerged at a recent meeting that mean global temperatures would go up by only 2°C by the year 2050 (Anderson, 1990).

Associated with such a global warming would be a sea level rise of 0.5-1m, caused by temperature-induced expansion of surface water volume and strongly increased melting of ice in polar regions. These predictions are also fraught with uncertainties, as discussed by Pirazzoli (1989). A rise of only about 0.3 m would be the best estimate according to a recent review in Nature (Meier, 1990).

The global precipitation would increase by 7-15% (Mitchell, 1989), though the effect on freshwater availability would be largely offset by increased evapo(trans)piration. The precipitation pattern would also change: a strong increase is predicted for the northern high latitudes; non-change or decrease in the mid-latitudes and minor increases in the tropics. Estimates on the geography of annual and seasonal precipitation vary widely between the GCM models. Often the predicted changes would not be more than "noise" (Schlesinger and Mitchell, 1985), because of problems in modelling of the seemingly chaotic regime of the weather, particularly in the northern higher latitudes (North America, Western Europe). For the tropics the scarcity of reliable long-term weather records is a serious drawback.

Some models give the net effect per region of changing seasonal rainfall patterns and increased evapo(trans)piration as expressed in soil moisture availability, though not taking into account changed run-off conditions. An example is the NCAR model described in Washington and Meehl (1984). It gives a degree of winter and strong summer drying in the northern

SOIL MOISTURE DIFFERENCES, DJF



SOIL MOISTURE DIFFERENCES, JJA

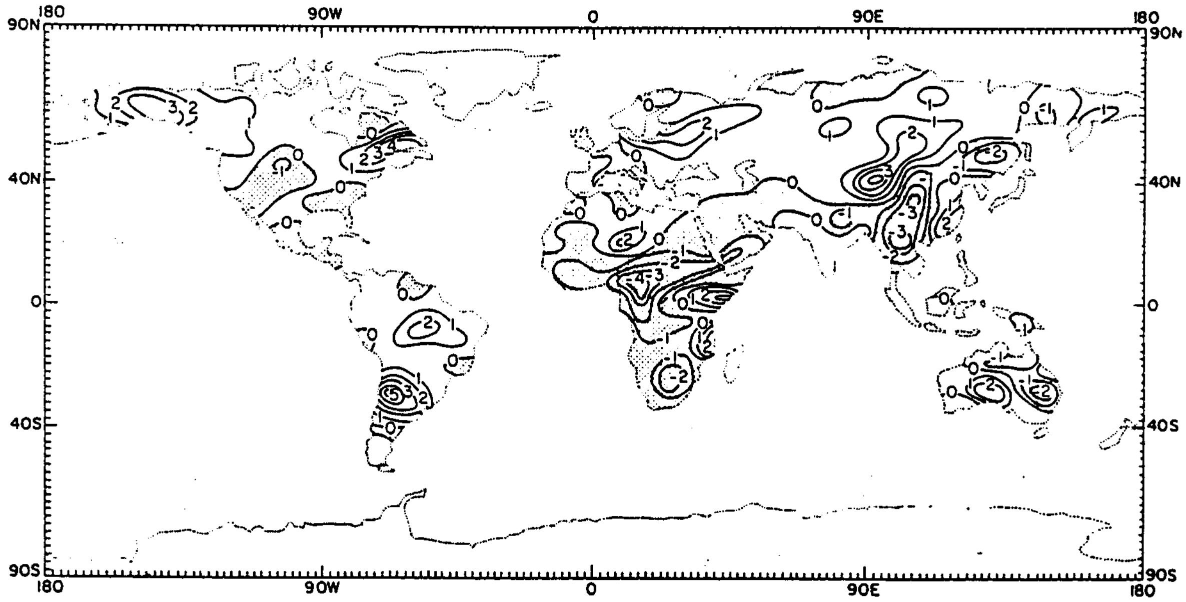


Figure 1: Geographical distribution of soil moisture differences in cm for December-February and June-August obtained by Washington and Meehl (1984) for 2 × CO_2 - 1 × CO_2 (NCAR model).

mid-latitudes (southern USA, *Indochina*) but more soil moisture in the northern high latitudes, especially in the winter. In the tropics, the model outputs on seasonal soil moisture changes are complicated:

- little or no change in the year-round soil moisture conditions in the monsoon climate of *south-east Asia*
- up to 30 mm increase in soil moisture in December-January-February (DJF) for eastern *Amazonia* but up to 30 mm decrease for western Amazonia and central Brazil; a 10-20 mm increase in eastern Amazonia and central Brazil in June-July-August (JJA) which is at present a dry season in that region, but no change in western Amazonia (no dry season at present).
- little change in DJF for *west-central Africa* but a decrease of up to 40 mm in JJA, nowadays the middle of the wet season.
- up to 40 mm decrease in available soil moisture in *eastern Africa* for DJF (at present already the "long" dry season), and 20-30 mm increase in JJA (at present the "short" dry season). The implication of this is the attenuation of the bimodal pattern of rainfall effectiveness in this region ("long rains" moving more smoothly in the "short rains") but a more outspoken (long) dry season - not considering effect of local orography; in *south-eastern Africa* however, with a single rainy season in DJF, this rainy season would be less pronounced.

Whatever the merit of the NCAR model, on its own and in comparison with the other models (for instance the one by Manabe and Wetherald, 1987, as reproduced in chapter 14), the above predicted regional changes in soil moisture will be taken as starting point for discussion of the effects on tropical soil formation and conditions in this paper. First, however, the effect of changing atmospheric CO_2 and temperature on tropical plant growth will be discussed.

III EFFECTS OF RISING ATMOSPHERIC CO_2, OF TEMPERATURE AND OF SEA LEVEL ON PLANT GROWTH IN THE TROPICS AND SUBTROPICS

An increase of global mean annual near-surface temperatures will stimulate plant growth in the world-at-large, other conditions remaining the same. A 1°C increase would result in 5-10% extra biomass production worldwide (Idso et al., 1987). The model-surmised higher temperatures will be reflected in the Holdridge Classification of biotemperatures, resulting in changed patterns and acreages of its "life zones" or schematized biomes. The modelling results of Emanuel et al. (1985) show only minor shifts in the main tropical life zone belts ("tropical wet forests", "tropical dry forests", etc.) but it should be noted that any changing rainfall patterns have not been taken into account in that study.

In the tropics and subtropics, where temperatures are normally not a limiting factor, the increase in annual biomass production will be modest and grain yields of some major agricultural crops may decline if temperatures happen to surpass 24°-27°C (see chapter 22). Only in mountain areas such as the Andean Cordillera and the highlands of Eastern Africa the change will be spectacular: the successive natural vegetation or crop growing belts will shift upwards by 1000 feet at an increase of 2°C. In these areas more land would be vegetation-covered, though the net acreage of individual altitudinal crop-belts, such as coffee and tea (Ackland, 1971 for East-Africa, and Braun's report on the Agroclimatic Zone map of Kenya, in Sombroek et al., 1982) will become smaller. A preliminary case study by UNEP-GEMS-GRID for Uganda has shown that suitable conditions for Robusta coffee in Uganda would decrease in acreage to near zero (GRID, 1987) - assuming no gradual adaptation by introduction of new crop cultivars. The changing acreages are exemplified in figure 2.

Increase in near-surface temperatures over oceans will increase evaporation substantially. The present-day annual evaporation of all oceans is $4.4 \times 10^{20} cm^3 yr^{-}$, at a global mean annual surface temperature of 11.5°C (Holland, 1978). An increase of temperature of only 1°C worldwide would result in about 20% extra evaporation (Handbook of Chemistry and Physics, 1987 edition) or $1.0 \times 10^{20} cm^3 yr^{-}$ (10.000 km^3 water; compare with 85 km^3 annual discharge of the Nile river). The resulting extra water vapour will induce more cloud formation and ultimately more rain- and snowfall. Part of the increased rain- or snowfall will be on the land surface, enlarging the present body of fresh water in rivers and lakes and the availability of water for plant growth. Models of the world hydrologic cycle are, however, not yet able to predict how much of this increased fresh water body will accumulate in subhumid and semi-arid tropical land areas where it could contribute to increase crop production through irrigation.

