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RK Naresh
Department of Agronomy,
Sardar Vallabhbhai Patel
University of Agriculture &
Technology, Meerut, Uttar
Pradesh, India

SK Tomar
KVK Belipar, Gorakhpur,
Narendra Dev University of
Agriculture & Technology,
Kumarganj, Faizabad, Uttar
Pradesh, India

Sudhir Kumar
Division of Plant Physiology,
Indian Agriculture Research
Institute, New Delhi, India

NC Mahajan
Institute of Agricultural Science,
Department of Agronomy,
Banaras Hindu University,
Varanasi, Uttar Pradesh, India

SS Tomar
Rajmata Vijayaraje Scindia
Krishi Vishwavidyalaya, Gwalior
Zara-a, b. Road Morena, Madhya
Pradesh, India

Vivek Kumar
Department of Agronomy,
Sardar Vallabhbhai Patel
University of Agriculture &
Technology, Meerut, Uttar
Pradesh, India

Mayank Chaudhary
Department of Genetics & Plant
Breeding, Sardar Vallabhbhai
Patel University of Agriculture
& Technology, Meerut, Uttar
Pradesh, India

Correspondence
RK Naresh
Department of Agronomy,
Sardar Vallabhbhai Patel
University of Agriculture &
Technology, Meerut, Uttar
Pradesh, India

Soil organic carbon dynamics and their driving factors on cereal cropping systems productivity in confronting weather change challenges of sub tropical conditions: A review

RK Naresh, SK Tomar, Sudhir Kumar, NC Mahajan, SS Tomar, Vivek Kumar and Mayank Chaudhary

Abstract

Agro-ecosystems play an important role in regulating global changes caused by greenhouse gas emissions. Restoration of soil organic carbon (SOC) in agricultural soils can not only improve soil quality but also influence weather change and agronomic productivity. With about half of its land area under agricultural use, sub -tropical conditions exhibits vast potential for carbon (C) sequestration that needs to be researched. Sub -tropical conditions cropland has experienced SOC change over the past century. The study of SOC dynamics under different bioclimatic conditions and cereal cropping systems can help us to better understand this historical change, current status, the impacts of bioclimatic conditions on SOC and future trends. Nationwide, 67.6% of the national arable land is considered to be in good condition. Appropriate farm management practices should be adopted to improve the poor C balance of the remaining 32.4% of cropland to promote C sequestration.

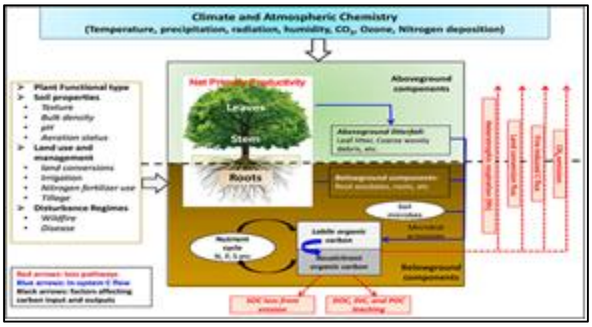
Although sandy loam soils on most sub -tropical conditions smallholder farms inherently contain a small amount of SOM, large variability in soil productivity exists between adjacent fields or field sections within the same farm. This review study was based on the SOM, a renewable resource, is the driving force behind sustainable crop productivity on depleted sandy loam soils. Organic inputs with a C: N ratio >25 (the bulk of available resources on-farm) contributed significantly to overall particulate organic matter (POM) size in typic ustochrespt soils. The intensity of C management was reflected more in meso-POM (53-250 μm diameter) compared to the macro-POM (250-2000 μm diameter) fraction suggesting that the larger POM fraction has a high turnover and is not protected from degradation. The overall size of the organo-mineral fraction (<53μm diameter) in these soils was small (<250g kg^{-1} soil) and stable, and was not influenced by quality and quantity of C inputs and time over which they had been applied.

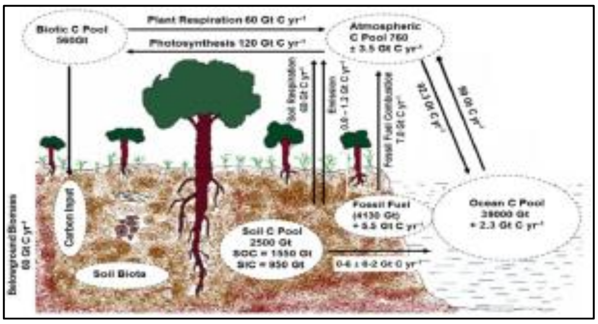
Keywords: soil organic carbon, cropland productivity, microbial community, plant-microbe interaction

Introduction

On a global scale, the soil is the largest terrestrial carbon (C) pool, and it stores approximately three times the quantity of C that is in the atmosphere. Consequently, a small variation in soil carbon stock can lead to substantial changes in atmospheric carbon dioxide (CO2) concentrations (Scharlemann *et al*., 2014) [48]. Soil organic carbon (SOC) stored in croplands constitutes approximately 10% of the global soil carbon stock (Jobbagy and Jackson, 2000) [26], and cultivation generally leads to marked changes in SOC by influencing the processes regarding soil C production and decomposition (Wang *et al*., 2016) [59]. Changes in cropland SOC are regulated by complex interactions between the local soil environmental and climatic conditions as well as the management regimes (Brady and Weil, 2008) [10]. Moreover, continuity in the soil C monitoring data over meaningfully large scales of both time and space is lacking. Consequently, the ability to characterize the SOC dynamics on a fine spatiotemporal resolution over a large scale is substantially hindered.

Among the most vulnerable systems are cereal systems in semi-arid regions, which account for much of global food production. These include regions dominated by large scale industrial agriculture and others where small-holder production predominates (Lowder *et al*., 2016) [34]. These regions share vulnerability to fluctuations in precipitation and periods of elevated temperature that will present increasing challenges under climate change (Challinor *et al.*, 2014; Wilcox and Makowski, 2014) [13]. Some of the challenges are common to all systems, inviting collaboration to address them, while others are specific to regions, farming systems, and the social, economic, and ecological systems that support them. Identifying the common and unique challenges and finding solutions for local and regional conditions is a high priority to ensure global food security.



