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Review Article
Potential Effects of Climate Change on Soil Properties: A Review

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Abstract
Soils form through the multifarious interaction of a number of forces, including climate, relief, parent material, organisms, all acting over time. It takes thousands of years for a soil to form and most soils are still developing following changes in some of these soil forming factors, particularly climate and vegetation, over the past few decades. Climate is one of the most important factors affecting the formation of soil with important implications for their development, use and management perspective with reference to soil structure, stability, topsoil water holding capacity, nutrient availability and erosion. Further Indirect effects corresponds to changes in growth rates or water-use efficiencies, through sea-level rise, through climate-induced decrease or increase in vegetative cover or anthropogenic intervention. Assuming constant inputs of carbon to soils from vegetation, different estimate predict that expected changes in temperature, precipitation and evaporation will cause significant change in organic matter turnover and CO_2 dynamics. In conclusion, increased productivity would generally lead to greater inputs of carbon to soil, thus increasing organics.

Key words: Soil C, C_3 and C_4 plants, CENTURY, ROTH-C, erosion

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INTRODUCTION

With progressing earth history, the parameters of climate such as temperatures and precipitation have globally, regionally and locally changed. In addition to extraterrestrial reasons also terrestrial reasons like volcanism, forest fires, changes of global ice, snow and vegetation cover have caused such changes. For the last 100 years the global mean temperature has increased to actually more than 15°C, which is widely assumed to have not only natural but anthropogenic reasons: A reduced water evaporation from agricultural land in contrast to natural forest, emissions of warmth and carbon dioxide especially in urban-industrial agglomerations and the release of methane and nitrous oxide in agriculture are the most important impacts. It is assumed that in the 21st century the global mean temperature will rise by another 2-3°C, mainly caused by a higher use of fossil fuels and an intensified conventional agriculture.

Before going to the main topic let see how climate affects the agricultural productions. Farmers often achieve far less than 50% of the climatic and genetic yield potential for a given sowing date, cultivar choice and site. Figure 1 illustrates factors that define yield gaps at different levels. The potential yield or maximum yield (Y_{max}) is limited by climate and crop cultivar only, all other factors being optimal. Therefore, climate plays a major role while attaining Y_{max} or potential yield. A lot of studies have been carried out by agriculturalists, scientists and economists on the adverse effects of climate change[1-4]. Since soil has a major role in supplying macro and micro nutrients to all kinds of crops grown on it, studies on change of its physical, chemical and biological properties with respect to climate change is important. Defining soil properties in relation to climate change should consider the impacts of a range of predicted global climate change such as rising atmospheric carbon dioxide (CO_2) levels, elevated temperature, altered precipitation (rainfall) and atmospheric nitrogen (N_2) deposition, on soil chemical, physical and biological functions. Many studies have progressed our understanding of relationships between particular soil properties and climate change, e.g., responses to temperature, CO_2 or rainfall[5-8] however, it is noted that "A comprehensive explanation of the factors at the heart of the issue is currently lacking"[9].

The aim of this presentation is to describe the brief impact of climate change on different soil properties, their mitigation or adaptation strategies and thereby making a solution to the impact of climate change on physical, chemical and biological properties of soil.

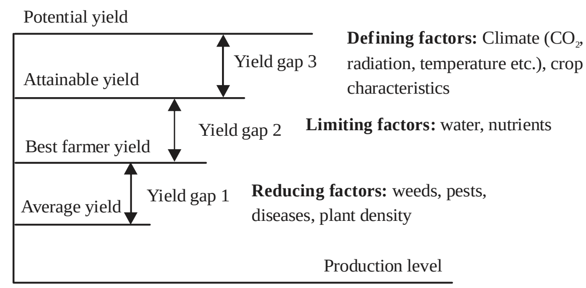


Fig. 1: Role of different factors on different yield stages

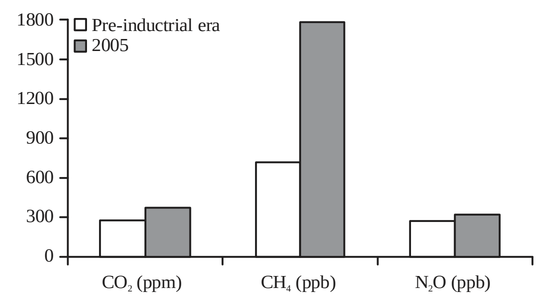


Fig. 2: Increase of global atmospheric concentration of CO_2, CH_4 and N_2O from pre-industrial era to 2005[10]

WHAT IS CLIMATE CHANGE?

Climate change in Intergovernmental Panel on Climate Change (IPCC) usage refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the Framework Convention on Climate Change (FCCC), where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods. According to IPCC[10] the global atmospheric concentration of carbon dioxide, methane and nitrous oxide has increased from pre-industrial era to 2005 (Fig. 2). The annual carbon dioxide concentration growth-rate was larger during the last 10 years' average (1995-2005, 1.9 ppm per year), than it has been since the beginning of continuous direct atmospheric measurements (1960-2005, average 1.4 ppm per year) although there is year-to-year variability in growth rates.

Rahmstorf and his co-workers[11] explained the changes in key global climate parameters since 1973, compared with the scenarios of the IPCC, shown as dashed lines and gray ranges in Fig. 3. Mountain glaciers and snow cover have declined on average in both hemispheres. Widespread decreases in glaciers and ice caps have contributed to sea level rise. Global average sea level rose at an average rate of 1.8 mm per year

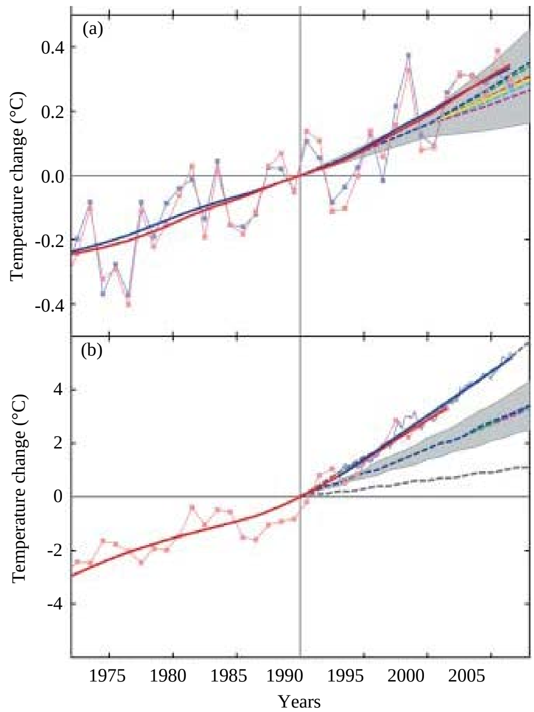


Fig. 3(a-b): Changes in key global climate parameters since 1973, compared with the scenarios of the IPCC (shown as dashed lines and gray ranges), (a) Annual global mean land and ocean combined surface temperature from GISS (red) and the Hadley Centre/Climatic Research Unit (blue) up to 2006, with their trends and (b) Sea-level data based primarily on tide gauges (annual, red) and from satellite altimeter (3-month data spacing, blue, up to mid-2006) and their trends. All trends are nonlinear trend lines and are computed with an embedding period of 11 years and a minimum roughness criterion at the end (6), except for the satellite altimeter where a linear trend was used because of the shortness of the series. For temperature and sea level, data are shown as deviations from the trend line value in 1990, the base year of the IPCC scenarios[11]

over 1961-2003. The rate was faster over 1993-2003, about 3.1 mm per year. Mid-latitude westerly winds have strengthened in both hemispheres since the 1960s. More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics. Increased drying linked with higher temperatures and decreased precipitation has contributed to changes in drought. Changes in Sea Surface Temperatures (SST), wind patterns and decreased snowpack and snow cover have also been linked to droughts. The frequency of heavy precipitation events has increased over most land areas, consistent with warming and observed increases of atmospheric water vapour.

WHAT CAUSES CLIMATE CHANGE?

In Climate Change 2007: The Physical Science Basis, IPCC has discussed on the human and natural drivers of climate change. Changes in the atmospheric abundance of greenhouse gases and aerosols, in solar radiation and in land surface properties alter the energy balance of the climate system. These changes are expressed in terms of radiative forcing (A measure of the influence that a factor has in altering the balance of incoming and outgoing energy in the earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism) which is used to compare how a range of human and natural factors drive warming or cooling influences on global climate[10]. The causes of climate change with both human and natural drivers are discussed below (Fig. 4).

Natural drivers: The earth's climate is dynamic and always changing through a natural cycle. The climate changes are being studied by scientists all over the world who are finding evidence from tree rings, pollen samples, ice cores and sea sediments. There are a number of natural factors responsible for climate change. Some of the more prominent ones are continental drift, volcanoes, ocean currents, the earth's tilt, comets and meteorites.