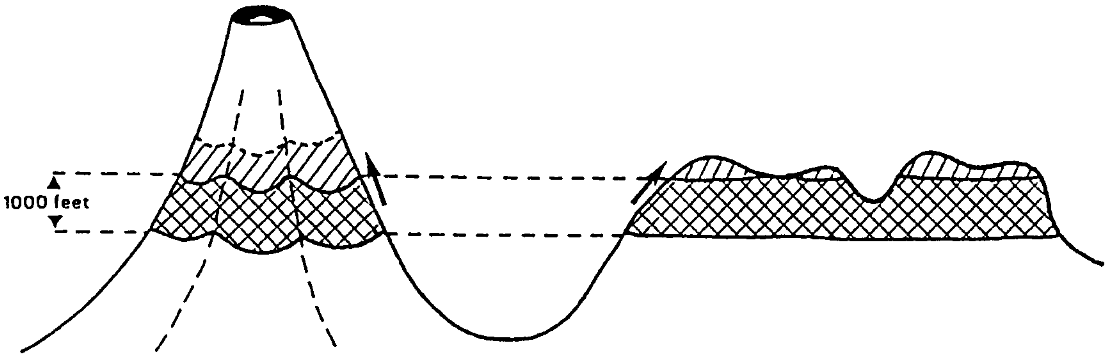


Figure 2: Upward changes in altitudinal cropping c.q. vegetation belts in the tropics at a 2.C increase of annual temperature (a = mountains of eastern Africa: relatively small decrease in acreage; b = high lands of Uganda: near disappearance of the belt concerned).

The effect of a rising sea level will be dramatic, especially in the tropics. Many parts of tropical coastal plains and river deltas such as those of the Mekong, the Sunderbans, the Congo, the Nile, the Amazon and the Orinoco will become flooded to such a depth that natural vegetation and crop growth will be impossible - unless huge empoldering works are executed (cf. Brammer and Brinkman's contribution, chapter 12, for details). This loss of land based plant growth will only partially be offset by plankton and algae growth in coastal waters. Interior parts of deltas will have poorer drainage conditions.

In contrast, the positive effect of rising atmospheric CO_2 levels on land-based biomass production ("CO_2 fertilization") will be significant. This effect has not yet been duly incorporated in the GCMs. As already mentioned in the contribution by Scharpenseel (chapter 1), laboratory experiments on a range of crops at doubled atmospheric CO_2 level have shown an average increase of about 30% in vegetative productivity (Kimball, 1983; Goudriaan and Unsworth, 1988; Schleser and Kirstein, 1989). In natural environments, light and CO_2 are normally suboptimally present. Hence, photosynthesis of green plants can be stimulated by an increase of ambient CO_2, by suppression of photorespiration particularly in C_3-plants. These plants include nearly all leguminosae and woody plants, and many crops such as cotton, rice, wheat, soya beans, barley, sunflower, and tuber crops (cassava, potatoes). The reaction to increased CO_2 is less strong, about 10%, in C_4-plants, such as many tall tropical grasses, halophytes and the crops maize, sugar cane, sorghum and millets. CAM-plants such as pineapple, Opuntia and agaves show an intermediate reaction.

Another effect of higher atmosphere CO_2 concentrations is a reduction of plant stomatal openings, hence smaller water vapour diffusion (higher stomatal resistance). This will increase the plant's water use efficiency, and the process would be particularly strong in some C_4 plants such as maize (37% smaller stomatal conductance, leading to a 26% lower transpiration -Cure, 1988). The combined result of modest extra assimilation and much smaller transpiration of this crop would also be in the order of 30%, comparable to the pure assimilation effect on C_3-plants (see also Schleser and Kirstein, 1989). The likelihood of increased dark respiration (dissimilation) because of higher night temperatures may however have a mitigating effect.

In this context, it is likely that the measured gradual increase in atmospheric CO_2 over the past 100 years of about 20% is responsible for part of the approximately doubling of the agricultural crop productivity worldwide over that period (Allen et al., 1985, estimated the CO_2-induced increase to be 15% for soya). Such a CO_2-induced increase of terrestrial net primary production would also account for the "missing" sink in the global carbon cycle, resulting from the smaller reported CO_2 uptake in ocean surface waters of the Northern Hemisphere than assumed previously (Tans et al., 1989).

Doubling of CO_2 in combination with a 3°C mean global air temperature rise would result in another 25% extra biomass production (Idso et al., 1987). For the tropics the combined effect would be smaller because of

- less than average predicted temperature rise.
- the chance that plants become overheated because of too limited evapotranspiration - especially in dry-season regions.
- the likelihood that daylight will become a limiting factor - especially in the below-canopy growth environment of standing vegetation and crops.
- the likelihood that soil nutrients become limiting - especially in the humid tropics where strongly weathered soils are widespread.