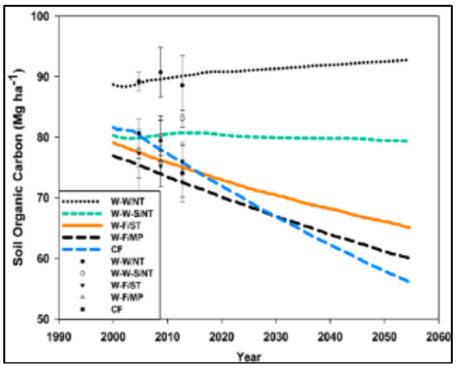


Agriculture is sensitive to short-term changes in weather and to seasonal, annual and longer-term variations in climate. Weather risk, or variability in weather, is one of the important factors affecting agricultural production and land allocation (Tao *et al*. 2008) [54]. As a result, weather-induced changes in agriculture affect the livelihood of farm households1 because they are likely to affect both farm income received by poor rural farm households and food prices paid by households in general (Burke and Lobell, 2010) [12]. To cope with fluctuating weather, farm households engage in several risk management strategies. These include food crop choice mix (or crop diversification), off-farm work and weather insurance. As a self-insurance mechanism to manage climatic variability's, in the presence of pervasive risk, farm households are likely to employ a number of adaptation strategies (Lashley and Warner 2015) [31]. The agriculture sector represents 23% of India's Gross Domestic Product (GDP), plays a crucial role in the country's development and continues to occupy an important place in the national economy. Additionally, about 59% of the population still lives in rural areas and heavily 6 depends on agriculture for employment and livelihood (Mishra and Tripathi, 2014). Agriculture is sensitive to short-term changes in weather and to seasonal, annual and longer-term variations in climate. Climatic variability in the sense of inter-season or intra-season fluctuations for agriculturally relevant weather conditions is an important source of instability in farming (Dash and Hunt, 2007) [16]. However, in subsistence oriented societies, like India, most of the formal means of combating instability and risk are not readily available. Rural farm households still rely heavily on traditional farming systems. In such a system, farmers make their own decisions with regard to risk management strategies. Farmers first try to ameliorate the effects of drought or rainfall variability through crop management.

Cereal systems in semi-arid regions, like all food production systems, are social-ecological systems (SES), as such it is widely recognized that they can be productively studied within a broad framework that encompasses genetics, environment, management and social dimensions and their interactions (G×E × M × S) (Hatfield and Walthall, 2015; Tonnang *et al*., 2017). Hence, efforts to improve them must be transdisciplinary [Wigboldus *et al*., 2016], bridging traditional agricultural and related ecological, biogeochemical, hydrological, meteorological, social, and economic disciplines (Hatt *et al*., 2016). In addition, these efforts must engage food system stakeholders to incorporate their understanding of the opportunities, constraints, and risks involved in implementing adaptive farming practices. Stakeholder participation helps research arrive at tenable "best management practices" (BMP's), including "climate friendly BMPs" (cfBMP's) (Pan *et al*., 2017) that are more readily adopted (Schaap *et al*., 2013). These collaborations must encompass the temporal and spatial scales relevant to agricultural landscapes undergoing climate change to encompass the extent of these systems and the processes that affect them. Efforts to do so are underway in different parts of the world and their effectiveness could be improved by cross-project communication or coordination. This review provides soil organic carbon dynamics and their Driving factors on cereal systems productivity in confronting weather change challenges.

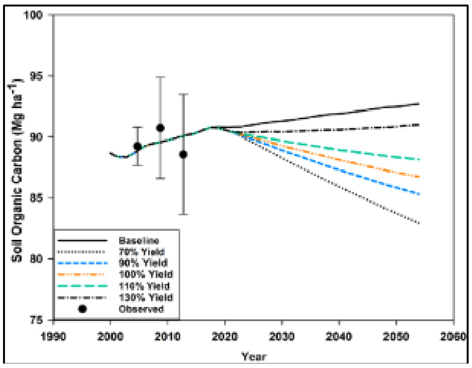
Predicted rates of SOC loss over the 40 yr were 0.03, 0.24, 0.30, and 0.47 Mg C ha^{-1} yr^{-1}, respectively, for the W–W–S/NT, W–F/ST, W–F/ MP and CF treatments. Reducing fallow period from 15 to 3 mo with conversion to W–W/NT increased SOC, whereas other treatments progressively lost SOC stocks in the following order as fallow period increased: W–W–S/NT < W–F/ST < W–F/MP < CF. The increase in simulated and measured SOC in W–W/NT could be due to the combination of elimination of tillage, reduced fallow period, and increasing the total amount of crop residues returned [Fig.1a]. Stockmann *et al*. (2013) [51] revealed that SOC were positively correlated with plant residue inputs and negatively correlated with tillage.

Loss of SOC was predicted for W–W/NT under RCM3-CGCM3 [Fig.1b] for all wheat yield scenarios except the 130% yield scenario, as well as under OCAR3–RCP4.5 and OCAR3–RCP8.5 simulation scenarios [Fig.1b]. The predicted SOC in the W–W/NT increased by 0.71, 0.88, and 1.16 Mg C ha^{-1} with 30% wheat yield increase under OCAR3–RCP4.5, RCM3-CGCM3, and OCAR3–RCP8.5, respectively [Fig.1b]. Elevated temperatures and CO_2 fertilization could modify soil water content and improve water use efficiency by wheat, stimulate crop net primary productivity, and increase crop residue returned to the soil. Pendall *et al*. (2013) [44] reported that warming reduces C losses from grassland exposed to elevated atmospheric CO_2. A projected warmer growing season and increased precipitation in the next decade or two for this region could also promote expanded growing seasons, whereas CO_2 enrichment may increase yields under increasing atmospheric CO_2 (Abatzoglou *et al*., 2014; Dalton *et al*., 2017) [2, 17]. Kimball and colleagues (2017) [30] concluded that the lethal average air temperature for wheat production must be close to 32°C. However, losses of SOC were predicted for W–F/ST under all yield and RCM3-CGCM3 scenarios [Fig.1c]. With a crop yield increase of 30% without climate change, the predicted rate of SOC stocks tripled (0.18 vs. 0.06 Mg C ha^{-1} yr^{-1}) for W–W/NT compared with W–W–S/NT, whereas the predicted rate of SOC losses decreased from −0.28 in W–F/MP to −0.19 Mg C ha^{-1} yr^{-1} in W–F/ST. This is most likely because of different tillage and biomass inputs into CQESTR. Uncertainty in the root biomass input can also affect total biomass inputs to the model and consequently the SOC prediction.



