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Impact of climate change on soil health: A review

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Abstract

Soil health has been described as integral to the concept of sustainable agriculture. Climate change has a potential impact on the soil health through physical, chemical and biological properties of soil. The change in the statistical properties of the climate system when considered over long periods of time, regardless of the cause is called as climate change. It is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climatic variability observed over comparable time periods. Soil health is a composite set of measurable physical, chemical and biological attributes related to functional soil processes, which can be used to evaluate soil health status as affected by management practices and climate change. Defining soil health in relation to climate change should consider the impact of range of predicted global change drives such as rising atmospheric carbon dioxide levels, elevated temperature, altered precipitation and atmospheric nitrogen deposition on physical, chemical and biological functions of soil.

Keywords: Climate change, soil health, soil properties, crop yield

Introduction

Soil health is the continued capacity of a soil to function as a vital system, within ecosystem and land use boundaries, to sustain biological productivity, maintain the quality of air and water, environment, and promote plant, animal and human health. Indian agricultural soils are low in organic carbon content and for achieving higher agricultural production; we have to depend on the fertilizers. All India Co-ordinated Long Term Fertilizer Trial (around 25 years) results indicated that regions having higher organic carbon content (>0.60%) in the beginning showed a declining trend in the organic carbon. Whereas, regions with lower organic carbon content remained more or less static or slightly increase in the organic carbon content was noticed. At low levels of water availability, it is difficult to decide optimal levels of N fertilizers for maximizing yield returns. Changes in rainfall due to global climate change may affect the surface moisture availability, which becomes important for germination and crop stand establishment in the rainfed areas. Microbes have emerged as major contributor as well as consumer of greenhouse gases as they are the main intermediates of carbon turnover in the soil. Microbes are also considered as sole agents for soil humus formation, cycling of nutrients, soil tilth and structure and perform myriad of other functions. For real measurement of the impact of soil processes, one needs to consider proportion of total organic C or N within the microbial biomass i.e. microbial quotient.

The interaction of nitrogen, irrigation and seasonal climatic variability particularly at low input of irrigation has several implications. Under adequate moisture supply situation like Punjab and Haryana states the yield benefits are obtained at higher nitrogen application. Whereas, in the regions of limited to moderate water supply situations, the increasing trends in yields are not up to relatively lower values of nitrogen. At low levels of water availability it is difficult to decide optimal levels of N fertilizer for maximizing yield returns in view of uncertainty N responses which is strongly related to a good post monsoon rainfall receiving during crop growing period (Kalra and Aggarwal, 1994) [18]. Farmers often achieve far less than 50% of the climatic and genetic yield potential for a given sowing date, cultivar choice and site. The potential yield or maximum yield is limited by climate and crop cultivar only, all other factors being optimal. Therefore, climate plays a major role while attaining potential yield or maximum yield (Karmakar *et al.*, 2016) [19].

Climate change has an impact on the soil, a vital element in agricultural ecosystem. Higher air temperatures cause higher soil temperatures, which generally increases solutions chemical reaction rate and diffusion controlled reactions (Buol *et al.*, 1990) [8].

Solubility of solid and gaseous components may either increase or decrease, but the consequences of there may take many years. Furthermore, higher temperature will accelerate the decomposition of organic matter, resulting in release of CO_2 to atmosphere and decrease in carbon to nitrogen ratio's (C:N) although these two effects should be offset somewhat by the greater root biomass and crop residues resulting from plant response to higher CO_2.

Soil temperature influences the rate at which organic matter decomposes. It resulted into release, uptake of nutrients and plant metabolic processes. Chemical reactions that affect soil minerals and organic matter are strongly influenced by higher soil and water temperature. Soil productivity and nutrient cycling are therefore influenced by the amount and activity of soil micro-organisms. Soil micro-organisms fulfill two major functions i.e. they act as agents of nutrient element transformation and transportation, as well as store carbon and mineral nutrients (mainly N, P and S) in their own living biomass acting as a liable reservoir for plant available nutrients with fast turnover. The changes in C:N ratios of plant residues returned to the soil have impact on soil microbial processes and affect the production of trace gases.

Climate change could increase rate of soil erosion, further hampering food production. Increases in rainfall will accelerate the rates of soil loss, reducing the farm productivity even more. A further negative consequence of accelerated soil erosion will be increased sedimentation in streams and reservoirs. Another way, in which erosion could accelerate, is through a decrease in rainfall, which could lead to dry spell and increased risk of wind erosion (Parry *et al*., 1999) [25]. If erosion rates go unchecked, continued soil impoverishment would eventually force farmers to abandon their lands. Thus, erosion is among the major threats to food production in warmer climate. Other land degradation problems, such as water logging, soil salinity and sodicity development are emerging due to rapid land use pattern and land cover changes.