Human causes: Human-caused global warming is often called anthropogenic climate change. Industrialization, deforestation and pollution have greatly increased atmospheric concentrations of water vapor, carbon dioxide, methane and nitrous oxide, all greenhouse gases that help trap heat near earth's surface. Humans are pouring carbon dioxide into the atmosphere much faster than plants and oceans can absorb it. These gases persist in the atmosphere for years, meaning that even if such emissions were eliminated today, it would not immediately stop global warming.

Greenhouse gases: Our planet is made habitable by the presence of certain gases which trap long-wave radiation emitted from the earth's surface, giving a global mean temperature of 15°C as opposed to an estimated -18°C in the absence of an atmosphere[12]. This phenomenon is popularly known as the "Greenhouse" effect (Fig. 5). By far the most

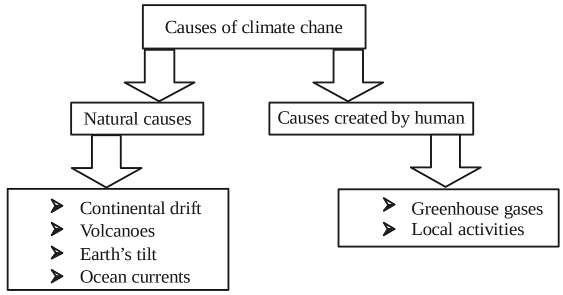


Fig. 4: Different causes of climate change

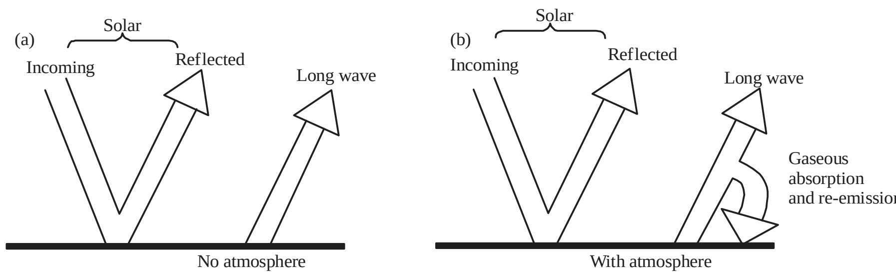


Fig. 5(a-b): Schematic illustration of the greenhouse effect showing (a) No atmosphere, where long-wave radiation escapes directly to space and (b) An absorbing atmosphere where long-wave radiation from the surface is absorbed and reemitted both downward, warming the surface and lower atmosphere and upward, maintaining radiative balance at the top of the atmosphere[13]

important greenhouse gas is water vapor. However, there is a substantial contribution from carbon dioxide and smaller contributions from ozone, methane and nitrous oxide. The concentrations of carbon dioxide, methane and nitrous oxide are all known to be increasing and in recent years, other greenhouse gases, principally chlorofluorocarbons (CFCs), have been added in significant quantifies to the atmosphere. There are many uncertainties in deducing the consequential climatic effects. Typically, it is estimated that increased concentrations of these gases since 1860 may have raised global mean surface temperature by 0.5°C or so and the projected concentrations could produce a warming of about 1.5°C over the next 40 years[13].

Local activities: Many studies have revealed the extent to which changes in the land surface have affected local and regional (multinational) climates[14,15] and it is increasingly clear that some changes in the land surface can have significant impacts on the climate in distant parts of the Earth. It has been long appreciated that changes in forest cover in the Amazon basin affect the flux of moisture to the atmosphere, regional convection and hence regional rainfall[16,17] argue that drought in Sahelian Africa has been an important positive feedback from the destruction of regional vegetation.

IMPACT OF CLIMATE CHANGE ON SOIL FUNCTIONS

The impact of climate change on soils is a slow complex process as because soils not only be strongly affected by climate change directly (for example effect of temperature on soil organic matter decomposition and indirectly, for example changes in soil moisture via changes in plant related evapotranspiration) but also can act as a source of greenhouse gases and thus contribute to the gases responsible for climate change. In addition changes in the functions and uses soils may be driven more by socio-economic factors than environmental ones. However the interaction of the various soil forming processes, particularly biological ones, makes difficult to quantify the changes. Generic trends in climatic variables given by the UKCIP02 scenarios were therefore used, namely[18].

Direct impacts of climate change on soil functions: Soil-climate models assuming constant inputs of carbon to soils from vegetation predicts the expected changes in temperature, precipitation and evaporation with a concomitant increase in organic matter turnover facilitating increased losses of CO_2 in mineral and organic soils. These losses of soil carbon will also affect other soil functions like poorer soil structure, stability, topsoil water holding capacity, nutrient availability and erosion. The loss of soil carbon is also accelerated by the increase in temperature. However, these effects could be counteracted by enhanced nutrient release resulting in increased plant productivity vis-a-vis litter inputs. Increased rainfall could expect increased peat formation and methane release, whilst areas experiencing decreased rainfall could undergo peat, CO_2 loss, increased moisture deficit for arable crops (especially on shallow soils) and for forest soils thereby affecting foraging patterns, reproduction and survivability of the soil invertebrates[19] of the food web and natural plant pathogens. Increased droughts will increase the likelihood of shrink-swell in clay soils and disturbance to building foundations and increased soil temperature may also exacerbate chemical attack to foundations to engineered structures based on clay caps (e.g., in contaminated landfills), with likelihood of increased leachate generation and release of landfill gases[18]. The fate and losses of pesticide could be complex nature depending upon the interactions between pesticides and the environment, incidence of pests and diseases under a changing climate (increased temperature causes rapid degradation, drier climate increases pesticide persistence, increased rainfall enhances by pass flow and downward movements). Increased rainfall could increase atmospheric N deposition to soils, may promote soil disturbances, flooding and subsidence which changes in wetland and waterlogged habitats and also enhance soil erosion, potentially leading to the pollution of surface waters.

Indirect impacts of climate change on soils: The integrated impact of climate change is expected to generally increase crop yields (with winter wheat, sunflower and sugar beet) as a result of the combined effects of CO_2 fertilisation, radiation use efficiency and longer growing seasons which mostly applies to species with the C_3 photosynthetic pathway[22,23] and not necessarily to species with the C_4 pathway [24]. Elevated CO_2 increases the size and dry weight of most C_3 plants and plant components (Fig. 6). Relatively more photoassimilate is partitioned into structural components (stems and petioles) during vegetative development in order to support the light-harvesting apparatus (leaves)[24]. The harvest index tends to decrease with increasing CO_2 concentration and temperature. Increased yields were expected for sunflower might whereas smaller increases in yield or possible decreases in yield for potatoes, oilseed rape and high quality horticultural crops was expected when grown under water stressed light textured soils. Increases in grass yields are also generally expected. Both climatic warming and rising CO_2 levels in the atmosphere will enhance tree growth in the short term (Fig. 7).

In summary, increased productivity would generally lead to greater inputs of carbon to soil, thus increasing SOM. However, this depends on[18]:

- How elevated CO_2 and temperature and changes in rainfall affects the allocation of C above and below ground

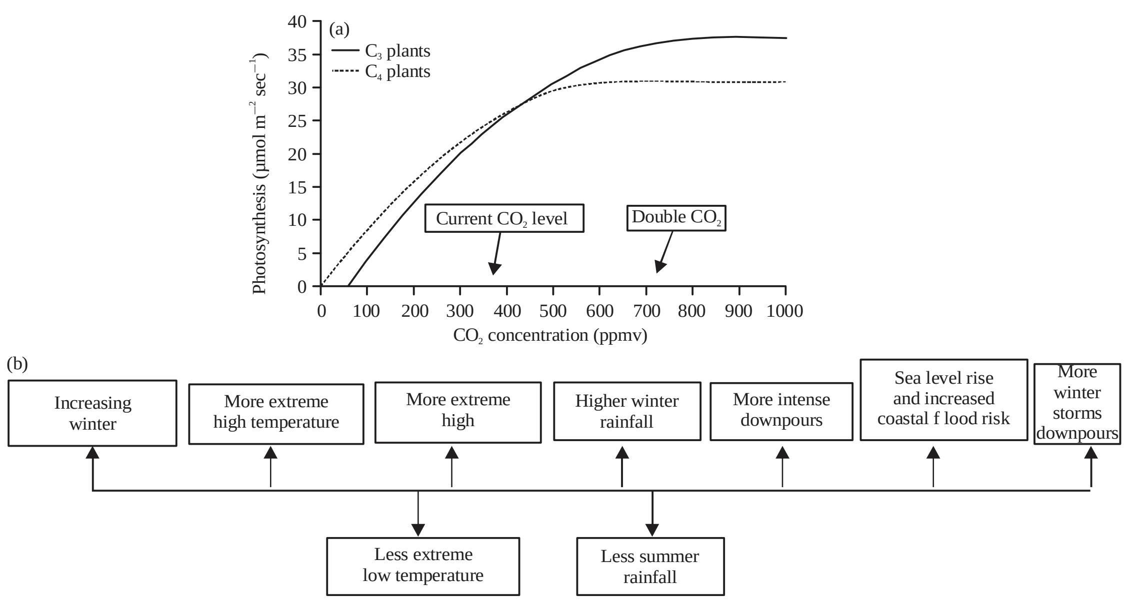


Fig. 6(a-b): Schematic effect of CO_2 concentrations on C_3 and C_4 plants (after Wolfe and Erickson, 1993[20]). The main mechanism of CO_2 fertilization is that is depresses photo-respiration, more so in C_3 than in C_4 plants adapted from Bazzaz and Sombroek, 1996[21]

