

Review Article

Soil Organic Carbon Dynamics: Drivers of climate change-induced soil organic carbon loss at various ecosystems

ABSTRACT

At roughly 2500 Peta gram (Pg) C, soil organic carbon (SOC) is the biggest carbon store in terrestrial ecosystems and is a crucial contributor to vital soil functions and ecosystem services, such as agricultural soil productivity. SOC stocks are in a dynamic equilibrium between C inputs, primarily from crop residues and organic manures, and C loss owing to decomposition and mineralization of soil organic matter (SOM) under long-term constant land management and environmental circumstances. In addition, the rate of C addition in native ecosystems is governed by the nature and productivity of the local flora, which is mostly influenced by climatic conditions. However, being a complex system, various factors, such as soil management and land-use change influence the soil C pool. Along with temperature gradients from temperate to tropical regions, SOC supplies were shown to be shrinking on a global and regional basis. This reflects the rates of SOM decomposition as a function of temperature, which fluctuates more rapidly than net primary production (NPP). SOM decomposition rates are also influenced by several parameters, including soil temperature and moisture, soil respiration and pH, and soil physical properties including texture and clay mineralogy. Nonetheless, increased temperatures as a result of climate change are thought to be the primary driver of accelerated decomposition, which results in considerable reductions in SOC supplies and sequestration. Furthermore, climatic change contributes to soil deterioration by increasing the mineralization of the SOC pool and causing desertification (irreversible expansion of desert landforms). Similarly, erosion is a degrading process that affects C dynamics and leads to terrestrial carbon loss through the breakdown of structural aggregates, as well as lower productivity in eroding areas due to a lack of soil nutrients. Thus, for an in-depth understanding of worldwide soil C dynamics and to provide support to C management and decision support systems to policymakers and land managers in the face of changing climates, comprehensive research on the influence of multiple climate-induced drivers on soil C is required.

Keywords: Carbon dynamics, Carbon sequestration, Climate change, Land use change, Desertification

1. Introduction

Climate change caused by greenhouse gas emissions is a major threat in all parts of the world (Hansen *et al.*, 2013). Since the beginning of the Industrial Revolution, the level of greenhouse gases has risen at an exponential rate. Carbon dioxide (CO₂) concentrations in the atmosphere have increased by 40% globally, from 278 parts per million in the preindustrial era to 410 parts per million now (GMD, 2017). Although rising levels of greenhouse gases like methane (CH₄) and nitrous oxide (N₂O) are primarily linked to agriculture, soil serves as both a sink and a source for one of the most important greenhouse gases, carbon dioxide (CO₂) (IPCC, 2006). Soil organic carbon (SOC) is one of the greatest reservoirs of organic carbon (OC) (1462–1584 Pg in the top 100 cm) (Batjes, 1996), and it is important for global C balance as well as soil functioning. Indeed, soil OC content is roughly three times that of air or terrestrial vegetation pools (Schmidt *et al.*, 2011), and it has long been recognized that even minor changes in soil C stock can have a big impact on atmospheric C concentrations (Eglin *et al.*, 2010).

Soil organic matter (SOM) is made up of both live and dead organic materials in soils (Stevenson, 1994). It contains an endless number of organic compounds, ranging from simple, easily mineralizable organic leftovers to complex, resistant products and microbial biomass (Kögel-Knabner, 2002). The carbon percentage stored in this organic matter represents the total organic carbon (TOC) in the soil, and it is assumed that SOM comprises 58 percent carbon for all practical reasons. The SOM components are especially important in maintaining overall environmental quality since they make up a significant portion of global carbon reserves. According to the calculations, a 0.01 percent increase in TOC content in soil may readily counteract annual CO₂-C increases in the atmosphere through soil carbon storage (Lal, 2014). Although SOM is made up of a variety of materials that vary in size and decomposability, the carbon polymers in them may be divided into three categories for ease of use: active, slow, and passive carbon polymers (Tan *et al.*, 2007). The active pools are labile forms of carbon that are very susceptible to change and have a mean residence duration of 1–5 years. Due to its susceptibility to quick oxidation, this pool has the potential for rapid breakdown, which would increase CO₂ efflux to the atmosphere. This pool of carbon, on the other hand, is critical for

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feeding the soil food web and influences a wide range of soil activities and processes, from nutrient cycling to soil maintenance. Changes in land use and management practices have an impact on soil production and quality (Verma *et al.*, 2010). Slow SOC pools have a mean residence period of 20–40 years, while passive SOC pools have a mean residence duration of 200–1500 years. Because the stabilized carbon fractions are highly resistant to microbial activity, they are not a good measure of soil quality (Majumder *et al.*, 2008), but they do contribute to overall carbon fixation.