Impact of climate change on soil health

The potential impact on soil health resulting due to the climate change is through organic matter supply, temperature regimes, hydrology and salinity. Following are the major consequences of global climate change on soil health.

Soil physical parameters

The major physical processes in soils are related to gains, losses, transfers and movement of water, air, organic matter, soluble salts, carbonates, silicate clay minerals, sesquioxides and silica. These gains are normally consists of addition of organic matter and of oxygen and water through oxidation and hydration, but in some sites slow continuous addition of new mineral materials take place at the surface of soluble materials are deposited from groundwater. Losses are chiefly of materials dissolved or suspended in water percolating through the profile or running off the surface along with water and through the porous soil. The higher temperature, high and low extremes of rainfall, increase in CO_2 concentration and their interactions due to climate change are expected to influence several soil physical process which will subject the soils to significant risk of salinization, decreased water availability and changes in C and N dynamics, nutrient storage in soil and reduction in soil biodiversity (Benbi and Kaur, 2009) [3]. The physical properties and processes of soil affect soil health by altering water movement through soil, root penetration in soil and water congestion. Important soil physical properties that affect soil health due to impact of climate change are as follow.

Soil texture

Soil texture is the relative proportion of sand, silt and clay in a soil. It has direct impact of climate change. The four potential climate scenarios (Arid, Semi-arid, Sub-humid and Humid) have great impact on important soil processes as the texture differentiation in the soil profile (Brinkman and Brammer, 1990; Scharpenseel *et al*., 1990) [7, 34].

Soil structure and Aggregate stability

The arrangement and organization of primary and secondary particles in a soil mass is known as soil structure. It controls amount of water and air present in soil. Aggregate stability, the resistance of soil aggregates to external energy such as high intensity rainfall and cultivation is determined by soil structure as well as a range of chemical, biological properties and management practices (Dalal and Moloney, 2000; Moebius *et al*., 2007) [24, 9]. It is considered as a useful soil health indicator since it is involved in maintaining important ecosystem functions in soil including organic carbon accumulation, infiltration capacity, movement and storage of water, root and microbial community activity. It can also be used to measure soil erosion and management changes. 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 and freeze-thaw behaviour. A decline in soil organic matter levels lead to a decrease in soil aggregate stability, infiltration rates and increase in susceptibility to compaction, run-off furthermore susceptibility to erosion (Bot and Benites, 2005; Karmakar *et al*., 2016) [19, 5].

Porosity

Porosity a measure of the void spaces in a material as fraction (volume of voids to that of total volume) and pore size distribution provide the ability of soil to store root zone water and air necessary for plant growth (Reynolds *et al*., 2002) [29]. Pore characteristics are strongly linked to soil physical quality, bulk density, micro porosity and functions of pore volume. While soil porosity and water release characteristics directly influence a range of soil indices including soil aeration capacity, plant available water capacity and relative field capacity. Since root development and soil enzyme activities are closely related soil porosity and pore size distribution. And because of future climate change scenarios (elevated CO_2 and temperature, variable and extreme rainfall events) may alter root development and soil biological activities. Soil porosity and pore size distribution consequently soil functions are likely to be affected in unexpected directions. This aspects needs alteration in future studies on the relationship of soil health and climate change. Decreased microbial activity, reduced root growth and exudates, reduce aggregate stability, increased rainfall intensities where rain droplets impact causes surface sealing on sodic soils. It will leads to poor crop emergence, growth and increases chances of surface runoff.

Infiltration and plant available water

The water availability for plant growth and important soil processes are governed by a range of soil properties including porosity, field capacity, lower limit of plant available water (thus excluding osmotic potential), micro pore flow and texture (Jarvis, 2007; Reynolds *et al*., 2002) [17 29]. Plant available water capacity has been used as part of integrative soil health tests to assess management impacts. Further, more the soil available water and distribution may respond rapidly to climate change, especially to variable and high intensity rainfall or drought events and thus management strategies, could be planting of cover crops, conservation tillage and incorporation of organic matter, that maintain or even enhance water infiltration and available water in soil may help in mitigating the impact of severe rainfall and drought events or severe erosion events (Lal, 1995; Salvador Sandris *et al*., 2008) [23, 33].