Higher CO_2 concentrations would, however, also stimulate root growth which, combined with more organic matter production and its even stronger decomposition, would intensify rock weathering (see below) - hence deeper soils with extra availability of some nutrients such as potassium from the freshly weathered substratum. There is yet another factor: higher CO_2 concentrations would induce shorter growing periods to maturity for many annual plants (Oecher and Strain, 1985) which implies increased possibilities for plant growth in (sub)tropical regions with a short rainy season (plus less sensitivity to soil salinity), and more crops per year in humid areas. Finally, several indirect effects should be mentioned:

- increased biomass production leads to better soil cover, hence less erosion (unless the seasonal or annual ratio between rainfall and evaporation changes for the worse).
- the competitive force of perennial grassy weeds - predominantly C_4-plants - relative to many crops would become smaller at higher CO_2, hence weed control would be less costly (the situation becomes more complex in case the crops concerned are C_4-plants too, such as sorghum and millets in the Sudano-Sahelian zone of West Africa or semi-arid India).

In summary, atmospheric CO_2 doubling and related temperature rise on their own are likely to have a definite positive effect on plant biomass production in tropical forests (C_3 plants), less so in tropical savannas (C_4-plants), and a significant increase of production potential of most agricultural crops. The demand for fertilizers ,especially the nitrogen and phosphorus based ones, will however strongly increase. It also remains to be established whether other biological influences such as the activity of pathogens, pests, decomposers and symbionts will change at the same or higher rate as biomass productive capacity per se.

In contrast with CO_2, the rising concentrations of atmosphere trace gases CH_4 and N_2O have no effect on plant growth. In view of their stronger and longer-term forcing of the surmised global temperature rise, and their chemical reactivity, they may even turn out to be the most worrisome eventually. One can however imagine systems of "harvesting" CH_4 gas in paddy fields and garbage piles for local fuel supply.

IV INFLUENCES OF AN ENHANCED GREENHOUSE EFFECT ON SOIL CONDITIONS AND SOIL DEVELOPMENT IN THE TROPICAL AND SUBTROPICAL UPLANDS

A distinction should be made between soil features that have a short "response time" (RS) and those that change only very gradually (rapidly adjusting soil features vs. slowly adjusting ones). Walker and Graetz (1989) give three RS classes: short (<50 years), long (50-1000 years) and very long (>1000 years). A more detailed scheme is given in chapter 4 by Varallyay.

It is obvious that in soils the moisture, temperature and the organic matter and nutrient/salts dynamics are easily changed. Within the time frame of Global Change, say 50-100 years, this would not normally affect pedological soil classification, since the current systems are based on more stable/static soil characteristics (a partial exception is the US Soil Taxonomy system, where soil moisture and partly also soil temperature regimes figure at high catagoric level). The modest surface air temperature rise surmised for the tropics (maximally 2°C) is likely to be even smaller in the soil, because of the denser vegetative covers (higher biomass production because of higher atmospheric CO_2, see above). With regard to soil moisture and salinity much depends on the regional changes in the rainfall/evaporation patterns, but here the models are vague and contradictory.

Changes in dominant soil forming processes

Soil forming factors acting slowly, the type of dominant soil forming process within the Global Change time frame of 50-100 years would not change significantly. There are, however, some fragile ("ecotonal" or "treshold") soil situations, where a slight change in one of the factors would induce a major change in the dominant process ("ferralitisation" vs. "podzolisation"; "illuviation" vs. "homogenisation"; "salinization" vs. "leaching"), without even considering landscape processes such as wind and water erosion. Examples of ecotonal soil situations where a transition to a different genetic soil group may occur within a time span of tens of years, upon only slight changes of climatic conditions or somewhat higher frequency of extreme events are the following:

(a) the lighter textured yellowish ferralitic soils of eastern Amazonia, the Congo basin and Kalimantan (xanthic Ferralsols and ferralic Arenosols in the FAO terminology) may become rapidly podzolized upon small changes in precipitation (total annual amount or more seasonal concentration) and/or increasing acidic organic matter production, resulting in Podzols or albic Arenosols ("Giant Podzols") of which gleyic variants are already present in large areas in the Rio Negro-Rio Branco area of north-western Amazonia.
The fragility of the present ferralitisation process in the Amazon region has been amply demonstrated by detailed studies on short distance sequences of ferralitic soils-podzols by French pedologists (for instance Turenne, 1975, for French Guyana; Dubroeucq and Volkoff, 1988, for the Brazilian Rio Negro area; Lucas et al., 1987, for the Amazon in general).
The predicted increase of 30 mm effective soil moisture in the NCAR model during the dry season of eastern and southern Amazonia may be just enough to induce podzolisation over large areas of sandy Pleistocene terraces - where up till now Podzols are of patchy occurrence only (Sombroek, 1966).