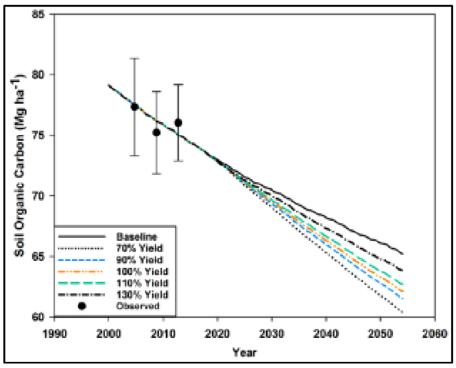
(a)

Fig 1(a): Measured (symbols) and CQESTR predicted (lines) soil organic carbon in the 1 m soil depth for treatments (continuous wheat under no tillage, W–W/NT; wheat–wheat– sorghum ´ sudangrass hybrid under no tillage, W–W–S/NT; wheat–fallow under sweep tillage, W–F/ST; wheat–fallow under moldboard plow tillage, W–F/MP; and continuous chemical fallow, CF) [Source: Gollany and Polumsky, 2018] [21]



(b)

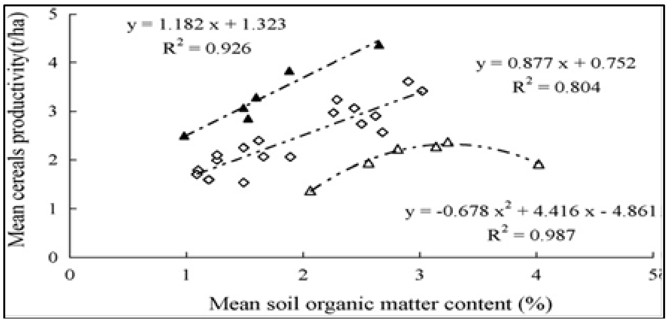
Fig 1(b): Measured (circles) and CQESTR-predicted (lines) soil organic carbon in the 1-m soil depth for continuous winter wheat under no tillage [Source: Gollany and Polumsky, 2018] [21]



(c)

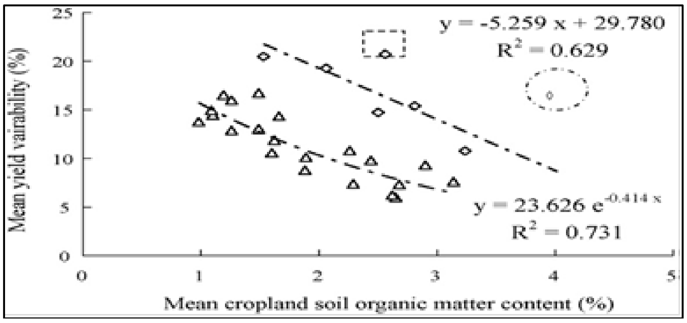
Fig 1(c): Soil organic carbon of measured (circles) and CQESTR-predicted (lines) in the 1-m soil depth for wheat–fallow under sweep tillage [Source: Gollany and Polumsky, 2018] [21]

Pan *et al*. (2009) [43] reported that a positive correlation of mean cereal production with the average cropland SOM level for most of the crop area [Fig.2a]. It shows that in most eco-climate zones, where the climatic drivers of yield are similar, the provinces with higher SOM also tend to have a statistically higher yield. Causality cannot be firmly attributed as a high yield is associated with higher plant production, potentially higher carbon inputs to the soil and therefore higher levels of SOM over time. Nevertheless, within regions with similar current climatic growing conditions, which should give similar yields if climate is the over-riding factor determining current yield, those provinces with higher SOM tend to have higher yield. This supports the argument that higher SOM levels improve yields in areas that, climatically, one would expect similar yields.



(a)

Fig 2(a): Mean cereal productivity 1949–1998 correlated with mean cropland soil organic matter content [Source: Pan *et al*. 2009] [43]



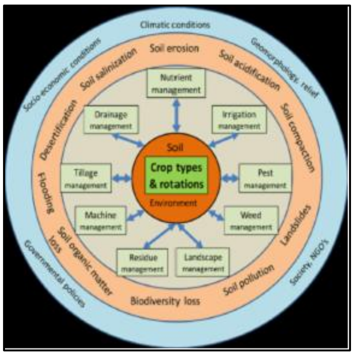
(b)

Fig 2(b): Mean cereal yield variability (%) 1949–1998 against mean cropland soil organic matter content (%) [Source: Pan *et al*., 2009] [43]

Pan *et al*. (2009) [43] also found that the variability followed an exponentially decreasing trend, and a weaker linearly decreasing trend with the average cropland SOM content for most provinces, and for provinces with marginal climate, respectively. An exponential regression of cereal yield stability against adverse disturbance with average SOM level occurred in 73% of the provinces, apart from those with marginal climate and severe land degradation. From this regression, an increase of the average SOM content from 1% to 3% would be expected to decrease yield variability by 10%. Given that the total production for these provinces amounted to 416.4 Mt of cereals in 1998, the 10% decrease in yield variability could represent a yearly increase of over 40 Mt of cereal food per year [Fig.2b].

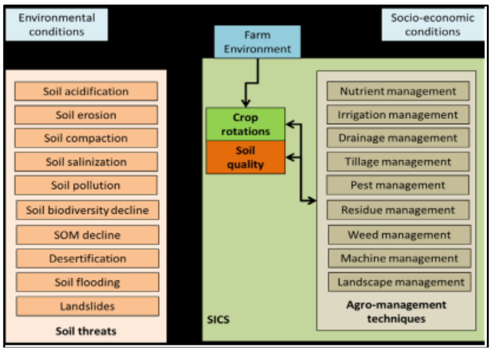
Oenema and Hessel, (2017) [41] reported that the potential of soil-improving cropping systems and to identify and test site-specific soil-improving cropping systems that have positive impacts on profitability and sustainability [Fig.3a]. The external driving forces of both soil threats and SICS. Various drivers have been distinguished, including (i) natural (climate, geomorphology, and hydrology), (ii) socio-economic conditions (development in markets, including developments in science and technology), (iii) societal opinions and NGO's, and (iv) governmental policies. The adoption of components of SICS, including crop rotation, permanent cropping systems, bio-diverse strips, soil organic matter maintenance (Frelih-Larsen *et al*., 2017; Berge *et al*., 2017) [7]. Mazoyer and Roudart, (2006) [38] reported that in SICS, the decisions about crop rotations and agro-management techniques are also based on (i) preventing soil threats, (ii) alleviating the effects of soil threats, and (iii) enhancing soil quality and functions in general. This requires that the farmer is (a) convinced about the need to do so, (b) is able to do so, and (c) has the information and tools to do so. Hence, the crop rotations and agro-management techniques are also based on the occurrence of soil threats and the need to enhance soil quality and functions [Fig.3b].

Bolinder *et al*. (2015) [9] observed that the highest effects occurred for municipal solid ROMs and sewage sludge, with relative increases and SOC sequestration rates ranging from 98 to 117% and 1650 to 5290 kg C ha^{-1} yr^{-1}, respectively [Fig.3c]. Aigulera *et al*. (2013) [3] also assessed the effect of liquid animal manure in their study, but it was not significant. However, as pointed out in the meta-analysis by Maillard and Angers (2014) [37], there is a lack of studies allowing realistic comparisons between the effects of liquid versus solid manures on SOC stocks.