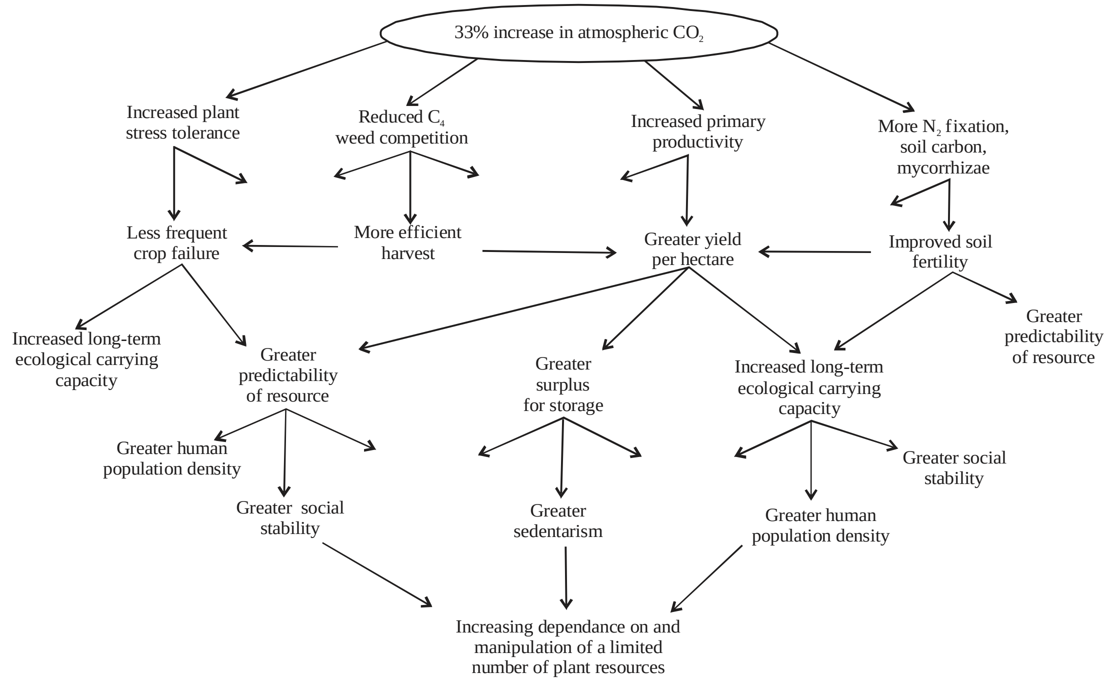


Fig. 7: Possible linkages between an increase in atmospheric CO_2 from 200-270 mol per mol and increased human specialization on a limited number of plant resources[25,26]

- Harvest index of future crop varieties and management in forestry (e.g., type of harvesting)
- How changes in temperature and moisture affect SOM turnover

Potential impacts of land use change: The possible impact of land use change includes reduced arable land, conversion of grassland to arable afforestation, alteration of soil properties like changes in the soil biota which may have modified effects on soil structural stability, soil biodiversity, plant-soil interactions and nutrient cycling. Further changes in vegetation cover could alter runoff and nutrient losses as well as SOM content. However, socio-economic trends may have a dominant role in determining land use patterns.

Cacciotti and his co-workers[27] reported that afforestation results in a decrease in soil respiration and hence decrease soil CO_2 emissions although the reasons for this are not clear as there is only a significant relationship with temperature. Soil respiration has been shown to be driven by certain climatic parameters such as air temperature, precipitation and soil water status.

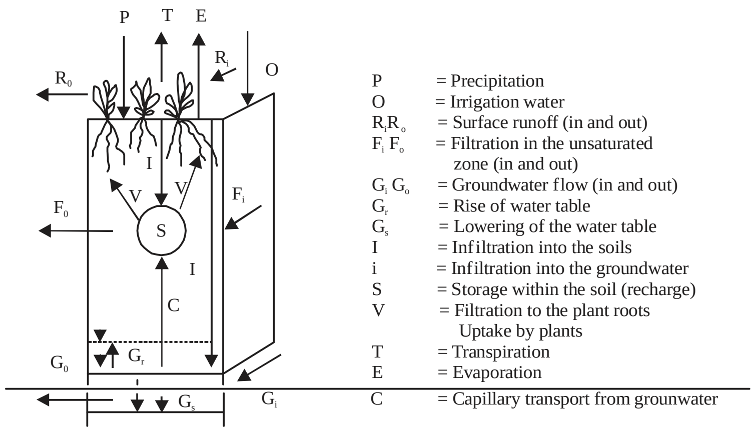
Timescale for change: The diverse range of physical, chemical and biological processes that affect soil formation and modify soil properties will respond to climate change according to varying timescales (Table 1).

IMPACT OF CLIMATE CHANGE ON DIFFERENT SOIL PARAMETERS

Soil physical parameters

Soil water: Soil water can be fluctuated by a number through climate change such as precipitation causing rapid changes in soil water since the time-scale for response is usually within a few hours, temperature increase resulting in greater evapotranspiration loss of water from the soil and lastly the type of land use. The integral influence of climate-hydrology-vegetation-land use changes are reflected by the field water balance and soil moisture regime[28,29,30]. Their components and the potential impact of four plausible climate change scenarios on these factors are summarized in their components and the potential Fig. 8.

As for 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[31]. Whereas the decrease in atmospheric precipitation 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



Factors	CI			
	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

Fig. 8: 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)[31]. Reproduced with minor modifications from[28,29,32] Influence of climatic change on soil moisture regime, texture, structure and erosion[33]

Table 1: Time scale for changes in soils with change in climate[18]

Time scale categories	Soil parameter	Properties and characteristics	Regimes
$<10^{-1}$ year	Temperature, moisture content, bulk density, total porosity, infiltration rate, permeability, composition of soil air and nitrate content	Compaction, drainage and workability	Aeration and heat regime
10^{-1}-10^{0} year	Total water capacity, field capacity, hydraulic conductivity, pH, nutrient status and composition of soil solution	Microbiota	Microbial activity, human controlled plant nutrient regime and erosion
10^{0}-10^{1} year	Wilting percentage, soil acidity, cation exchange capacity and exchangeable cations	Type of soil structure, annual roots biota, meso-fauna, litter, fluvic, gleyic, stagnic properties and slickensides	Moisture, natural fertility, salinity-alkalinity, desertification and permafrost
10^{1}-10^{2} year	Specific surface, clay mineral association and organic matter content	Tree roots soil biota, salic, calcareous, sodic and vertic properties	
10^{2}-10^{3} year	Primary mineral composition and chemical composition of mineral part	Tree roots and colour (yellowish/reddish), iron concretions, soil depth, cracking, soft powdered lime and indurated sub-soil	
$>10^{3}$ year	Texture, particle-size distribution and particle density	Parent material, depth and abrupt textural change	

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[31].

These direct influences are modified with the impact of vegetation characteristics (type, density, dynamics, species composition, biomass production, litter and root characteristics), human intervention like land use, cropping pattern, agrotechnics, amelioration (including water and wind erosion control, chemical reclamation, irrigation and drainage) and other activities radically modify ing 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[34-37].

Several soil forming processes, including organic matter turnover, structure formation (it affects the processes of run off, infiltration, percolation and drainage vital in the distribution of water across the landscape), weathering, podzolisation, clay translocation and gleying are strongly affected by soil moisture contents.

Soil temperature: Trends in soil temperature are important but rarely reported, indicators of climate change. There is a close relationship between air temperature and soil temperature and a general increase in air temperature will inevitably lead to an increase in soil temperature. The temperature regime of the soil is governed by gains and losses of radiation at the surface, the process of evaporation, heat conduction through the soil profile and convective transfer via the movement of gas and water. Qian and co-workers[38] studied the soil temperature trends associated with climate change in Canada where he found the warming trend in soil temperatures which was associated with trends in air temperatures and snow cover depth over the period of 30 years. It is also observed that a significant decreasing trend in snow cover depth in winter and spring was associated with increasing air temperatures. As with soil moisture, soil temperature is a prime mover in most soil processes. Warmer soil temperature will accelerate soil processes, rapid decomposition of organic matter, increased microbiological activity, quicker nutrients release, increase nitrification rate and generally accentuate chemical weathering of minerals. However, soil temperatures will also be affected by the type of vegetation occurring at its surface, which may change itself as a result of climate change or adaptation management[18].