Carbon sequestration is the process of absorbing CO₂ from the atmosphere and storing it in a way that prevents it from being released back into the atmosphere. Organic matter (OM) can be stabilized in soils through three mechanisms: biochemical recalcitrance, creation of organo-mineral complexes through chemical interactions with minerals and metal ions, and/or physical protection due to occlusion inside soil aggregates (Barre *et al.*, 2014). However, climate–soil–land use/management interactions influence a soil's ability to hold OC.

2. Global pools of C/ Sources and sinks of Global C

There are five major C pools in the world. The oceanic pool, with 38,000 Pg (Pg = petagram = 10¹⁵ g = 1 billion metric tonne), is the largest, followed by the geologic pool, with 5000 Pg, which includes 4000 Pg of coal and 500 Pg each of oil and gas. Carbonates in sedimentary rocks are not included in the geologic pool described here. The terrestrial C pool, which includes soil and vegetation, is the third-largest. Both inorganic and organic types of soil C can be discovered. The organic form (SOC) is formed from the activities of animals, microbes, and plant materials, as well as their subsequent breakdown (Bronick and Lal, 2005), whereas the inorganic forms are predominantly carbonates of alkaline soil cations (Wang *et al.*, 2016). With a total soil C pool of roughly 2300 Pg to 1-m depth (Batjes, 1996), the SOC pool is estimated to be 1550 Pg and the soil inorganic carbon (SIC) pool is estimated to be 750 Pg (Batjes, 1996). The terrestrial C pool is predicted to be around 2860 Pg, with a vegetation pool of 560 Pg. The atmospheric pool currently stands at 760 Pg and is growing at a pace of 3.2 Pg C each year. As a result, the 2300 Pg soil C pool is around 4.1 times the biotic/vegetation pool and roughly 3 times the atmospheric pool. The terrestrial C pool, at 2860 Pg, is around 57 percent of the geologic pool and four times the atmospheric pool. All of these pools are linked together. Each year, for example, 60 Pg C is transferred between biota/vegetation and the atmosphere in both directions.

Similarly, the ocean absorbs 92 Pg of the 90 Pg emitted each year (Schimel *et al.*, 2001). In comparison, fossil fuel burning emits just 6.3 Pg/year, while land-use change emits 1.6–2.0 Pg/year. As a result, improving photosynthetic fixation and sequestering even 5% of photosynthetic C into terrestrial ecosystems can significantly reduce industrial emissions.

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3. Vertical distribution of SOC

The identification of stable and recalcitrant SOC pools at deeper depths is vital to understanding the influence of human activities and climate on the terrestrial C cycle, and the depth-wise distribution of SOC has recently received increased attention. Changes in land use have an impact on SOC pools in perennial crops that is not limited to surface soils, as their influence is also important in sub-surface soils. The majority of previous research on dynamic representations of C has been on the soil layer considered by agronomists, namely the 0-30 cm depth. However, because half of the soil carbon is found below 30 cm depth (Mulder *et al.*, 2015), carbon-14 dating and natural tracing by ¹³C have revealed that the median age of carbon at 1 m depth is larger than 1000 years, interest in understanding the subsurface mechanisms are developing. The 30-100 cm layer renews 7-10 times slower than the 0-30 cm layer (Mathieu *et al.*, 2015; Balesdent *et al.*, 2017). Deep carbon, on the other hand, is not inert. According to the studies, the 30-100 cm layer in cultivated soils comprises 25% of the "young" carbon stock (i.e., less than 20 years) of the 0-100 cm layer and less than 20% in permanent grasslands. Several studies have found significant effects of land-use changes or agricultural practices on deep soil carbon, such as a decrease in C when grasslands or forest areas are cultivated (Guo and Gifford, 2002), and an increase when forests are converted to pasture (Stahl *et al.*, 2017), or the introduction of legumes (Guan *et al.*, 2016).