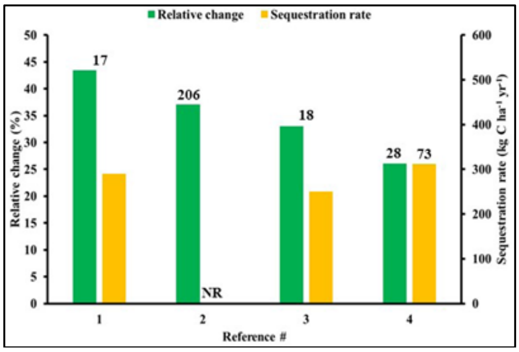
(a)

Fig 3(a): Soil Improving Cropping Systems (SICS), with crop rotations and the soil environment in the centre and the nine key agro management techniques [Source: Oenema and Hessel, 2017] [41]



(b)

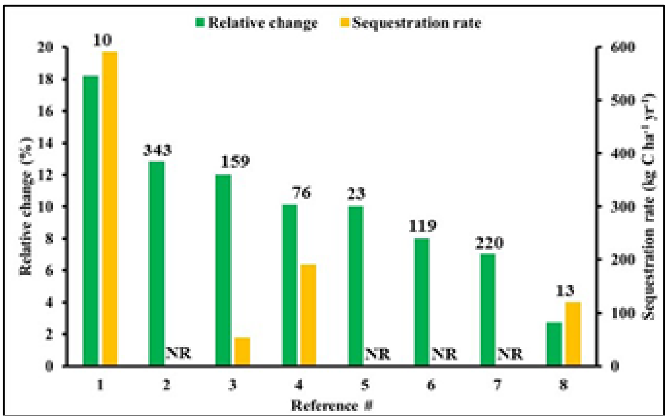
Fig 3(b): Main driving forces and components of cropping Systems [Mazoyer and Roudart, 2006] [38]



(c)

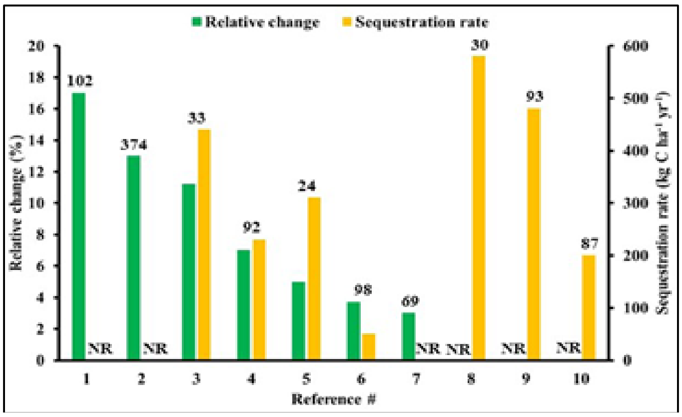
Fig 3(c): The effect of solid recycled organic material (manure) on the relative change and soil organic C (SOC) sequestration rates [Bolinder *et al*., 2015] [9]

Wang *et al*. (2015) [61] revealed that the consequence of straw retention on crop yields were positive, increasing by 6%. However, compared to the control treatment with straw removal, the mean relative increase in SOC with aboveground residue incorporation ranged from a low of 2.7 to a high of 18.2%. Four of the studies that allowed a reporting of data as SOC sequestration rates, showed a range of values from 53 and 590 kg C ha^{-1} yr^{-1} [Fig. 4a].The effect of different crop types and rotations was generally not significant, except in one study that observed a trend for a lower relative effect (9 to 10%) when rice was present, compared with maize- and wheat-based (13 to 14%) rotations (Lu, 2015) [35].



(a)

Fig 4(a): The effect of aboveground crop residue handling on the relative change and soil organic C (SOC) sequestration rates [Wang *et al*. (2015] [61]



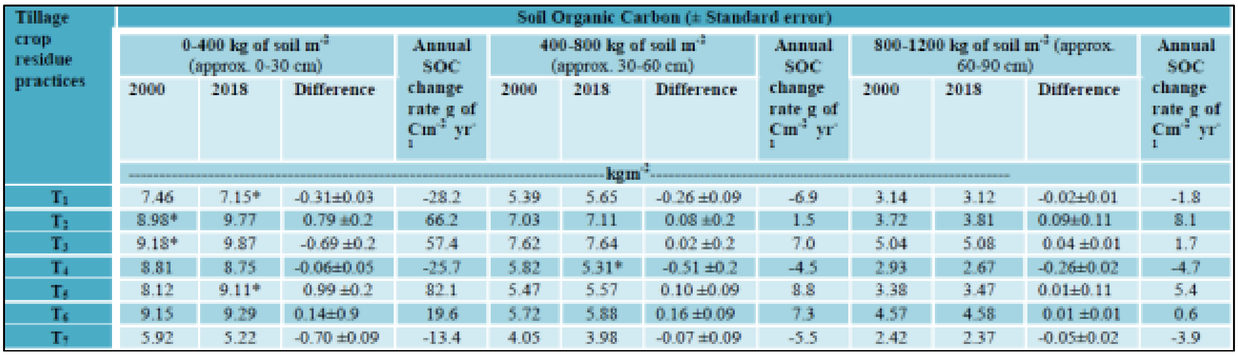
(b)

Fig 4(b): The effect of no-tillage on the relative change and soil organic C (SOC) sequestration rates [Aigulera *et al*., 2013] [3]

Aigulera *et al*. (2013) [3] shown that most of the changes occurs in the 0-10 cm layer, with as much as 85% of the differences being accounted for in the top 7 cm and that they thereafter asymptotically tends to reach a no-difference around 30 cm [Fig.4b]. Luo *et al*. (2010) [36], having 70 to 100% of their pairwise comparisons involving depths greater than 30 cm, found the effect of NT was not significant in intermediate soil layers (10-20 cm); the gain in SOC for NT only occurring in the 0-10 cm and the reverse effect found below the plough layer (20-35 cm).

Quantities of SOC at the 0-400 kg of soil m^{-2} interval decreased under T_1, T_4 and T_7 treatments evaluated. Stocks of SOC in the top 400 kg of soil m^{-2} decreased from 7.46 to 7.15 kg of C m^{-2} represented a change of -0.31 ±0.03 kg of C m^{-2} in T1, 8.81 to 8.75 kg of C m-2 represented a change of -0.06 ±0.05 kg of C m^{-2} in T_4, and 5.92 to 5.22 of C m^{-2} represented a change of -0.70 ±0.09 kg of C m^{-2} in T_7 between 2000 and 2018, [Table 1]. Our results clearly show that for the given conditions of this study (climatic conditions, soil type, tillage system and nutrient) zero tillage and permanent raised with 4 and 6 tha^{-1} of the residue retention evaluated treatments were able to sequester atmospheric C or even achieve a balance between inputs and outputs. Levels of SOC were clearly lower after 18 years of cultivation under without residue retention zero tillage, permanent raised beds and conventional tillage practices and future research will be necessary to determine if and when the system achieves a balance or steady state. Soil C content in the 400-800 and 800-1200 kg of soil m^{-2} intervals performed similar change after 18 years. Changes over the length of the study averaged over tillage crop residue practices were -0.07±0.09 and -0.05±0.02 kg C m^{-2} in the 400-800 and 800-1200 kg of soil m^{-2} intervals. This is equivalent to an average yearly change rate of -5.5 and -3.9 g C m^{-2} yr^{-1} for each mentioned soil mass interval [Table 1].