Soil structure and texture differentiation: Soil structure is an important property which indicates how the soil particles combine together. Soil structure is responsible for the movement of gases, water, pollutants/contaminants, seepage, nutrients, maintenance of water quality, building foundations, soil fauna and the emergence of crops. The nature and quality of the structure is strongly influenced by the amount and quality of organic matter present, inorganic constituents of the soil matrix, cultivation methods and natural physical processes such as shrink-swell (soils with high clay contents, particularly smectitic mineralogy) and freeze-thaw behaviour. A decline in soil organic matter levels lead to a decrease in soil aggregate stability, infiltration rates and increase in

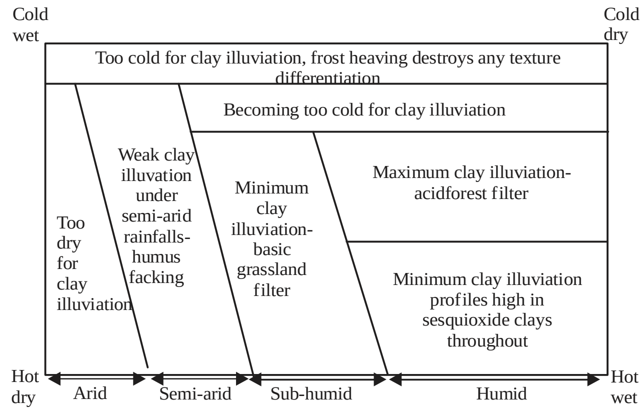


Fig. 9: Effect of climate scenarios on texture differentiation of soils[35,40,41]

susceptibility to compaction, run-off furthermore susceptibility to erosion (Similar to the observations of[39]. In some areas there could be an increase in flash flooding as a result of increased cracking and change in structure.

Texture is the differentiation of sand silt clay percentages is soil. It had direct impact of climate change. In Fig. 9, the impact of four potential climate scenarios on two important soil processes as the texture differentiation in the soil profile[40,41].

Soil biological parameters

Soil organic matter: Soil organic matter is undoubtedly the most important soil component as it improves soil quality though the influences in soil structure, water holding capacity, soil stability, nutrient storage and turnover and oxygen-holding capacity. Organic matter is particularly important as the prime habitat for immense numbers and variety of soil fauna and microflora, which play a critical role in the health and productivity of soils. Soil organic matter is highly susceptible to changes in land use and management, soil temperature and moisture. In the last decades changes in land use and management have already led to a significant decline in organic matter levels in many soils which increases the susceptibility to soil erosion. These interpretations were made by Bot and Benites[39].

Soil organic matter is capable of acting both as a source and sink of carbon in the biosphere uring climate change. The impact of climate change and increasing atmospheric CO_2 was modeled for 31 temperate and tropical grassland sites using "CENTURY" model by Parton and his co-workers[42] where, they reported that except in cold desert steppe regions, CO_2 increased production everywhere. Climate change caused soil carbon to decrease overall, with a loss of 4 Pg global grasslands after 50 years. Combined climate change and elevated CO_2 increased production and reduced global grassland C losses to 2 Pg, with tropical savannas becoming small sinks for soil C. Similar impacts of soil carbon loss reports were observed by[43] in Australian soil. Davidson and Janssens[44] studied the temperature sensitivity of soil carbon decomposition and feedbacks to climate by employing two

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What is q-theory of organic matter dynamics?

The q theory suggests that quality is related to the number of enzymatic steps required for a carbon atom to be metabolized (and released) by a decomposer[44].

The equation can be described as starting from an initial mean litter quality, q0, the development of the quality of a litter cohort over time, t, is given[45] in Eq. 1:

$$q(t) = q0(1+\beta fC\eta 11u_0q^{\beta}t)^{-1/\beta} \quad (1)$$

where, fC is the C concentration in decomposer biomass, parameter β is a shape parameter determining how rapidly the decomposer's growth rate changes with quality. This parameter includes the interaction with soil texture and increases with clay content[46]. The parameter η11 describes the rate of change of quality. The parameter u0 is a basic decomposer growth rate and depends on external factors such as temperature and humidity.

The fraction of C remaining in the litter when quality has decreased to q is given in Eq. 2:

$$g(q) = (q/q_0)^{(1-e0)/\eta 11e0} \quad (2)$$

The initial decomposition rate of C of quality q0 is given in Eq. 3:

$$k(q0) = [(1-e_0)/e_0]\times fCu_0q\beta_0 \quad (3)$$

Most parameters are given previously estimated values.The parameter β, which has been shown to depend on soil texture (clay content), is given the basic value of β = 7 corresponding to zero clay content[46]. The values of the other decomposer-related parameters e0 and 11 were shown by[47] to be constant for a large range of litters and physical conditions (e0 = 0.25, η11 = 0.36). Needle, root and ground vegetation litters were assigned an initial quality q0 = 1, whereas a value of q0 = 0.99 was used for other litter fractions[45]. The basic decomposers growth rate u0 for needlelitters. The Eq. 1 were obtained by least squares fit of measured and predicted mass losses. The value of the parameter u0 as a function of temperature (T) is estimated from measured mass loss of needle litter[48]. The value of tmax was set to 3 year for branches and cones and to 34 year for stems[49].

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models namely CENTURY33 and ROTH-C34. Most efforts to characterize the kinetics of SOM decomposition have stratified carbon compounds into 'Pools' that share similar mean residence times (MRTs) within the soil. The MRT is the inverse of the decomposition reaction rate (k) and therefore reflects a combination of inherent reactivity of the compound and the environmental constraints on its decomposition. The two best-known biogeochemical models of soil carbon dynamics-the CENTURY33 and ROTH-C34 models-compartmentalize soil carbon into 5-7 conceptual pools, including 2-4 pools of decomposable plant material

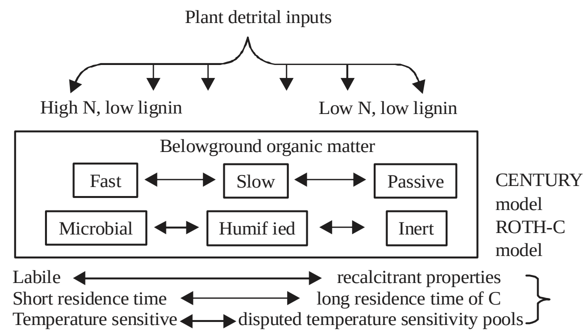

Fig. 10: Properties of conceptual pools of belowground carbon stocks in two well-known models[44]

near the soil surface (litter layer) and three pools of carbon in the mineral soil, with MRTs ranging from years to millennia (Fig. 10). Decomposition of the plant detritus in the litter layers is based on well-supported functions of climate and indices of substrate decomposability, such as carbon-to-nitrogen ratios and lignin content[50,51]. The three C pools in the mineral soil, from the most labile to the most recalcitrant to decomposition, are called fast, slow and passive in CENTURY and 'Microbial biomass', 'Humified organic matter' and 'Inert' in ROTH-C. Many attempts have been made with partial success to measure these various pools through physical and chemical fractionation of the soil[52] but they remain largely simplified modelling constructs. In lieu of discrete pools, a continuum of soil C substrates of varying chemical complexity and MRTs has also been used to simulate soil C dynamics[53].

Although, direct measurements of the sizes and MRTs of these conceptual pools of soil C remain imperfect, a consensus has emerged that using multi-pool soil C models to simulate changes in soil C stocks is a major improvement over treating soil C as a single, homogeneous pool[54,55]. A substantial fraction of the SOM resides in the most recalcitrant pool that decomposes very slowly. The importance of this model structure was demonstrated when the multipool ROTH-C model was used in lieu of a single soil C pool model for a global simulation of climate change using the Hadley general circulation climate model. Soil C losses and gains were less severe with the multipool model, both regionally and globally. While these models have proven effective for explaining local and regional variation in current soil C stocks and changes in stocks due to management and land-use change, a consensus has not emerged for their applicability to climate change. Typically, most models of soil C dynamics assume that decomposition of all SOM is nearly equally sensitive to temperature[56,57] but this assumption is contrary to kinetic theory. The Kinetic theory suggests that SOM quality is the number of enzymatic steps required to release as carbon dioxide a carbon atom from an organic compound. The larger the number of steps the lower is the quality of the carbon atom. Such a measure connects quality to thermodynamics. It also explains the rapid decrease in decomposition rate with decreasing quality suggested in the q-theory of organic matter dynamics and shows that the decomposition rate of low quality substrates has stronger temperature dependence than that of high quality substrates.

Moreover, decomposition rates may be slow (and MRTs may be long) either because the complex structures of the molecules render them resistant to decomposition or because environmental constraints restrict access of enzymes to the molecules or because of a combination of these two factors. Both protected simple compounds and more complex unprotected compounds might be lumped together into a common pool with common MRTs. If the causes of varying MRTs and their potential for change are to be understood, the distinction between intrinsic and apparent temperature sensitivities needs to be addressed explicitly[44].