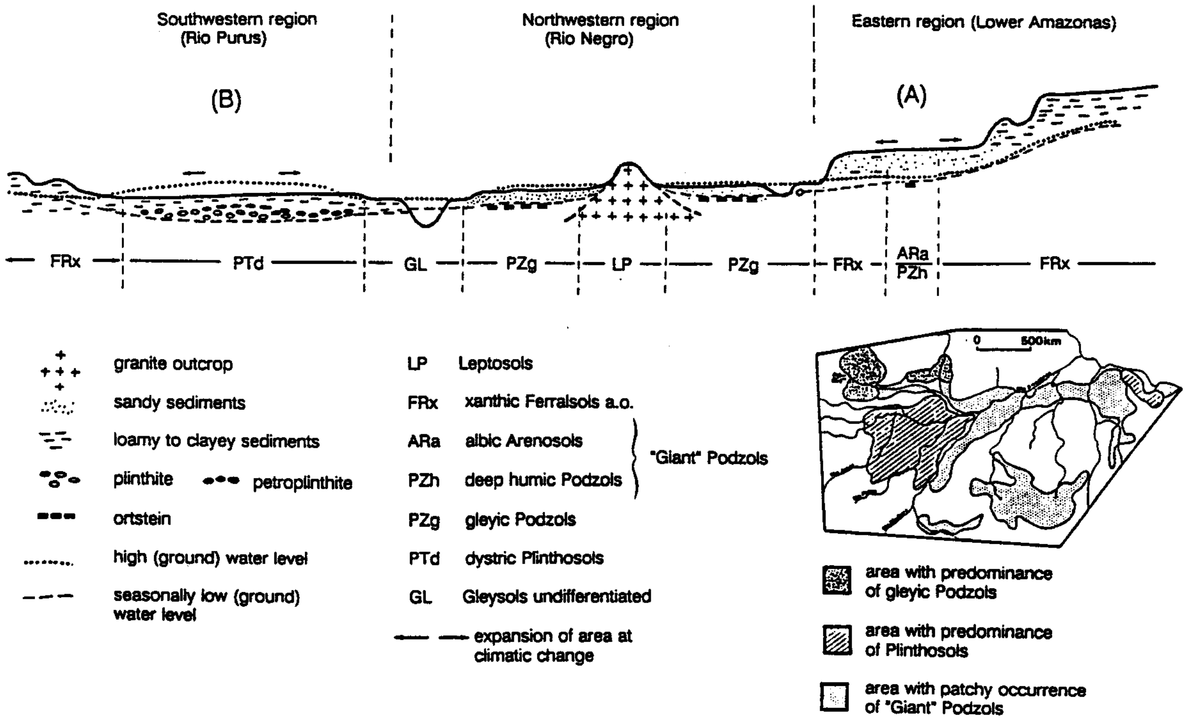


Figure 3: Schematic presentation of some Amazonian ecotonal soil situations (A and B).

(b) the imperfectly drained loamy soils on the flat water divide areas of the western Amazon with their plinthitic subsoil (the Madeira-Purus area south-west of Manaus) may dry out, resulting in an irreversible hardening of this subsoil into "laterite" (change from Plinthosol or plinthic Acrisol into Acrisol, petroplinthic phase - see Sombroek, 1984). The decrease in soil moisture availability in DJF predicted by NCAR may induce such drying-out, especially if the overall river hydrology would become more erratic.

(c) the deeply weathered reddish, loamy to clayey and porous soils of the forest-savannah transition zones of Eastern Africa, which are stable under their present-day natural vegetation, may be leached to an extent that a relatively dense clay-illuviated horizon develops below an unstable topsoil low in organic matter (changing the soil from rhodic or orthic Ferralsol into an orthic Acrisol or Lixisol). This in fact is happening already at present-day land clearing in parts of the region, because of the sudden diminution of the homogenizing action of soil biologic life.
The NCAR predicted changes in soil moisture conditions for this area would therefore stimulate the replacement of ferralitisation by illuviation as a dominant soil forming process, especially in the present bimodal rainfall areas (Sombroek et al., 1982).

(d) certain silty sedimentary deposits in the wide riverine valleys of the Sudan-Sahelian zone of West Africa ("fadama's"; the interior delta of the Niger river) may develop from Fluvisols into saline and/or sodified soils at an even minimal change in precipitation and flooding regimes - as exemplified by current human actions with the same soil-hydrological implications (Sombroek and Zonneveld, 1971).
The NCAR model for this region predicts a decrease in precipitation during the rainy season, hence less suppression of salinity.