The dynamics of soil organic carbon (SOC) have long been recognized as a major source of uncertainty in biogeochemical interactions between land, atmosphere and climate. González Jaramillo *et al.* (2016) found that deep soil layers can hold substantially more carbon than previously thought (limited evidence, medium agreement). Deep SOC can be quite old, with habitation times of several thousand years (Rumpel and Kögel-Knabner, 2011) or perhaps several tens of thousands of years (Okuno and Nakamura, 2003). Most of the research reviewed in this area does not address the dynamics associated with such deeply buried carbon, which are poorly investigated and neglected by models. Deep soil carbon is assumed to be stabilized by

mineral interactions; however, recent tests show that CO₂ release from deep soils can be boosted by warming (Hicks Pries *et al.*, 2017), or by adding fresh carbon (Fontaine *et al.*, 2007).

4. Causal agents or Drivers of soil C loss

Due to the single as well as interacting impacts of biotic and climatic variables, the dynamic balances of SOC with the atmosphere are spatially variable, and they have been investigated extensively at various spatiotemporal scales (Karhu *et al.*, 2014). Climate conditions, particularly temperature and moisture, have long been thought to be the key determinants of SOC decomposition; they overestimate the input of terrestrial pools to the atmosphere (Carvalhais *et al.*, 2014). The size of the SOC pool is determined by a variety of parameters that influence carbon input and decomposition, including plant type and net primary production (Ren *et al.*, 2012), and soil characteristics (Tian *et al.*, 2010). Temperature (Davidson and Janssens, 2006), moisture (Ryan and Law, 2005), and disturbance regimes such as fire (Harden *et al.*, 2000) and land-use change (Ryan and Law, 2005) are also factors to consider (Post and Kwon, 2000). Because soil carbon cycles are one of the largest pools, minor changes in the processes regulating them could have unanticipated repercussions for positive carbon feedback to the atmosphere and global warming.

4.1 Drought and Aridity

Drought, or a lack of water, is one of the most common environmental factors that affect crop development, quality, and production, especially in arid soils. Aridity is the result of a persistent lack of rainfall in the area. Drought in agriculture is defined by low soil moisture levels, which result in significant agricultural yield losses (Dai, 2011). The Indian Meteorological Department has identified dry areas with rainfall exceeding 75% of normal. Drought-prone terrain accounts for roughly 68 percent of India's arable land (Dubey *et al.*, 2019). Because of inadequate rainfall and high temperatures, groundwater recharge has been modest over the years, worsening the situation

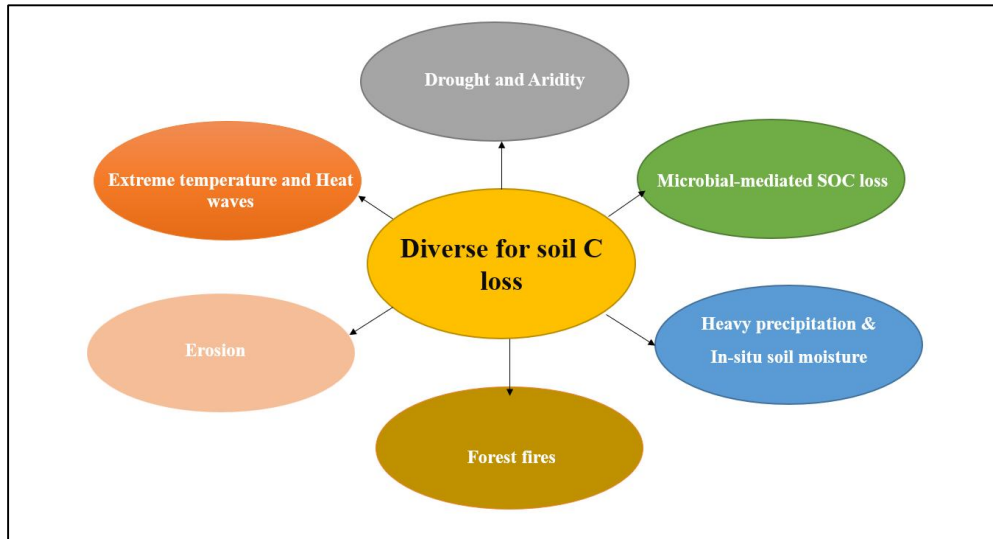


Fig 1: Different drivers for climate-induced Soil carbon loss.

and causing severe drought in many parts of India. Drought episodes have a significant impact on forest carbon cycling due to productivity losses and carbon losses due to mortality (Reichstein *et al.*, 2013). Droughts accounted for 60 to 90% of the biggest climate extremes in the last 30 years, explaining up to 78 percent of the variation in worldwide gross primary output.