Globally, the amount of carbon stored in soils is over three times that found in the atmosphere[58]. How climate change will impact on soil organic matter is a matter of considerable debate. On the one hand it is recognised that global warming and increasing CO_2 levels in the atmosphere can favour increased plant growth, which in turn could provide more organic matter for the soil. On the other hand a rise in air temperature and that of the soil would be consistent with an increase in decomposition and loss of soil organic matter. There is thus significant interest in the fate of such carbon, particularly the extent to which soils and land use can be used to regulate the sequestration of carbon from the atmosphere or the loss of soil organic carbon to the atmosphere. The balance of opinion currently is that in the absence of mitigating action, losses through organic matter decomposition are likely to exceed levels gained from increased plant growth, thus adding to atmospheric CO_2 levels and the greenhouse gas effect and to lower levels of soil organic matter. This is similar to the findings of Beedlow and co-workers[59]. Increased water-use efficiency under higher CO_2 conditions will lead to higher productivity, especially in water-limited systems; but the magnitude of the response will depend on other limiting factors such as soil nitrogen[60,61]. Some experiments have shown an "Acclimatization" or "Acclimation" effect, in which the growth response to higher CO_2 in the longer term is less than in short-term experiments[62]; whether this effect applies at the ecosystem level over many years remains untested, however.

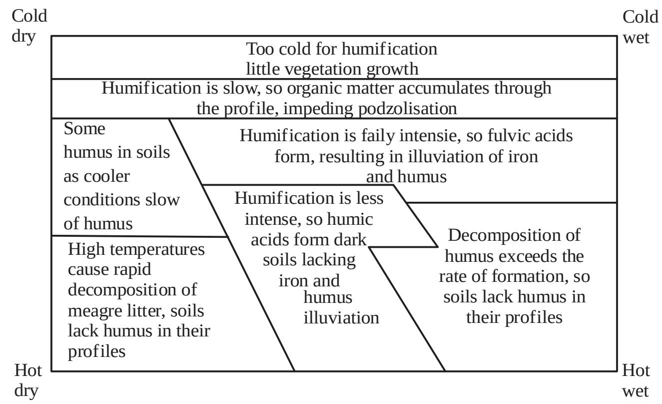

Fig. 11: Role of organic matter in soil formation in response to climate[40,41]

A group of soils that are particularly vulnerable to climate change are the peat soils. These are soils that are dominantly composed of organic matter throughout their whole depth. Already they have been under threat because of drainage for use in crop production. Further drying out of the soils in a warmer drier climate with concomitant oxidation could lead to losses of this important, highly productive soil type (Similar to the observations of[63]) so incurring large losses of carbon and therefore contributing to a potential positive climate feedback. In Fig. 11, the impact of four potential climate scenarios on two important soil processes on the soil organic matter cycle.

Soil fauna and soil flora: Soil fauna and flora (thousands of species found in a metre square of most soils) are essential components of all soils which play vital role in the retention, breakdown and incorporation of plant remains, nutrient cycling and their influence on soil structure and porosity. Global warming may not have a direct effect on the ecological composition because soil fauna and flora have a relatively broad temperature optimum. However, changes in ecosystems and migration of vegetation zones may seriously affect less migratory soil flora and fauna through increased temperature and rainfall changes. A further significant impact of climate change on soil fauna and flora is through enhanced CO_2 levels in the atmosphere which leads to enhanced plant growth and allocation of carbon below ground rendering the microbial population to accelarate nitrogen fixation rates, nitrogen immobilisation and denitrification (Similar to the findings of[64]), increased mycorrhizal associations, increased soil aggregation and lastly increased weathering of minerals. However as noted above, much will depend on what balance between increased plant growth on the one hand and increased decomposition of soil organic matter on the other will emerge under a changing climate.

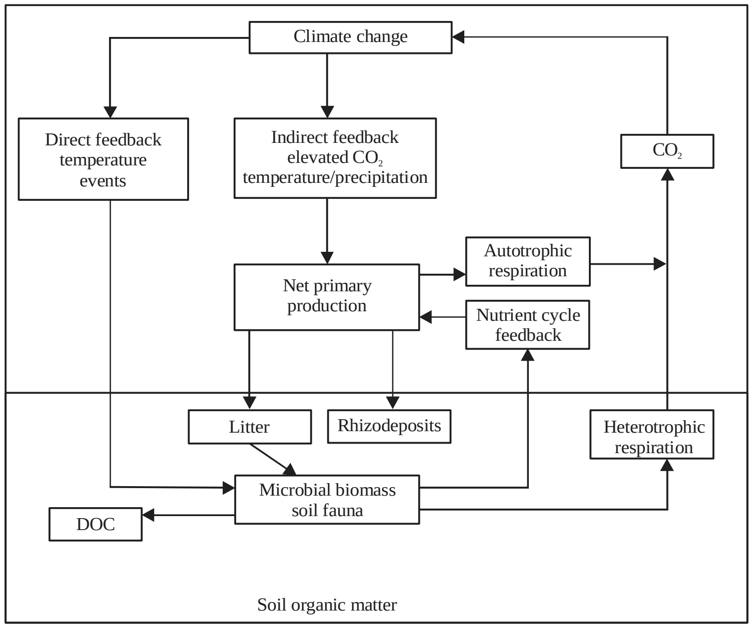

Fig. 12: Direct and indirect effects of climate change on soil microbial communities and routes of feedback to global warming through carbon dioxide production. Direct effects include the influence on soil microbes and greenhouse gas production of temperature, changing precipitation and extreme climatic events, whereas indirect effects result from climate-driven changes in plant productivity and vegetation structure which alter soil physicochemical conditions, the supply of carbon to soil and the structure and activity of microbial communities involved in decomposition processes and carbon release from soil. Background image courtesy of Jill Colquhoun Bardgett[65]

Climate change has both direct and indirect effects on the activities of soil microbes that feedback greenhouse gases to the atmosphere and contribute to global warming (Fig. 12): Direct effects include the influence on soil microbes and greenhouse gas production of temperature, changing precipitation and extreme climatic events, whereas indirect effects result from climate-driven changes in plant productivity and diversity which alter soil physicochemical conditions, the supply of carbon to soil and the structure and activity of microbial communities involved in decomposition processes and carbon release from soil (Fig. 12)[65]. Direct climate-microbe feedbacks is organic matter decomposition and the notion that global warming will accelerate rates of heterotrophic microbial activity, thereby increasing the efflux of CO_2 to the atmosphere and exports of dissolved organic carbon by hydrologic leaching[66,44]. Because rates of soil respiration are thought to be more sensitive to temperature than primary production[66], it is predicted that climate warming will increase the net transfer of carbon from soil to atmosphere, thereby creating a positive feedback on climate change[67].

Indirect climate-microbe feedback is the indirect effects on soil microbial communities and their activity and hence the potential for microbial feedback to climate change-through its influence on plant growth and vegetation composition[65]. Such plant-mediated indirect effects of climate change on soil microbes operate through a variety of mechanisms, with differing routes of feedback to climate change but these can broadly be separated into two. The first mechanism concerns the indirect effects of rising atmospheric concentrations of carbon dioxide on soil microbes, through increased plant photosynthesis and transfer of photosynthate carbon to fine roots and mycorrhizal fungi[68-70] and heterotrophic microbes[71,72]. It is well established that elevated carbon dioxide increases plant photosynthesis and growth, especially under nutrient-rich conditions and this in turn increases the flux of carbon to roots, their symbionts and heterotrophic microbes through root exudation of easily degradable sugars, organic acids and amino acids[73,71]. The consequences of increased carbon flux from roots to soil for microbial communities and carbon exchange are difficult to predict, because they will vary substantially with factors such as plant identity, soil food web interactions, soil fertility and a range of other ecosystem properties[74,72]. But, some potential outcomes for soil microbes and carbon exchange include: Increases in soil carbon loss by respiration and in drainage waters as dissolved organic carbon due to stimulation of microbial abundance and activity and microbial contributions to climate change[65].

Soil chemical parameters

Chemical processes in soils: The most rapid processes of chemical or mineralogical change under changing external conditions would be loss of salts and nutrient cations where leaching increases and salinization where net upward water movement occurs because of increased evapotranspiration or decreased rainfall or irrigation water supply[63]. The clay mineral composition per mineralogy of the coarser fractions would generally change little, even over centuries but exceptions found regarding the transformation of halloysite formed under perennially moist conditions subjected to periodic drying or the gradual dehydration of goethite to haematite under higher temperatures or severe drying, condition or both. Changes in the surface properties of the clay fraction is generally slower than salt movement which take place much faster than changes in bulk composition or crystal structure. Such surface changes have a dominant influence on soil physical and chemical properties [75,76].

Changes in the clay mineral surfaces or the bulk composition of the clay fraction of soils are brought about by a small number of transformation processes, listed below[77]. Each of these processes can be accelerated or inhibited by changes in external conditions due to global change as[63]:

- Hydrolysis by water containing carbon dioxide, which removes silica and basic cations, may be accelerated by increased leaching rates
- Cheluviation, which dissolves and removes especially aluminium and iron by chelating organic acids, may be accelerated by increased leaching rates
- Ferrolysis, a cyclic process of clay transformation and dissolution mediated by alternating iron reduction and oxidation, which decreases the cation exchange capacity by aluminium interlayering in swelling clay minerals, may occur where soils are subject to reduction and leaching in alternation with oxidation: In a warmer world, this may happen over larger areas than at present, especially in high latitudes and in monsoon climates
- Dissolution of clay minerals by strong mineral acids, producing acid aluminium salts and amorphous silica e.g., where sulphidic materials in coastal plains are oxidized with an improvement of drainage; however, a rise in sea level would reduce the likelihood of this occurring naturally
- Reverse weathering, i.e., clay formation and transformation under neutral to strongly alkaline conditions, which may create, e.g., montmorillonite, palygorskite or analcime; it could begin in areas drying out during global warming and would continue in most presently arid areas

Acidification, salinization, sodicity problem in soil: While temperature increases are forecast for most parts of the world, there is less certainty about precipitation changes. Significant increases in rainfall will lead to increases in leaching, loss of nutrients and increasing acidification, depending on the buffering pools existing in soils. The direction of change towards increased leaching or increased evaporation will depend on the extent to which rainfall and temperature change and consequent changes to land use and its management. In either case the situation could lead to important changes in soils.