Table 1: Soil organic carbon (SOC) stocks and annual rate of change in multiple soil mass intervals (averaged over tillage crop residue practices and nutrient management rate) in 2000 and in 2018 at Meerut, U.P [Source: Naresh *et al.*, 2018] [39]



Tillage crop residue practices	Soil Organic Carbon (± Standard error)											
	0-400 kg of soil m^{-2} (approx. 0-30 cm)			Annual SOC change rate g of Cm^{-2} yr^{-1}	400-800 kg of soil m^{-2} (approx. 30-60 cm)			Annual SOC change rate g of Cm^{-2} yr^{-1}	800-1200 kg of soil m^{-2} (approx. 60-90 cm)			Annual SOC change rate g of Cm^{-2} yr^{-1}
	2000	2018	Difference		2000	2018	Difference		2000	2018	Difference	
	kgm^{-2}											
T$_1$	7.46	7.15*	-0.31±0.03	-28.2	5.39	5.65	-0.26 ±0.09	-6.9	3.14	3.12	-0.02±0.01	-1.8
T$_2$	8.98*	9.77	0.79 ±0.2	66.2	7.03	7.11	0.08 ±0.2	1.5	3.72	3.81	0.09±0.11	8.1
T$_3$	9.18*	9.87	-0.69 ±0.2	57.4	7.62	7.64	0.02 ±0.2	7.0	5.04	5.08	0.04 ±0.01	1.7
T$_4$	8.81	8.75	-0.06±0.05	-25.7	5.82	5.31*	-0.51 ±0.2	-4.5	2.93	2.67	-0.26±0.02	-4.7
T$_5$	8.12	9.11*	0.99 ±0.2	82.1	5.47	5.57	0.10 ±0.09	8.8	3.38	3.47	0.01±0.11	5.4
T$_6$	9.15	9.29	0.14±0.9	19.6	5.72	5.88	0.16 ±0.09	7.3	4.57	4.58	0.01 ±0.01	0.6
T$_7$	5.92	5.22	-0.70 ±0.09	-13.4	4.05	3.98	-0.07 ±0.09	-5.5	2.42	2.37	-0.05±0.02	-3.9

*Significant difference between years at α = 0.05

Year-to-year weather variability affects the growth, development, and yield of crops (Salinger *et al*., 1995) [47]. Higher temperatures and CO$_2$ levels will likely change the wheat growth patterns and duration by shortening the growth cycle and altering the phonological stages (Tadesse *et al*., 2016) [52]. Increased CO$_2$ levels reduce stomatal conductance and transpiration rates (Gunther *et al*., 2002) [22]. However, higher early spring temperatures and fewer frost days may improve the early growth and vigour of the plants. With higher CO$_2$ levels, plants may transpire less. A combination of increased temperature with increased atmospheric levels of CO$_2$ will modify crop water use patterns, affecting the soil water status and the moisture uptake by the crops (Tadesse *et al*., 2016) [52]. Rising temperatures will decrease the length of grain-filling period of wheat and other small grains (Chowdhury and Wardlaw, 1978) [15]. Rising temperatures and changes in rainfall patterns have direct effects on crop yields, as well as indirect effects through changes in irrigation water availability (Nelson *et al*., 2009) [40]. Pushpalatha *et al.* (2008) [46] observed that RUBISCO activity decreased in wheat plants with a reduction in the photosynthetic rate when wheat plants were exposed to high temperatures. Increases of temperature above 25 to 35ºC, common during grain filling of wheat, will shorten the grain filling period and reduce wheat yields (Hatfield *et al*., 2011) [24]. When these temperature increases are extrapolated to the global scale a 5.4% decrease in wheat yield per 1oC increase in temperature is expected (Lobell and Field, 2007) [32]. Exposure to 36/31ºC temperatures for only 2 to 3 dates before anthesis created small unfertilized kernels with symptoms of parthenocarpy, small shrunken kernels with notching, and chalking of kernels (Tashiro and Wardlaw, 1990) [55].

Valizadeh *et al.* (2014) [57] reported that wheat production in the future will be affected by climate change and will decrease; to reduce these risks, the impact of climate change mitigation strategies and management systems for crop adaptation to climate change conditions should be considered. Temperature and CO$_2$ influence plant growth and development through their effects on stomatal opening and rate of physiological processes. Higher temperatures speed up the biochemical reactions and also increase transpiration losses. Stomatal conductance declines with increasing CO$_2$ concentration for crop which fix and reduce inorganic CO$_2$ into organic compounds (C$_3$ plants) (Olivier Abayisenga, 2015) [42]. Rising atmospheric CO$_2$ concentrations provide some counteracting tendencies to the otherwise negative impacts of rising Temperature and reduced soil moisture (Lobell & Gourdji, 2012) [33]. This seems to benefit more in terms of dry matter production from a higher CO$_2$ level, due to higher leaf expansion, increase in the photosynthetic rate per unit area, increase in water use efficiency and increase in photorespiration rates (Warrick *et al*., 1986) [62]. First, higher CO$_2$ has a fertilization effect in C$_3$ species such as wheat, rice, and most fruit and vegetable crops, given that photo-respiratory costs in the C$_3$ photosynthesis pathway are alleviated by higher CO$_2$ (Lobell & Gourdji, 2012) [33]. The lack of expected rainfall has also leaded to water and pasture shortage within the country, which is absolutely one of the biggest problems (Hendrix, 2012) [25]. Farmer's sensitivity to changing climate and the way they perceive the notable changes in rainfall and temperature condition and its impacts on crop production (Tewodros, 2013) [56].

Kimball *et al.* (2001) reported that grain quality reduced due to low nitrogen is further reduced by high concentrations of CO$_2$. At low nitrogen levels, protein content was reduced by 39% under elevated CO$_2$ compared to a 33% reduction under ambient CO$_2$ (Takle, 2011) [53]. Blumenthal *et al.* (1991) [8] showed that there was a highly significant positive correlation of grain protein with hours above 35°C during grain filling, and negative correlations with dough strength and loaf volume. Randall & Moss (1990) showed that dough strength increased with temperatures up to 30°C, but decreased for even short periods above this. Jolánkai *et al.* (2016) [27] reported that weather impacts may have direct or indirect influence on the performance of agricultural production and food industry. The present problems are various, however, they can be sorted into two major groups: (1) factors that can be related to weather change processes like water scarcity, drought, meteorological extremities (temperature anomalies– frost, heat days, duration of unfavourable periods; precipitation – heavy rains, hail storms, land slide; air – storms, high wind, alterations of radiation and its postulates, (2) economic, social, and policy problems, that may have negative impact on the adaptability to meteorological factors in general and climate change processes in particular regarding food and agricultural production.