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4.2 Extreme temperature and Heat waves

Physical and chemical protective mechanisms are among the soil and climatic restrictions that can impact SOC decomposition's temperature sensitivities:

(i) **Physical protection:** SOC within soil aggregates will be exposed to microbial activity to a limited extent and will be in an oxygen-depleted environment. Organic molecules can also be shielded against water-soluble enzymes due to their low water solubility or hydrophobicity (Spaccini *et al.*, 2002).

(ii) **Chemical protection:** Interactions between minerals and organic matter (inner or outer-sphere complexes) help chemically protect these complexes from breakdown forces (Oades, 1988).

The first and second greatest carbon fluxes from terrestrial ecosystems to the atmosphere in the global carbon cycle are gross primary production (GPP) and soil respiration (Beer *et al.*, 2010). Heat extremes modify ecosystem-atmosphere CO₂ fluxes and the ecosystem carbon balance, which has an impact on the carbon cycle. In comparison to single-factor extremes, compound heat and drought events result in a higher carbon sink loss because GPP is greatly reduced and ecosystem respiration is less.

Extreme heat episodes may have long-term consequences on the carbon cycle. The carbon cycle can be slowed or sped up depending on whether or not lower vegetation productivity and/or widespread death following an intense drought are not compensated by regeneration, or if the productive tree and shrub seedlings produce rapid regrowth after windthrow or fire (Frank *et al.*, 2015).

Reduced carbon sequestration by ecosystems, as well as degradation of ecosystem health and loss of resilience, are likely a result of projected changes in the frequency and severity of severe temperatures and heat waves (Trumbore *et al.*, 2015). Agricultural productivity (Lesk *et al.*, 2016), hydrology, vegetation productivity and distribution (Zhou *et al.*, 2014), carbon fluxes and stocks, and other biogeochemical cycles are all influenced (Schlesinger *et al.*, 2016). Due to their huge carbon pools and fluxes, potentially large lagged impacts, and extended recovery times to restore lost stocks, carbon stocks are particularly vulnerable to catastrophic events (Frank *et al.*, 2015).

4.3 Erosion

Erosion is the loss of soil due to physical factors such as water, wind, or farming practices such as tillage (Ginoux *et al.*, 2012). Global estimates (FAO 2015) of soil erosion range from roughly 20 Gt_{yr}⁻¹ to more than 200 Gt_{yr}⁻¹ depending on scale, study period, and method used (García-Ruiz *et al.*, 2015). Climate change has the potential to exacerbate water-induced soil erosion, particularly in areas where precipitation volumes and intensity are expected to rise (Nearing *et al.*, 2015). On the other hand, wind erosion is a common occurrence in places like West Asia and the Arabian Peninsula (Klingmüller *et al.*, 2016), but there is no evidence of its effects on climate change. The light SOC component is preferentially removed by erosive processes, and soil C is transferred into depression regions and aquatic habitats may operate as a

C sink. 0.8 Pg of the 1.9 Pg C transferred into inland waters each year from terrestrial sources is released into the atmosphere, with the rest buried in aquatic sediments (Cole *et al.*, 2007). Reduced decomposition at depositional sites and dynamic replacement of eroded C are two factors that lead to erosion-induced C sinks (Van Oost *et al.*, 2007). An eco-geomorphologic perspective on SOC migration through the landscape may help to determine if soil erosion is a source or sink of atmospheric CO₂. Restoration of degraded soils and desert lands can provide a considerable C-sink capacity since their ecosystem C pool is highly depleted (Lal, 2004). An eroded soil would simply have less soil material available for sequestering carbon than it did before agricultural operations began. The clay component of the soil, in particular, was discovered to play an important effect in preventing SOC loss due to erosion (Sissoko and Kpombrekou-A, 2010).

4.4 Forest fires

Forest fires are possibly the most well-known and well-quantified global disturbance and risk. Between 1997 and 2016, an average of 500 million hectares of land were burned annually, the majority of which was outside of forest ecosystems (Andela, 2017). Burned area is growing in many tropical, temperate, and boreal forest ecosystems, despite the fact that it is decreasing in grasslands and savannas (Samuel *et al.*, 2020). Forest fires release 1.8 Pg CO₂ per year (Chuvieco *et al.*, 2016). Annually, fire is responsible for around 12% of stand-replacing disturbances in forest ecosystems (Pugh *et al.*, 2019). Variations in fire behavior (i.e., fire temperature or scorch height) can influence tree mortality and in many temperate and boreal forests, the amount of fuel consumed in organic surface soil layers which are influenced by climate-driven changes in fire regimes. Forest fires release a lot of carbon into the atmosphere in a short amount of time (38 seconds) compared to what would take a human lifetime to decompose through SOC.