Increased salinization and alkalization would occur in areas where evaporation increased or rainfall decreased[78]. Transient salinity increases as capillary rise dominates, bringing salts into the root zone on sodic soils. Leaching during episodic rainfall events may be limited due to surface sealing. Increased subsoil drying increases concentration of salts in the soil solution. Conversely, the severity of saline scalds due to secondary salinisation may abate as groundwater levels fall in line with reduced rainfall; this development could have significant impacts on large areas semi-arid zones. In areas where salinity is a result of recharge processes, salinization would increase if the upstream recharging rainfall increased[79]. Increasing atmospheric CO_2 concentration can reduce the impact of salinity on plant growth[80].

Bush and his co-workers[81] anticipated impacts of climate change in the coastal lowland acid sulfate soils. The anticipated impacts of climate change are warmer conditions, an increasing proportion of rainfall to occur from heavy falls, increasing occurrence of drought in many regions, increasing frequency of intense tropical cyclones, rising sea levels and frequency of extreme high seas (e.g., storm surges). All of these predicted impacts have direct relevance to coastal acid sulfate soils landscapes, through either exacerbating sulfide oxidation by drought, re-instating reductive geochemical processes or changing the export and mobilisation of contaminants. The interaction of specific land management factors such as man-made drainage will also have a significant role in how the predicted impacts of climate change affect these landscapes. Understanding the potential impacts of climate change for coastal lowland acid sulfate soils is particularly important, given the utility of these areas for agriculture and urban communities, their unique capacity to cause extreme environmental degradation and their

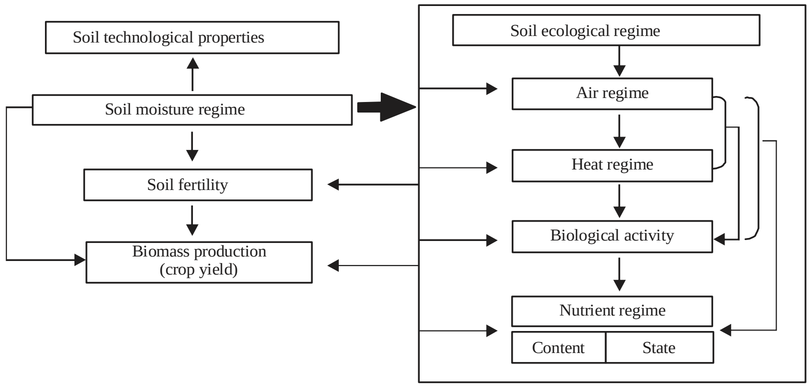

Fig. 13: Relationships between soil moisture regime, other soil ecological conditions and soil fertility[27]

sensitivity to climatic factors such as temperature and hydrology and susceptibility to sea-level inundation. Bush and his co-workers[81] investigated the hydrogeochemical consequences of seawater inundation of an 800 ha acid sulfate soil wetland and study of current drought triggered broad-scale oxidation (i.e., 20,000 ha of exposed soils) of lake bed sediments in the lower Murray-Darling River Basin, South Australia.

Soil fertility and nutrient acquisition: 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. 13).

Crop yields on soils in developing countries decrease exponentially with increasing aridity[82]. Soil moisture deficit directly impacts crop productivity but also reduces yields through its influence on the availability and transport of soil nutrients. Drought increases vulnerability to nutrient losses from the rooting zone through erosion[83]. Because nutrients are carried to the roots by water, soil moisture deficit decreases nutrient diffusion over short distances and the mass flow of water-soluble nutrients such as nitrate, sulfate, Ca, Mg and Si over longer distances[84,85]. Roots extend their length, increase their surface area and alter their architecture in an effort to capture less mobile nutrients such as phosphorus[86]. Reduction of root growth and impairment of root function under drought conditions thus reduces the nutrient acquisition capacity of root systems. Reductions in both carbon and oxygen fluxes and nitrogen accumulation in root nodules under drought conditions inhibit nitrogen fixation in legume crops[87-89]. Drought alters the composition and activity of soil microbial communities like the rediction of soil nitrifying bacteria.

Excessive precipitation causes significant source of soil nutrient loss in developing countries[90,91] like nitrate leaching[92]. Agricultural areas with poorly drained soils or that experience frequent and/or intense rainfall events can have waterlogged soils that become hypoxic. The change in soil redox status under low oxygen can lead to elemental toxicities of Mn, Fe, Al and B that reduce crop yields and the production of phytotoxic organic solutes that impair root growth and function. Hypoxia can also result in nutrient deficiency since the active transport of ions into root cells is driven by ATP synthesized through the oxygen dependent mitochondrial electron transport chain[93,94]. Significant nitrogen losses can also occur under hypoxic conditions through denitrification as nitrate is used as an alternative electron acceptor by microorganisms in the absence of oxygen[95].

Soil warming can increase nutrient uptake from 100-300% by enlarging the root surface area and increasing rates of nutrient diffusion and water influx[96,97]. Since warmer temperatures increase rates of transpiration, plants tend to acquire water soluble nutrients (nitrate, sulfate, Ca, Mg primarily move towards roots through transpiration-driven mass flow) more readily as temperature increases. Temperature increases in the rhizosphere can also stimulate nutrient acquisition by increasing nutrient uptake via faster ion diffusion rates and increased root metabolism[98]. However, any positive effects of warmer temperature on nutrient capture are dependent on adequate soil moisture. If under dry conditions higher temperatures result in extreme vapor pressure deficits that trigger stomatal closure (reducing the water diffusion pathway in leaves)[99], then nutrient acquisition driven by mass flow will

Table 2: Potential interactions of global change variables with mineral stress[101]

Process	Global change variables	Interaction with mineral stress
Erosion	Heavy precipitation, drought	general losses of soil nutrients, SOC and fertilizer
Transpiration-driven mass flow	Drought, temperature, RH, CO_2	NO_3, SO_4, Ca, Mg and Si
Root growth and architecture	Drought, soil temperature, CO_2	All nutrients, especially P and K
Mycorrhizas	CO_2	P, Zn (VAM) N (ecotomycorrhizas)
Soil microbes (N cycling)	Drought, soil temperature	N
Biological N Fixation	Drought, soil temperature	N
Soil redox status	Flooding	Mn, Fe, Al and B
Soil leaching	Heavy precipitation	NO_3, SO_4, Ca and Mg
Plant phenology	Temperature	P, N and K
Soil organic carbon status	Soil moisture, soil temperature, CO_2	All nutrients
Salinization	Precipitation, temperature	Na, K, Ca and Mg

decrease[100]. Emerging evidence suggests that warmer temperatures have the potential to significantly affect nutrient status (especially reduced P acquisition) by altering plant phenology[32]. Besides higher temperature accelerates SOC losses from soil (Table 2).

Other soil degradative parameters

Soil erosion and degradation: Soil erosion is the movement and transport of soil by various agents, particularly water, wind and mass movement; hence climate is a key factor. The increase in soil erosion is strongly linked with the clearance of natural vegetation, to enable land to be used for arable agriculture and the use of farming practices unsuited to the land on which they are practised. This, combined with climatic variation and a predicted increase in extreme weather events, has created ideal conditions for soil erosion. The main climatic factors influencing soil erosion are rainfall (amount, frequency, duration and intensity) and wind (direction, strength and frequency of high intensity winds), coupled with drying out of the soil. Land use, soil type and topography are the other key factors.

Nearing and his co-workers[102] studied that increased rainfall processes, amounts and intensities due to climate change lead to greater rates of erosion. They reported erosion will increase approximately 1.7% for each 1% change in annual rainfall. The dominant factor related to the change in erosion rate is the amount and intensity of rainfall that falls in the storm, rather than the number of days of precipitation in a year. Lee and his co-workers[103] reported the linear relationship between precipitation volume and runoff that was reported between precipitation and soil erosion. A -20 to 20% percent increase in precipitation resulted in an estimated -40 to 40% change in runoff. From the relationship between runoff and precipitation intensity and frequency it was found that rainfall intensity had a greater effect than rainfall frequency on runoff. Each 1 percent change in precipitation amount resulted in an average 2.5% change in runoff if a change in intensity accounted for all of the change in amount; an average 1.28% change in runoff occurred if a change in frequency accounted for all of the change in precipitation amount and an average 1.97% change in runoff occurred if a combination of change in intensity and frequency accounted for the change in precipitation volume. The second dominant process related to erosion and climate change is biomass production. Biomass levels ill change under climate change due to changes in temperature, moisture and atmospheric carbon dioxide levels and biomass ranks right next to rainfall in terms of its impact on erosion rates[102]. The third major process of erosion rate changes under climate change and the wild card is land use. Detailed land use changes as a function of future climates (both weather related and economic climates) are nearly impossible to predict with any degree of accuracy. In general the erosion impact of landuse change was found in the Midwest through the shifting of cultivation of wheat and corn by soybean.