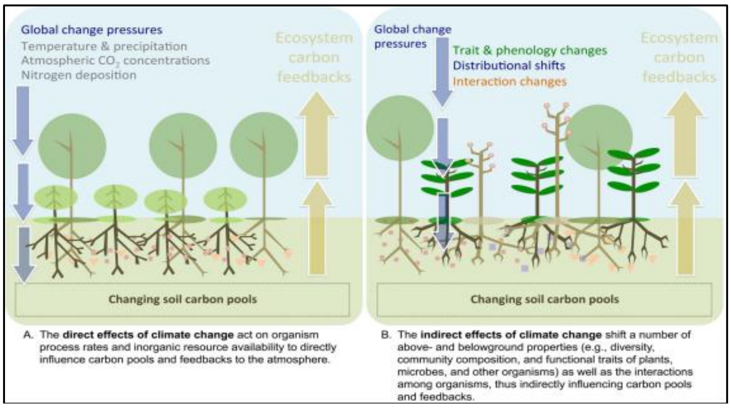
Crop residue management for soil carbon conservation and sequestration

Carbon accumulates in the soil when the nitrogen input (i.e. from nitrogen fixation, organic matter restitutions or fertilizers) is higher than the nitrogen exported with harvested produce and lost through leaching or emissions in gaseous forms (Corsi *et al*., 2012). The crop management practices that regulate the composition of the residues accumulating on the soil surface, and the potential to augment soil carbon stocks:

- Effective crop rotations for carbon accumulation maintain a positive nitrogen balance. Crop residues with an average carbon-to-nitrogen ratio in range of 25 to 30 can be achieved by rotating between crops high in carbon and crops high in nitrogen. This allows the carbon to accumulate in the soil and enables the nitrogen in the decaying surface residues to be released slowly to the next crop. If the amount of nitrogen in the crop residues is too low, microorganisms use the mineral nitrogen existing in the soil (nitrogen immobilization), which reduces the amount of nitrogen available to the growing crop until (weeks) the carbon in the crop residues starts to deplete (Gál *et al*., 2007) [20].
- Increasing the complexity of the crop rotations and integrating legume crops supports carbon sequestration. Active roots produce exudates and, notably in the case of legumes, favourable mycorrhizal associations. The decomposition of old rooting systems adds organic matter at greater depths. Deep rooting systems are ideal for taking carbon deep into the soil, where it is less susceptible to oxidation. In agricultural ecosystems, about 80 per-cent of biological nitrogen fixation is achieved through the symbiotic association between legumes and the soil bacteria Rhizobia. Farmers have some scope to influence these natural processes by selecting legume species that are particularly effective at fixing nitrogen; increasing the proportion of legume and grass seed in forage mixtures; inoculating the legumes with bacteria (e.g. Rhizobia); improving crop nutrition, especially nitrogen and phosphorous; managing diseases and pests; choosing the best planting time, cropping sequence and cropping intensity; and managing the defoliation frequency of forage swards.
- Keeping the soil covered with a layer of evenly distributed crop residues with an average carbon to-nitrogen ratio in the 25-30 range after harvest produces a positive residual fertilizer effect on the subsequent crops.

  The removal of crop residues (e.g. burning, black fallows) leaves only the crop's root biomass to be incorporated into the soil organic matter pool, which causes the accumulation of soil organic carbon to decline. For the same reasons, grain legumes should be harvested by cutting the plants; they should not be pulled up and uprooted.
- Mixing crop residues with soil (e.g. by disking or chiselling) may cause or accelerate the immobilization of nutrients in the soil and make them unavailable for the subsequent crop during the early part of the growing season. Crop residues mechanically incorporated into the soil decompose more quickly than those left on the soil surface, and nitrogen immobilization can occur very early in the season. Incorporating crop residues rich in readily decomposable carbon, such as residues with low carbon-to-nitrogen ratio or liquid manure, generally induces a priming effect on soil organic matter and increases carbon dioxide emissions. In contrast, when crop residues are not mixed into the soil, their composition does not affect the decay of the stable soil organic matter already present in the soil (Sisti *et al*., 2004; Fontaine, 2007) [49, 18].
- Using best management practices for nitrogen fertilization minimizes residual soil nitrate, which reduces nitrous oxide emissions. Best management practices for nitrogen fertilization include integrated nutrient management, and targeted applications of the precise amount of mineral fertilizer required.
- Using controlled traffic and growing crops that produce large amounts of root biomass can keep the soil from becoming compacted and improve drainage. This can help farmers avoid anaerobic soil conditions, which can increase nitrous oxide emissions and create a generally unfavourable environment for plant growth.

(A'Bear *et al*., 2014; Chen *et al*. 2014) [1, 14] argue that while the indirect effects via shifts in plant-soil microbe and soil microbe-microbe interactions are less acknowledged they have the potential to mediate important processes such as plant chemistry, plant community composition, and mineralization rates much like shifts in other ecological interactions alter important functions. Microbial communities respond to warming and other perturbations through resistance, enabled by microbial trait plasticity, or resilience as the community returns to an initial composition after the stress has passed (Allison and Martiny, 2008) [5]. Shifts in microbial community composition are likely to lead to changes in ecosystem function when soil organisms differ in their functional traits or control a rate-limiting or fate-controlling step [Fig.5].



A. The **direct effects of climate change** act on organism process rates and inorganic resource availability to directly influence carbon pools and feedbacks to the atmosphere.

B. The **indirect effects of climate change** shift a number of above- and belowground properties (e.g., diversity, community composition, and functional traits of plants, microbes, and other organisms) as well as the interactions among organisms, thus indirectly influencing carbon pools and feedbacks.

Fig 5: Combined, the direct and indirect effects of global change on ecosystems

Global changes such as warming are directly altering microbial soil respiration rates because soil microorganisms, and the processes they mediate, are temperature sensitive. The role of elevated temperature in microbial metabolism has received considerable recent attention (Hagerty *et al*., 2014; Karhu *et al*., 2014) [23, 28] [Fig.6]. The transitory effects of warming on soil communities have been hypothesized to occur as labile soil carbon substrates are depleted by increased microbial activity and because of trade-offs as microbial communities either acclimate, shift in composition, or constrain their biomass to respond to altered conditions and substrate availability (Bradford, 2013) [11].