Changes in soil weathering rates

In non-ecotonal tropical upland soil situations, the pathway of soil forming processes would not change, but the weathering potential and -rate may increase somewhat. The weathering potential at a doubling of the atmospheric CO_2 per se, as measured by the increase of the solubility of calcite will be discussed first. The present CO_2 concentration of the atmosphere is taken as 300 ppm or 0.03%. The CO_2 concentration in the soil gaseous phase is 10 to 100 times higher, because of root respiration. The low values would occur under dry and cool climatic conditions, the high values in continuously warm and moist soils such as in tropical rainforests where root activity is very high (when the soil condition is anaerobic, such as in paddy fields the value of soil-CO_2 is up to 300 times the air-CO_2; Novozamski and Beek, 1976).

At a 10 times higher CO_2 concentration in the topsoil ($\approx$0.3%) the equilibrium pH of water would be 5.22 (in the absence of any mineral component). With a doubling of the CO_2 content such as in the GCM scenarios, the CO_2 concentration in the topsoil would become: 0.30 (original) + 0.10 (33% increase of biomass production) + 0.03 (increase of atmospheric CO_2) = 0.43%. The corresponding equilibrium pH would be 5.14*, meaning 20% more H-ions available for weathering (figure 4). This can be illustrated by the increased solubility of calcite. In the present situation 113 mg $CaCO_3$/l can be dissolved by soil water whereas in the future this would be 128 mg/l (figure 5) which means an increase of about 15%. In practice, however, the increase may be smaller than 10%, because the 33% increase in biomass production may not be reached, due to likely limitations of nutrients and light - as discussed before.

When the CO_2 content of the topsoil is taken to be 100 times the atmospheric content (e.g. tropical humid forest) then the solubility of $CaCO_3$ increases from 251 mg/l to 277 mg/l, which is an increase of ca. 10%. Thus, taking into account a slight increase of the effect of rate limiting factors at a higher rate of reaction (e.g. diffusion of components), an average increase of 10% in the rate of weathering due to a doubling of atmospheric CO_2 can be expected.

The increase in temperature will also lead to a higher rate of weathering. There are indications that a temperature rise of 10°C results in an increase of velocity of mineral weathering reactions by a factor of approx. 1.5 (Q_{10} or "van't Hoff's factor"; Loughnan, 1969,

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*The lowering of pH to 5.14 includes the slight effect of a 2° C temperature increase. If buffering minerals are present (which is usually the case in soils) then the equilibrium pH will of course be higher. On the other hand, this will be counteracted by an increase of the content of organic acids.