Bulk density

Bulk density is routinely assessed to characterize the state of soil compactness in response to land use and management (Hakansson and Lipiec, 2000) [15]. Bulk density in general negatively correlated with soil organic matter (SOM) or soil organic carbon (SOC) content (Weil and Magdoff, 2004) [38]. The loss of organic carbon from increased decomposition due to elevated temperature (Davidson and Janssens, 2006) [11] may lead to increase in bulk density and hence making soil more prone to compaction viz. land management activities and climate change stresses from variable and high intensity rainfall and drought events (Birkas *et al*., 2009) [4].

Rooting depth

Changes in rooting depth is likely to affect plant available water capacity, subsoil salinity, SOC content or other properties to indicate major constraints in the soil profile (Birkas *et al*., 2009; Dalal and Moloney, 2000) [4, 9]. Under prolonged drought, the impact of sub soil constraints such as salinity and high chloride concentrations (Dang *et al*., 2008; Rengasamy, 2010) [10, 27] is likely to be greater on plant available water and hence plant productivity.

Soil surface cover

Soil surface cover provides a range of important ecological functions including protection of soil surface water and nutrient retention, C fixation and in some instances N fixation and support native seed germination (Box and Bruce, 1996) [6]. Soil structural conditions such as soil crust and soil seal formation, primarily related to sodicity are used to characterize soil health under climate change. The formation of soil crusts and seals can affect a range of soil processes, including water infiltration, oxygen diffusion, runoff, surface water evaporation and soil erosion.

Soil temperature

The soil temperature regime is governed by gains and losses of sun radiation at the surface, the process of evaporation, heat conduction through the soil profile and convective transfer via the movement of gas and water (Karmakar *et al*., 2016) [19]. 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.

Soil chemical parameters

Soil pH

Soil pH is a function of parent material, time of weathering, vegetation and climate. It is consider as important indicators of soil health. Soil pH has thus been included in integrative soil health tests to assess impacts of land use change and agricultural practices. Most soils would not be subjected to rapid pH changes resulting from drivers of climate change such as elevated temperatures, CO_2 fertilization, variable precipitation and atmospheric N deposition. However, these drivers of climate change will affect organic matter status, C and nutrient cycling, plant available water and hence plant productivity, which in turn will affect soil pH (Reth *et al*., 2005) [28].

Electrical conductivity

Soil electrical conductivity (EC) is a measure of salt concentration. It can inform trends in salinity, crop performance, nutrient cycling and biological activity. Along with pH it can act as a surrogate measure of soil structural decline especially in sodic soils (Arnold *et al*., 2005) [2]. Electrical conductivity has been used as a chemical indicator to inform soil biological quality in response to crop management practices (Gil *et al*., 2009) [13]. Increasing temperatures and decreasing precipitation increase the electrical conductivity under climate change scenarios (Smith *et al*., 2002) [36]. The dynamics of soluble salts concentration in soils from four climatic regions (Mediterranean, Semi-arid, Mildly arid and Arid) and found a non-linear relationship between the soluble salts content and rainfall with sites that received <200 mm rainfall contained significantly high soluble contents and vice versa.

Sorption and Cation exchange capacity

Sorption and cation exchange capacity (CEC) are considered important properties particularly the retention of major nutrient cations Ca^{2+}, Mg^{2+}, K^{+} and immobilization of potentially toxic cations Al^{3+} and Mn^{3+}. These properties can thus be useful indicators of soil health informing of a soil's capacity to absorb nutrients as well as pesticides and chemicals (Ross *et al*., 2008) [31]. Since CEC of coarse-textured soils and low-activity clay soils is attributed to that of SOM, the increasing decomposition and loss of SOM due to elevated temperatures (Davidson and Janssens, 2006) [11] may lead to the loss of CEC of these soils. It may results in increased leaching of base cations in response to high and intense rainfall events, thus transporting alkalinity from soil to waterways.

Plant available nutrients

Measurement of extractable nutrients may provide indication of a soil's capacity to support plant growth; conversely, it may identify critical or threshold values for environmental hazard assessment (Dalal and Moloney, 2000) [9]. Nutrient cycling especially N is intimately linked with soil organic carbon cycling (Weil and Magdoff, 2004) [38] and hence drivers of climate change such as elevated temperatures, variable precipitation and atmospheric N deposition are likely to impact on N cycling and possibly the cycling of other plant available nutrients such as phosphorus and sulphur.