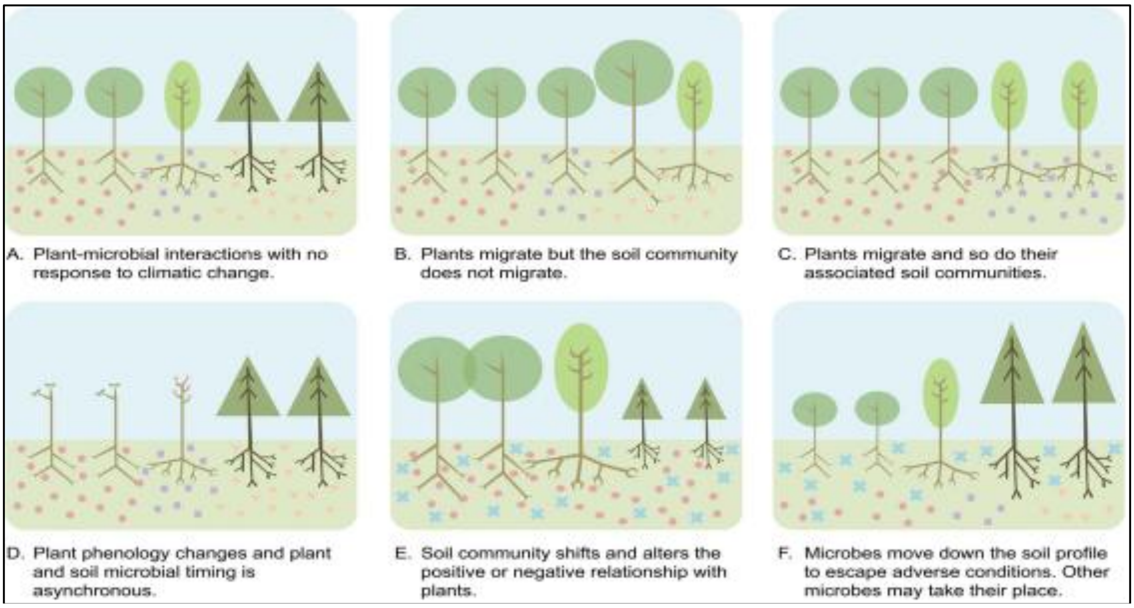
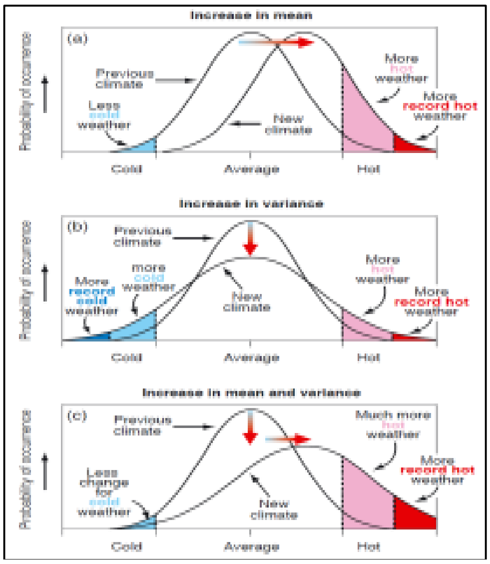


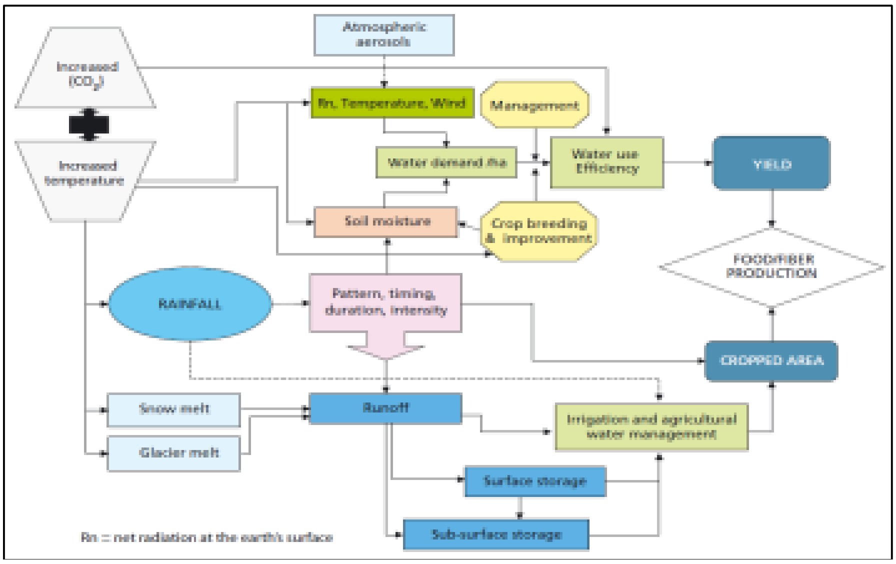
Fig 6: The potential responses of plant and associated soil communities to climatic change. Plants and microbes may respond by shifting population ranges, symbiotic partners, or timing of phonological events. Each panel illustrates plant and soil community responses to climate change and highlight possible mismatches between interacting plants and microbes. Shapes of plants and microbes signify different species.

Alcamo *et al*. (2005) [4] reported that the temperature reinforcing feedbacks result from the melting of polar and mountain ice caps at +4–5 ˚C (reduced albedo and reflection), thawing of permafrost with release of large volumes of methane, and higher atmospheric retention of CO_2 in future at higher temperatures. It is also anticipated that there will be considerable mobilisation of GHGs when temperature rise reaches around 5–6 ˚C, with expected large releases of methane from Tundra and permafrost areas in the northern latitudes. These temperature and CO_2 concentration changes will have direct impacts on plant growth [Fig.7a]. However, at high latitudes crop yields are expected to rise with temperature increases of 1–3 °C, but fall, due to declining crop health, once 3 °C is exceeded. At lower latitudes, crop yields are expected to decline with temperature raises as little as 1–2 °C [Fig. 7b]. Overall, the benefits of carbon dioxide enrichment on photosynthesis are likely to be outweighed by increased temperature and lower rainfall (Smith *et al*., 2008) [50]. It is expected that agriculture (without any further adaptation), especially in the dry and wet tropics, will be more affected by an increased frequency of extreme events, rather than the mean change in climate (Porter and Semenov, 2005) [45].