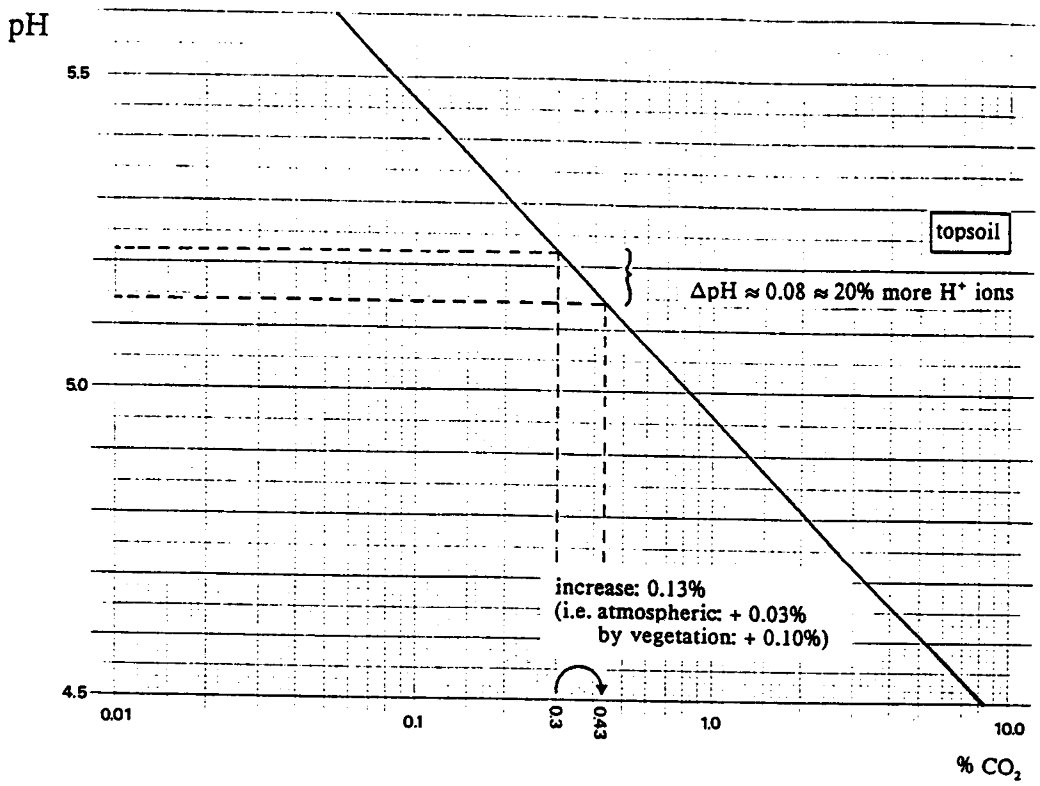

Figure 4: pH of water as a function of % CO_2 in air.

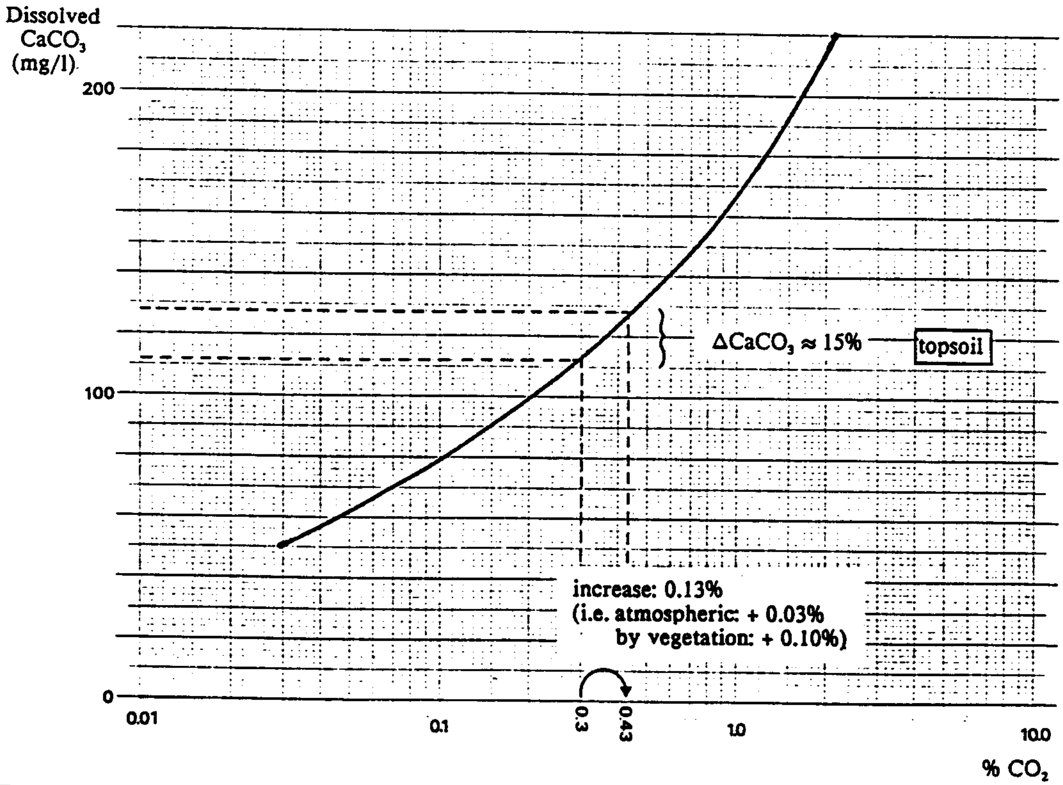

Figure 5: Solubility of $CaCO_3$ in water of 25°C as a function of % CO_2 in air.

Graphs developed by L.P. van Reeuwijk.

p.69; Zivkovic et al., 1983). A 2°C temperature increase would thus result in a 10% higher rate of weathering.

It follows that the combined effect of the increase of both the CO_2 content and the temperature on the rate and therefore the depth of weathering can be estimated at a minimum increase of 20%. Of paramount importance, however, is the influence of the change in climate on the effective rainfall i.e. the water available for the reactions and transport of components. The estimated minimum rate increase of 20% will only occur if the effective rainfall does not decrease.