Soil biological parameters

The soil biota is adaptive to changes in environmental circumstances. Under conditions of climate change, biological indicators form an integral component in soil health assessment. Key biological indicators selected for the scope of this study include SOM and its constituents, soil C, respiration and soil microbial biomass.

Soil organic matter

Soil organic matter comprises an extensive range of living and non-living components; SOM is one of the most complex and heterogeneous components of soils which vary in their properties, functions and turnover rates (Weil and Magdoff, 2004) [38]. It provide and/or support including the contribution to the charge characteristics of soils, a sink for and source of C and N, and to a variable extent regulates phosphorus and sulphur cycling. It possesses ability to form complex with multivalent ions and organic compounds. It provides microbial and faunal habitat and substrates, as well as affecting aggregate stability, water retention and hydraulic properties (Haynes, 2008; Weil and Magdoff, 2004) [16, 38]. As SOM drives the majority of soil functions, decreases in SOM can lead to a decrease in fertility and biodiversity, as well as a loss of soil structure, resulting in reduced water holding capacity, increased risk of erosion and increased bulk density and hence soil compaction. Land use and management practices that leads to build up of SOM will help in absorbing CO_2 from the atmosphere, thus mitigating global warming. By increasing water storage, SOM can play an important role in the mitigation of flooding impacts following extreme rainfall events, while storing water in the event of droughts thus increasing soil resilience.

Light fraction and Macro organic matter (Labile organic matter)

Light (or low-density) fraction and macro organic components of SOM consist mainly of mineral free particulate plant and animal residues, which serves as readily decomposable substrate for soil micro-organisms, as well as a labile nutrient reservoir (Post and Kwon, 2000; Wagai *et al*., 2009) [26, 37]. Since light fraction and macro organic matter are responsive to management practices, they may act as early indicators to measure the effectiveness of changing management practice in adaptive response to climate change (Gregorich *et al*., 1994) [14]. Labile SOC is rapidly depleted as the temperature rises (Knorr *et al*., 2005) [21].

Soil carbon and C:N ratio

Increased temperature and episodic rainfall stimulates microbial activity (mineralization/decomposition). This will leads to reduced biomass accumulation, depletion of soil carbon and decrease C:N ratio (Rosenzweig and Hillel, 2000; Anderson, 1992; Lal, 2004) [30, 1, 22]. Increased atmospheric CO_2 increases plant water use efficiency (WUE). It will increase biomass production per mm of available water (Kimball, 2003) [20]. A decomposition rate is greater than net primary production under increased water deficit. This process causes the drier condition favorable for organic carbon reduction. Drought induced losses of biomass; it reduces the annual and perennial vegetation. Management strategies include conservation tillage practices, crop residues management, green manuring and intercropping.

Potentially mineralisable C and N

Mineralisable organic matter acts as an interface between autotrophic and heterotrophic organisms during the nutrient cycling process (Gregorich *et al*., 1994) [14]. However, mineralisable organic matter may be a useful to assess soil health under climate change, since it affects nutrient dynamics within single growing seasons.

Soil respiration

Soil respiration is used as a biological indicator for soil health, since it is positively correlated with SOM content. Soil respiration particularly its temperature response is critical link between climate change and the global C cycle (Wixon and Balser, 2009) [39]. Soil respiration is relatively responsive to changes in the seasonal timing of rainfall.

Soil microbial biomass

Microbial biomass is the living component of SOM. It is considered as the most labile C pool in soils and sensitive indicator of changes in soil processes with links to soil nutrient and energy dynamics including mediating the transfer between SOC fractions (Saha and Mandal, 2009) [32]. However, soil microbial biomass similar to labile C has been shown to be responsive to short-term environmental changes (Haynes, 2008) [16].

Enzyme activity

Soil enzyme activities may serve to indicate change within the plant-soil system, since these are closely linked to the (1) cycling of nutrients and soil biology, (2) are easily measured, (3) integrate information on both the microbial status and the physicochemical soil conditions, and (4) show rapid response to changes in soil management (Garcia-Ruiz *et al*., 2009) [12]. Furthermore, altering the quantity and quality of below ground C input by plants, elevated CO_2 may stimulate microbial enzyme activities, abundance of microbial enzymes and C turnover possibly affecting microbial community functioning in soil. It is still to be known how soil microbial enzyme activities involved in organic C turnover, nutrient cycling and greenhouse gas emissions.