Soil erosion by water is more widespread and its impact greater than that by wind. Climate change is likely to affect soil erosion by water through its effect on rainfall intensity, soil erodability, vegetative cover and patterns of land use. General circulation models indicate a marked change in soil moisture regime for some areas and therefore changes also in soil erodability, vegetation and land use. For many areas, they also predict seasonally more intense drying out coupled with increased amounts and intensity of precipitation at other times, conditions that could lead to a large increase in rates of erosion by water.

Soil erosion also occurs by wind transport of soil particles by suspension, surface creep or saltation over distances ranging from a few centimetres to hundreds of kilometres. Wind erosion is particularly a problem on sandy and organic soils where they are subject to intermittent low moisture contents and periodic winds. Those areas where climate change is predicted to lead to more droughty soils under increasing temperatures will become increasingly vulnerable. Although general circulation models have in the past been unable to predict changes in wind speed and frequency with any certainty, the latest models are predicting increased summer continental drying and risk of drought in mid-latitude

Table 3: Influence of four main climatic scenarios on the main soil degradation processes, their natural and anthropogenic causative factors

	Climatic Scenarios				Causative Factors		
Soil degradation process	Cold and dry	Cold and wet	Hot and dry	Hot and wet	Natural	Anthro-pogenic	Numerical description of factors
Soil erosion by water	No/Negligible	Strong	No/Negligible	Strong	1, 2 and 3	9, 10, 11 and 12	**Natural**
Soil erosion by wind	Slight	No/Negligible	Medium	No/Negligible	3	9, 10, 11 and 12	1-Undulating surfaces, 2- Parent rock, 3- Lack permanent/dense vegeta-tion,
Acidification	Slight	Strong	No/Negligible	Strong	2 and 4	13 and 15	4-Litter decom-position, 5-Low lying lands, 6-Improper drainage, 7-High
Salinization/Alkalization	Medium	No/Negligible	Strong	No/Negligible	5, 6 and 8	14	water table(non-saline) and 8-High water table (saline)
Physical degradation	Slight	Medium	Medium	Strong	--	10 and 12	**Anthropogenous**
Extreme moisture regime (water logging)	No/Negligible	Strong	No/Negligible	Medium	5, 6 and 7	11, 12 and 14	9-Deforestation, 10-Over- grazing, 11- Irrational land use, 12- Improper tillage,
Biological degradation	Slight	Medium	Medium	Strong	--	11 and 16	13-Irrational fertilizer application,
Unfavourable nutrient regime	Slight	Medium	Medium	Strong	2 and 6	13	14- Improper irrigation, 15-Acid deposition, 16- chemical soil pollution
Soil pollution (toxicity)	No/Negligible	Slight	Slight	No/Negligible	--	16	

areas and an increase in tropical cyclone peak intensities in some areas, both sets of conditions favouring an increase in soil erosion by wind. However, it is important to note that erosion is site specific and different permutation of conditions can increase or decrease it.

Regarding soil degradation through climate change (Table 3) 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[104,105,106,78].

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

- **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 (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

- **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
- **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 (→increasing rate of downward filtration→leaching) will reduce, lower precipitation and higher temperature will intensify salinization/ sodification processes: Higher rate of evapo transpiration→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: Go>Gi+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
- **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
- **Biological degradation:** Temperature, precipitation and vegetation changes considerably influence biological soil processes but few data are available on these consequences
- **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 (→potential groundwater „pollution") and reductive processes. Low precipitation (→dry conditions) may reduce the solubility, mobility and availability of available elements and compounds

Impacts on flooded rice soils: The immediate impacts of climate change on rice production systems and food security will be felt in the form of adverse effects of extreme weather events on rice production. Floods also cause indirect damage to rice production by destroying the properties and production means of farmers and infrastructures supporting rice production such as dams, dikes, roads, etc. Less immediate but possibly even more significant impacts are anticipated due to changes in mean temperatures, increasing weather variability and sea level rising.

Impact of climate change on chemical and biological properties in contaminated soils: The relationship between climate parameters and soil properties can also be subject to confounding effect that may exist between different climate parameters. Recent development of remediation techniques showed that soil stabilisation and bioremediation treatments applied had good potential for the remediation of heavy metal and hydrocarbon contaminated soils[107]. The soil properties such as soil microbial activity, soil acidity, heavy metal leachability, metalloid toxicity (i.e., arsenic), rate of hydrocarbon contaminant degradation were shown to be higher in the summer season than in the winter season while the soil CEC has been shown to be stable over the two year period of the study. With respect to differences between the climate scenarios, different soil properties such as soil pH, soil redox potential, soil CEC and cadmium leachability showed no variability. However other soil properties such as the soil microbial activity, copper leachability and the rate of hydrocarbon degradation were shown to be lower by up to 30, 30 and 150%, respectively in the warmer and more arid climate change scenarios compared to the cooler and wetter baseline scenario[107]. In the case of hydrocarbon soil contamination, these findings suggest a revisit of remediation guidelines and risk assessment procedures with the aim of putting into perspective the expected slower rate of hydrocarbon degradation in coming years under arid climate change scenarios. In the case of heavy metal contaminants, there may be a shift in the risk and contamination pathway due to possible reduction in ground water contamination and increase in contaminant concentration in soil dust particles. Similar is the case of arsenic contamination in the soils of West Bengal where the warmer climate induces arsenic contamination build-up through the increased irrigation of arsenic contaminated groundwater[108]. The application of remediation strategies such as revegetation that reduce both the transport of contaminated dust by wind erosion and also reduce leachability by sequestration in plant parts have been suggested as adaptation to these changes. Ultimately, due to the complex interactions between climate parameters and soil properties the best response to these contamination condition in view of the impending climate change conditions would be site specific, determined by perceived contamination pathways which would be influenced by the end use purposes for the sites; both at the present and in the foreseeable future.

Overall Impact of Climate change on soil health: The Soil Science Society of America (SSSA) defines soil quality as: "The capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water quality and support human health and habitation"[14]. Soil quality could, in part, be viewed as a static (qualitative) measure of the capability of soil, where as 'Soil health' infers a dynamic state, where human impact causes a shift in quality. There are numerous potential indicators of soil quality/health. These indicators can be categorised broadly as visual (e.g., runoff, plant response, weed species), physical (e.g., topsoil depth, bulk density, aggregate stability, crusting, compaction), chemical (e.g., pH, salinity, organic matter action exchange capacity, contaminant concentrations) and biological (e.g., activity of micro-macro-organisms) indicators. Of the range of potential indicators used to infer soil health status, soil carbon is particularly important[109,110]. Organic matter is vital because it supports many soil processes that are associated with fertility and physical stability of soil across the various ecosystem services. In particular organic matter provides an energy source for microbes structurally stabilizes soil particles, stores and supplied plant essential nutrients such as nitrogen, phosphorus and sulphur and provides cation/anion exchange for retention of ions and nutrients. Carbon within the terrestrial biosphere can also behave as either a source or sink for atmospheric CO_2 depending on land management, thus potentially mitigating oraccelerating the greenhouse effect[111]. Cycling of soil organic carbon is also strongly influenced by moisture and temperature, two factors which are predicted to change under global warming. Overall, climate change will