The higher biomass production inevitably leads to a higher amount of decomposition products. In view of the somewhat higher soil temperatures, this decomposition of fresh organic matter is likely to be more complete, hence there may in fact be a smaller rather than a higher production of stable humus (see also Tinker's contribution in chapter 7). At the same time the deeper soil profiles offer extra space in the subsoil for fixation of the humus still produced on the newly formed silicate clay minerals. The net result may be a slow change in sesquioxide-rich clayey tropical soils such as Nitisols and rhodic Ferralsols with humic topsoils (mollic or umbric A horizons) into units with the stable humus distributed more evenly in the whole soil profile.

A more prominent presence of organic acids may favour organo-metallic complexing. This will particularly be the case where nutrient supply cannot keep pace with the increase in biomass production and a poorer type of organic matter (with a higher C/N ratio) is produced. The result may be a degree of podzolization where the soil is sandy and of relatively low sesquioxide content (sandy xanthic Ferralsols; see above).

All above considerations refer to the (sub)humid tropics. In the semi-arid tropical and subtropical uplands the weathering potential, its rate and direction, depend very much on the seasonal and annual changes in soil moisture availability - for which the GCMs, as stipulated above, give unreliable predictions. Higher surface temperatures in open savannah like conditions (predominantly C_4 grasses hence less increase in biomass production) would lead to faster combustion of soil humus already present, while soil fauna such as termites would carry more litter to their cool underground nests (which may lead to more methane emissions as a positive feedback to the Arrhenius effect).

Where free salts are available at some depth in the subsoil these may be transported upwards due to stronger evaporation and evapotranspiration, leading to a degree of soil salinization.

The likely combined result of a greenhouse warming on the semi-arid tropics is a strengthened hazard of desertification.

The statements given apply to whole continents or regions. The local pattern of soils in the tropics, often a reflection of former climatic conditions different from the present ones, coupled with the local implications of any anthropogenic climatic change in the near future, offer a large and intricate scala of possibilities of future soil development. This can not be discussed in the framework of this general review on tropical soils on a warmer earth. The modelling of soil genetic processes as proposed by Stewart in chapter 10 may however be put to good use for individual soil profiles and their present-day or surmised future environmental conditions.

V INFLUENCES ON SOIL CONDITIONS OF TROPICAL COASTAL LOWLANDS AND OF TROPICAL MOUNTAIN AREAS

The tropical coastal lowlands and wetlands, as well as the tropical mountain areas (roughly all areas above 2000 m altitude), merit special attention. Changes are likely to be substantially more dramatic than in tropical uplands.

The coastal wetlands will be affected principally by the expected rise of sea level of 0.5 to 1 m. Brackish water will penetrate in many coastal marshlands and swamps. The brackish water, in combination with the high organic matter accumulation of these lands, will result in soil forming processes favouring the formation of potential Acid Sulphate Soils (thionic Fluvisols, - Gleysols, and - Histosols). These are real problem soils, because they turn very compact and extremely acid upon artificial drainage, becoming unsuitable for most plant growth.

Coastal lands at present only a few meters above flooding would have shallower levels of ground water, often saline, resulting in salinization and/or sodification of soil profiles especially where the climate is subhumid or semi-arid. For details, also as regards low-level islands with coral reefs such as prevalent in the Pacific, see the contribution of Brammer and Brinkman in chapter 12.

Tropical mountain areas, as discussed before, will see a substantial shift of natural or agro-ecological zones in an upward direction, because of the predicted 2°C temperature increase.

The intensity of rock weathering will increase and soils will become deeper. This implies more agricultural potential where the adjoining uplands remain humid, such as is the case on the eastern slopes of the Andean Cordillera and the northeastern slopes of the Sumatran mountain ridge. If the associated uplands however become dryer, as may be the case in Eastern Africa, then the net agricultural area in the region may diminish. Whatever be the case, the surface and subsurface hydrology on the mountain slopes will change substantially, with a potentially strong effect on the drainage conditions of the lands and soils of the lower parts of the catchment areas concerned.

The details of soil changes in mountain areas depend not only on differences in parent materials, but also on past shifts, upwards and downwards, of the belts of climate conditions and associated plant communities. Systematic and detailed paleo-ecological studies, such as those already carried out on several altitudinal transects in the Colombian Andes (Van der Hammen et al., 1983 et seq.) will provide important clues as to the future soil development in tropical mountain regions under anthropogenic climatic change.

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