Because it removes plant cover, increases runoff and soil erosion, diminishes soil fertility, and changes the soil microbial population, wildfire is a driver of desertification (Liu and Wimberly, 2016). Increases in temperature and the severity of drought episodes in some dryland areas are expected to increase the likelihood of wildfires (Clarke and Evans, 2018). Fire can have a significant impact on observed vegetation, particularly the relative abundance of grasses to woody plants, in semi-arid and dry sub-humid environments (Balch *et al.*, 2013).

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4.5 Heavy precipitation & In-situ soil moisture

As a warmer temperature permits more water vapour in the atmosphere, as estimated by the Clausius-Clapeyron (C-C) connection, a warming climate is projected to increase the hydrological cycle, with subsequent consequences on regional extreme precipitation events (Manola *et al.*, 2018). Changes in atmospheric dynamics also exacerbate or decrease future precipitation extremes on a regional scale (Pfahl *et al.*, 2017). In many parts of the world, continued global warming is very likely to increase the frequency and intensity of intense rainfall (Mohan and Rajeevan, 2017; Preinet *et al.*, 2017). Extreme rainfall impacts soil CO₂ fluxes and CO₂ uptake by plants within ecosystems, resulting in changes in ecosystem carbon cycling (Frank *et al.*, 2015). Extreme rainfall and flooding reduce oxygen levels in soil, which can inhibit the activities of soil microbes and plant roots, as well as reduce soil respiration and so carbon cycling (Philben *et al.*, 2015). According to historical climate data, rainfall patterns have already shifted over the ages, and overall precipitation has increased. Drought spells will become more frequent, interspersed with high-intensity precipitation events, resulting in higher variability in soil moisture regimes, which could have an impact on GHG sources and sinks in terrestrial ecosystems. Although terrestrial ecosystems are extremely susceptible to changes in precipitation patterns, the amount to which expected changing rainfall regimes affect SOC cycling and storage in terrestrial ecosystems is highly varied.

Changes in climate and soil water content (SWC) significantly determine whether the soil C pool operates as a source or a sink for atmospheric CO₂. Another key aspect influencing SOC dynamics is the amount of water in the soil. Under various climate conditions, SWC is known to have a critical role in vegetation growth and C substrate supply for microbial activity (Schindlbacher *et al.*, 2012). In a warm climate, high SWC may boost C absorption (e.g., ecosystem productivity) or release it (e.g., soil respiration), while excessive SWC may lower them in a moderately moist environment (Liu *et al.*, 2018). High water availability, for example, can reduce C cycling in cold tropical forests while enhancing ecosystem production and SOC decomposition in warm tropical forests (Taylor *et al.*, 2017). High SWC can accelerate soil respiration in arid and semi-arid steppes, resulting in considerable C loss from the soil (Jia *et al.*, 2007). The SWC is also important in regulating the C cycle's responses to climate change (Wan

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et al., 2007). As the soil changes from wet to dry, the warming effects on C switch from positive to negative, illustrating the critical role of SWC in warming-induced C gain or loss (Liu *et al.*, 2018). According to a recent study, warming can increase net carbon uptake in wet situations but decrease it in dry conditions (Quan *et al.*, 2019). These findings show that the C cycle is intertwined with SWC and that this relationship may get more complicated as the world warms. Furthermore, in the context of climate change, precipitation-induced changes in soil water will continue to have an unpredictable impact on future C dynamics.

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Furthermore, the soil moisture content is an important factor in microbial SOC digestion. Extremes of moisture (e.g., drought or flooding) have a negative impact on microbial respiration rates. Drought restricts enzyme and substrate transport by breaking water films, whereas flooded circumstances promote less effective anaerobic breakdown by restricting oxygen passage. Microbial respiration's reaction to shifting precipitation patterns has been extensively researched. Droughts, whose intensity and frequency are expected to rise as a result of climate change, have a less clear impact on microbial respiration. The minimal data available, which was based on in-situ moisture modification research, demonstrated that moisture stress has a variety of impacts. However, due to lack of oxygen, intense or longer precipitation events might reduce microbial respiration. Also, abrupt increases in soil moisture may cause microbial cell lysis, resulting in a reduction in the total microbial population; yet, cell lysis can easily provide substrates to the surviving microorganisms, thus the net effect on microbial respiration is less definite. The use of microbial SOC is also influenced by soil moisture and temperature (Post and Kwon, 2000). Furthermore, it has been reported that under soil erosion, SOC redistribution and CO₂ emissions are strongly influenced by temporal variability of environmental conditions such as initial soil moisture, location, soil management, and rainfall (Wang *et al.*, 2014^a). The relationship between carbon decomposition rates and soil moisture content is complicated and contentious (Singh *et al.*, 2017). Several publications have reported contradictory results, claiming that the effect of soil moisture on the temperature coefficient, Q₁₀, varies from no change to a positive influence with seasonal moisture changes (Jassal *et al.*, 2008). Failure to relate estimates of soil carbon storage to future soil moisture changes could be attributed to (i) the lack of a sound relationship between soil moisture and soil carbon storage, and (ii) heterotrophic respiration and future soil moisture change direction and size uncertainty.