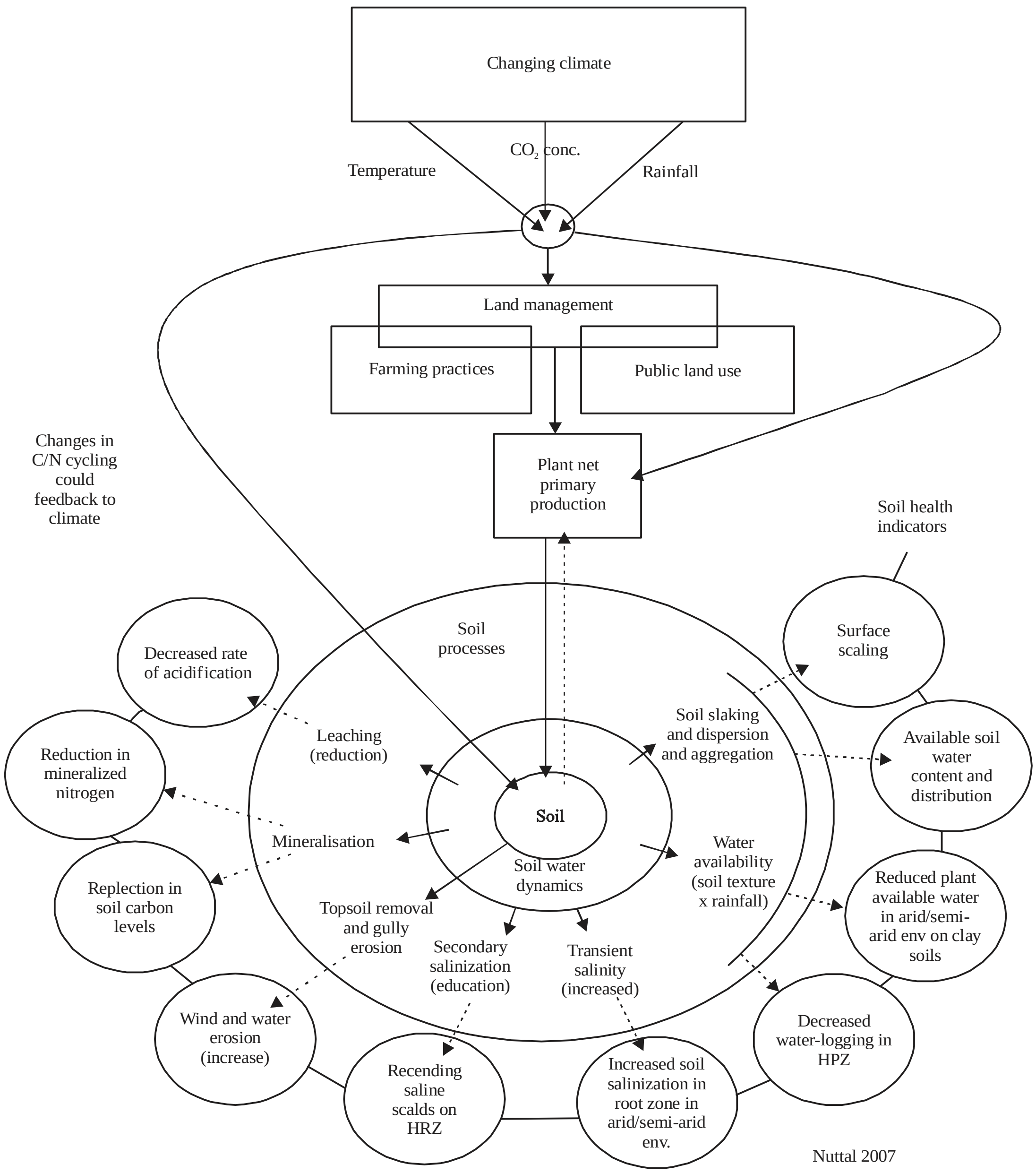

Fig. 14: Schematic representation of the potential links between climate change and soil health

shift the equilibrium, both directly and indirectly of numerous soil processes. These include carbon and nitrogen cycling, acidification, risk of erosion, salinisation, all of which will impact on soil health (Fig. 14).

CLIMATE CHANGE ADAPTION MEASURES RELATED TO AGRICULTURAL SOILS

- Decision making regarding the timing of agricultural operations, the type of operations used (e.g., minimum tillage) and by erosion control measures such as buffer strips could help reduce negative impacts on soil structure, erosion and runoff
- Soil moisture conservation measures such as mulching and minimum tillage could help minimise increased crop irrigation needs in summer. The possibilities and potential methods (technologies) for an efficient soil moisture control are summarized latter
- Careful planning of the amounts and timing of applications of fertilisers and pesticides
- Land management practices to increase SOM content (e.g., addition of cereal straw, animal manure, rotations

etc.) could help maintain SOM contents and avoid increased CO_2 fluxes from soils. Correct farming techniques can sequester carbon into the soil and reverse the greenhouse gases created by Agriculture. The processes to increase soil carbon can be divided into three steps

Use plants to grow soil carbon: It is estimated that between 30-60% of the atmospheric carbon dioxide (CO_2) absorbed by plants is deposited into the soil as organic matter in the form of bud sheaths that protect the delicate root tips and as a range of other root excretions. Research has shown that plant roots put many tonnes of complex carbon molecules and bio available minerals per hectare into the soil every year and are a very important part of the process of forming topsoils and good soil structure. If the weeds are managed properly and their residues are allowed to return to the soil, their nutrient removal from the soil is zero. In fact as they are adding between 30-60% of the organic compounds they create through photosynthesis into the soil they are increasing soil fertility.

Use microorganisms to convert soil carbon into stable forms: The stable forms of soil carbon such as humus and glomalin are manufactured by microorganisms[112]. They convert the carbon compounds that are readily oxidised into CO_2 into stable polymers that can last thousands of years in the soil[113]. The process of making composts uses microbes to build humus and other stable carbons. The microorganisms that create compost continue working in the soil after compost applications, converting the carbon gifted by plants roots into stable forms. Regular applications of compost and/or compost teas will inoculate the soil with beneficial organisms that build humus and other long lasting carbon polymers.

Avoid farming techniques that destroy soil carbon: The continuous application of carbon as composts, manures, mulches and via plant growth will not increase soil carbon levels if farming practices destroy soil carbon. The following are some of the practices that result in a decline in carbon and alternatives that prevent this loss:

- **Reduce nitrogen applications:** Synthetic nitrogen fertilisers are one of the major causes of the decline of soil carbon. This is because it stimulates a range of bacteria that feed on nitrogen and carbon to form amino acids for their growth and reproduction. These bacteria have a carbon to nitrogen ratio of around 30-1. In other words every ton of nitrogen applied results in the bacteria consuming 30 t of carbon. The quick addition of these nitrogen fertilisers causes the nitrogen feeding bacteria to rapidly multiply, consuming the soil carbon to build their cells
- **Carbon eaters rather than carbon builders:** The use of synthetic nitrogen fertilisers changes the soil biota to favour microorganisms that consume carbon, rather than the species that build humus and other stable forms of carbon. By stimulating high levels of species that consume soil carbon, the carbon never gets to increase and usually continues to slowly decline
- **Reduce herbicides, pesticides and fungicides:** Research shows that the use of biocides (Herbicides, Pesticides and Fungicides) causes a decline in beneficial microorganisms. Dr Elaine Ingham has shown that these chemicals cause a significant decline in the beneficial microorganisms that build humus, suppress diseases and make nutrients available to plants. Many of the herbicides and fungicides have been shown to kill off beneficial soil fungi[112]
- **Use correct tillage methods:** Tillage is one of the oldest and most effective methods to prepare planting beds and to control weeds. Unfortunately it is also one of the most abused methods resulting in soil loss, damage to the soil structure and carbon loss through oxidation when used incorrectly
- **Control weeds without soil damage:** A large range of tillage methods can be used to control weeds in crops without damaging the soil and losing carbon. Various spring tynes, some types of harrows, star weeders, knives and brushes can be used to pull out young weeds with only minimal soil disturbance
- **Avoid erosion:** Erosion is one significant ways that soil carbon is lost. The top few centimetres of soil is the area richest in carbon. When this thin layer of soil is lost due to rain or wind, the carbon is lost as well
- **Avoid burning stubble:** Practices such as burning stubble should be avoided. Burning creates greenhouses gases as well as exposing the soil to damage from erosion and oxidation
- **Encourage vegetation cover:** Vegetation cover is the best way to prevent soil and carbon loss. As stated in the previous section 'Managing weeds to increase soil Carbon', it is not always necessary to eradicate weeds.

Effective management tools such as grazing or mowing can achieve better long term results

- **Bare soils should be avoided as much as possible:** Research shows that bare soils lose organic matter through oxidation, the killing of microorganisms and through wind and rain erosion. Cultivated soils should be planted with a cover crop as quickly as possible. The cover crop will protect the soil from damage and add carbon and other nutrients as it grows. The correct choice of species can increase soil nitrogen, conserve soil moisture through mulching and suppress weeds by out competing them

- Careful planning of land management (e.g., timing and application of fertiliser applications) could help minimize potential increases in trace gas fluxes from soils
- Conservation measures to maintain peatland moisture could help avoid drying out of peatlands and associated CO_2 fluxes
- Coastal management options should consider measures to protect aquifers from saline intrusion due to sea level rise where appropriate
- Conservation measures for low-lying vulnerable coastal habitats need to be planned carefully with consideration of possible impacts on trace gas fluxes

CONCLUSION

Climate Change poses serious interlinked challenges in times to come with reference to scale and scope, never anticipated in the last century. More or less the most important change in soils expected as a result of these changes would be a gradual improvement in fertility and physical conditions of soils in humid and subhumid climate, change from one major soil-forming process to another in certain fragile tropical soil and changes in soil property due to poleward retreat of the permafrost boundary. Again changes due to climate change are expected to be relatively well buffered by the mineral composition, the organic matter content or the structural stability of many soils. As a matter of fact, the impact of climate change on soil system should be monitored in different agrocological regions on regular basis. Climate change and land degradation are closely linked issues and conservation farming has shown promise in minimizing land degradation. Hence, the potential of conservation agriculture in minimizing the impact of climate change needs thorough investigation. There is need for harmonization of data base on land degradation keeping in view the productivity and economic losses vis-à-vis climate change effects.

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