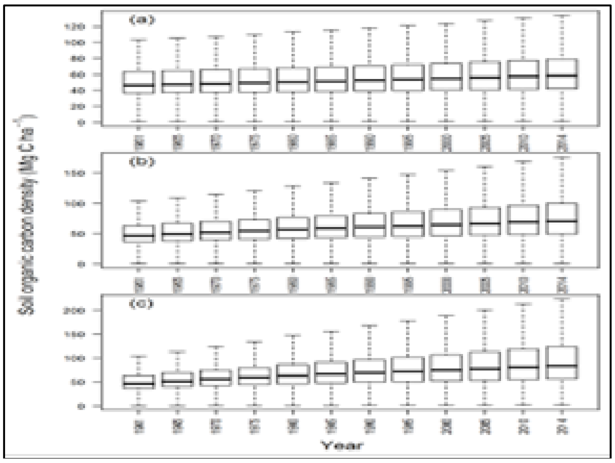
(a)

Fig 7(a): Effects of climate change (increase in mean in variance and in mean and variance)



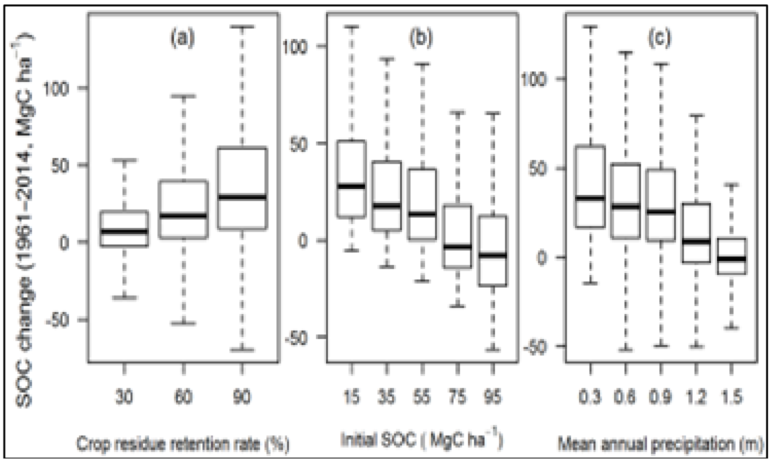
(b)

Fig 7(b): The agricultural production cycle as impacted by climate change



(a)

Fig 8(a): Temporal changes in the soil organic carbon (MgCha^1) of the main global cereal cropping regions under different aboveground crop residue retention rates of 30% (a), 60% (b) and 90% (c) [Source: Wang *et al*., 2017] [60].



(b)

Fig 8(b): Response of SOC change (1961–2014, MgCha^{-1}) to the three most influential variables of crop residue retention rate (a), initial SOC (b), and mean annual precipitation (c) [Source: Wang *et al*., 2017] [60].

Wang *et al*. (2017) [60] reported that, on a global average, the cropland SOC density increased at annual rates of 0.22, 0.45 and 0.69MgC ha^{-1} yr^{-1} under crop residue retention rates of 30, 60 and 90%, respectively. Increasing the quantity of C input could enhance soil C sequestration or reduce the rate of soil C loss, depending largely on the local soil and climate conditions. Spatially, under a specific crop residue retention rate, relatively higher soil C sinks were found across the different locations. Relatively smaller soil C sinks occurred in the high-latitude regions of both the Northern and Southern hemispheres, and SOC decreased across the equatorial zones [Fig.8a]. This is similar to the findings of our previous studies (Wang *et al*., 2016, 2015) [59], which found that higher amounts of C input can lead to higher soil C sink capacities. On a global average, the total amounts of C input to soils are 1.7, 2.7 and 3.7MgCha^{-1} under the crop residue retention rates of 30, 60 and 90%, respectively. However, higher SOC increases than the soils in one location with relatively higher initial SOC contents (Fig.8b).

Spatial patterns of lower initial SOC associated with higher SOC changes in neighbouring areas can also be found in other regions. The soil clay fraction has been suggested to benefit C stabilization through the mineralogical protection of soil C (Amato and Ladd, 1992) [6]. However, we identified a negligible but negative correlation between soil C accumulation and soil clay fraction in this study. Wang *et al*. (2014) [58] used a process-based agricultural system model (i.e., Agro-C model) to simulate the SOC dynamics in the semi-arid regions of the North China Plain and found positive effects of temperature and precipitation on SOC accumulation. This is because, in temperature and water deficient areas (e.g., the North China Plain), increased temperature and precipitation promote crop production and hence increases the C input to soils, which favours SOC sequestration.

Conclusion

It was recognized that soil organic matter levels are generally low and are still declining except in the few instances where appropriate management techniques have been introduced. Conservation system (CS) proved to be highly effective in enhancing SOC under the semi-arid conditions prevailing in western Uttar Pradesh. CS were observed to lead to differences in SOC beginning in the third year after a change in management practice, followed by larger increase in subsequent years. Minimum mechanical soil disturbance is a long-term management approach to increasing the amount of carbon stored in the soil. However, the accumulation of soil organic carbon is a reversible process, and any short-term disturbances, such as the periodic tillage of land otherwise under no-tillage will not bring about significant increases in soil organic carbon. Although the benefits and reduce risks and costs in the future gained from improving soil health and increasing soil organic carbon accrue slowly over decades, taking action can also bring immediate financial dividends, help maintain crop productivity. When soil rebuilds, it grows and stores more oil organic matter and water, thus improving ecosystem functions and services that are critical for weather change adaptation and mitigation. It can be suggested that weather change will be especially detrimental to crop production in cropping systems where soils have been degraded to a point where they no longer provide sufficient buffer against drought and water stress. These problems cannot be addressed by improving genetic adaptation to water or drought stress alone and will require agronomic interventions. Therefore, Practices that reduce soil evaporation include zero or minimum tillage, early and vigorous crop cover and keeping crop residues on the soil surface. Manage rainwater to prevent potential flooding, water logging, erosion, and nutrient leaching under increased rainfall; improving adaptations mechanism to climate change for agricultural sectors such as the resilient variety, cropping pattern, cropping system, irrigation techniques, sustainable land management, early warning and supply of inputs etc. In terms of risk management, some of the most relevant technologies relate to weather forecasting and early warning systems. The improved timing and reliability of seasonal forecasts and hydrological monitoring enables farmers to make better use of weather information take pre-emptive actions and minimize the impact of extreme events. This type of crop production requires that all stakeholders, including farmers, development cooperation professionals and policy makers, strengthen their ability to make decisions on matters that have typically been outside their area of expertise. A system-wide capacity development approach is recommended for bringing about a gradual transition towards climate-smart crop production.

Novel technological approaches will be pivotal in microbe-centric studies as we aim to reveal those taxa most sensitive to climate and those whose responses lead to shifts in microbial community function. Overall, these advances will be critical for making predictions about ecosystem tipping points, effects of extreme events, and the stability of communities under climate change. In sum, if we are to understand whether climate influenced shifts in microbe-microbe and plant-microbe interactions are equal or greater than the direct effects of climate change on the composition and function of ecosystems, we need to determine the best approaches to observe, quantify, and scale these interactions. Combinations of observations along natural gradients, with manipulations and experimental testing as well as modelling of plant and soil microbial communities and their interactions in response to climate change drivers is necessary to predict future ecosystem function.

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