Mitigation of adverse effect of climate change on soil health

The conservation tillage and residue management helps in the following ways in influencing some of the soil properties and mitigating the adverse effects of climate change on soil health (Sharma, 2011) [35].

Soil temperature

The surface residues significantly affect soil temperature by balancing radiant energy and insulation action. The radiant energy is balanced by reflection, heating of soil and air and evaporation of soil water. The reflection is more from bright residue.

Soil structure and Soil aggregation

It refers to binding together of soil particles into secondary units. Water stable aggregates help in maintaining good infiltration rate, good structure, protection from wind and water erosion. Aggregates binding substances are mineral substances and organic substances. The organic substances are derived from fungi, bacteria, actinomycetes, earthworms and other forms through their feeding and other actions. Plants themselves may directly affect aggregation through exudates from roots, leaves and stems, leachates from weathering and decaying plant materials, canopies and surface residues that protect aggregates against breakdown with raindrop impact, abrasion by wind borne soil and dispersion by flowing water and root action. Aggregates with 0.84 mm in diameter are non-erodible by wind and water action. The well aggregated soil has greater water entry at the surface, better aeration and more water holding capacity than poorly aggregated soil. Aggregation is closely associated with biological activity and the level of organic matter in the soil. The gluey substances that bind components into aggregates are created largely by the various living organisms present in healthy soil. Therefore, aggregation is increased by practices that favor soil biota. Because the binding substances are themselves susceptible to microbial degradation, organic matter needs to be replenished to maintain aggregation. To conserve aggregates once they are formed, minimize the factors that degrade and destroy them. The well aggregated soil also resists surface crusting. The impact of raindrops causes crusting on poorly aggregated soil by disbursing clay particles on the soil surface, clogging the pores immediately beneath, sealing them as the soil dries. Subsequent rainfall is much more likely to run off than to flow into the soil. In contrast, a well aggregated soil resists crusting because the water stable aggregates are less likely to break apart when a raindrop hits them. Any management practice that protects the soil from raindrop impact will decrease crusting and increase water flow into the soil. Mulches and cover crops serve this purpose well, as do no-till practices which allow the accumulation of surface residue.

Bulk density and Porosity

Bulk density and porosity are inversely related. Tillage layer density is lower in ploughed than unploughed (area in grass, low tillage area etc.). When residues are involved, tilled soils will reflect lower density. Mechanization with heavy machinery results in soil compaction, which is undesirable and is associated with increased bulk density and decreased porosity. Natural compaction occurs in soils, which are low in organic matter and requires loosening. But practicing conservation tillage to offset the compaction will be effective only when there is adequate residue, while intensive tillage may adversely influence the soil fauna, which indirectly influence the soil bulk density and porosity.

Soil crusting, Hydraulic conductivity and Erosion

Tillage also influences crusting, hydraulic conductivity and water storage capacity. It has been understood that the textural influences and changes in proportion of sand, silt and clay occur due to inversion and mixing caused by different tillage instruments, tillage depth, mode of operation and effect of soil erosion. Soil crusting which severely affects germination and emergence of seedling is caused due to aggregate dispersion and soil particles resorting and rearrangement during rainstorm followed by drying. Conservation tillage and surface residue help in protecting the dispersion of soil aggregates and helps in increasing saturated hydraulic conductivity. Increased hydraulic conductivity in conjunction with increased infiltration resulting from conservation tillage allows soil profile to be more readily filled with water. Further, less evaporation is also supported by conservation tillage, and profile can retain more water.

Soil organic matter and Soil fertility

Conservation agricultural practices help in improving soil organic matter by way of i) regular addition of organic wastes and residues, use of green manures, legumes in the rotation, reduced tillage, use of fertilizers, and supplemental irrigation ii) drilling the seed without disturbance to soil and adding fertilizer through drill following chemical weed control and iii) maintaining surface residue, practicing reduced tillage, recycling of residues, inclusion of legumes in crop rotation. It is absolutely necessary to spare some residue for soil application, which will help in improving soil tilth, fertility and productivity.

Conclusion

The quantitative evaluation of predicted climate change effect on soil health is a difficult task due to uncertainties in weather forecast. Land degradation issues are closely related with adverse effects of climate change. The conservation farming has shown positive results in minimizing land degradation. In adoption of conservation tillage and residue management, it is essential that complete package of practices may be identified based on intensive research for each agro ecological region. However, the site specific management practices for soil and water conservation, crop improvement and integrated nutrient management needs to be identified to overcome impact of climate change on physical, chemical and biological properties of soil.

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