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4.6 Microbial-mediated SOC loss

Climate change has been shown to have an impact on both micro and microorganisms (plants) and is a major worldwide issue affecting life on the planet (Sergakiet *al.*, 2018). Changes in the structure, quantity, composition, and functional activity of plant-associated microbial species are also influenced by changing climate. Because soil community taxa vary greatly in their physiology, growth rates, and temperature sensitivity, climate change is thought to have both direct and indirect effects on plant-soil-microbe interactions (Bojko and Kabala, 2017), by altering community structure, relative abundance, and function (Bagri *et al.*, 2018; Dubey *et al.*, 2019). It is widely assumed that indirect effects of climate change on soil microbial communities, as mediated by plants, may be far more powerful than direct effects on the below-ground microbial population.

Changes in the structure and composition of the microbial community lead to changes in ecosystem functioning; additionally, changes in the relative abundance of organisms that regulate key and explicit processes have a direct impact on the rate of that process (Schimel and Schaefer, 2012). Microbially mediated decomposition is the most common pathway for organic carbon loss from soil, with soil microbes consuming 10–15 percent of the released energy. Annually, 119 Gt C is expected to be exhaled from the terrestrial biosphere to the atmosphere, with soil microbial respiration accounting for nearly half of that (Auffret *et al.*, 2016). Making mechanistic and quantitative estimates regarding how numerous environmental conditions influence soil microbial respiration is still impossible (Dungait *et al.*, 2012). Temperature and moisture responses in soil warming tests vary significantly between biomes and regions. SOC reactions to warming through time have also been studied and found to be complex. Melillo *et al.* (2017) discovered that soil respiration response to warming went through numerous phases of rising and decreasing strength, which was linked to changes in microbial populations and available substrates throughout time in a multi-decadal warming experiment. Transient decomposition reactions to warming might be explained by depletion of labile substrates, but long-term SOC losses could be compounded by high-temperature sensitivity of slowly degrading SOC components, according to Conant *et al.* (2011) and Knorr *et al.* (2005). Long-term SOC reactions to warming are still unknown (Nishina *et al.*, 2014; Singh *et al.*, 2018b). As shown by a recent

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worldwide meta-analysis, soil moisture plays an essential role in SOM breakdown by regulating microbial activities.

5. Impacts of climate change

5.1 Direct impacts:

5.1.1 Soil communities

The functioning and relative abundance of microbial communities in soil are affected by climate change. On the basis of their growth rates, physiology, and temperature sensitivity, these bacteria frequently show a wide range of variance (Zhang *et al.*, 2018^b). In a study, DeAngelis *et al.* (2015) found that long-term warming of forest soil causes changes in microbial communities in temperate forest soils. As a result, increasing the temperature by 5 °Celsius in temperate forests changes the relative abundances of microbes in the soil, such as bacteria, and so increases the bacterial-fungal ratio (Bintanja, 2018). Because the mechanisms that soil bacteria mediate are temperature sensitive, global factors such as global warming directly affect their respiration rates. As a result, the effect of increased temperature on microbial metabolism has gotten a lot of attention in recent years (Gao *et al.*, 2018). However, some questions remain unanswered, such as (I) the impact of changing microbial communities on various functions such as the decomposition of old and new organic matter, and (II) how moisture, temperature, and their interactions affect only specific microbial communities within a community, such as methanogens, and (III) which mechanisms drive the net ecosystem response of microbial communities. Globally, soil microbial respiration is predicted to release 40–70 Gt C per year into the atmosphere (Hawkes *et al.*, 2017). Warming (which is projected to accelerate SOC losses through microbial respiration) and plant growth acceleration are the major processes affecting SOC stocks in terms of land–climate interactions (which increases inputs of carbon to soils). Although this reaction is not uniform, some studies have found that precipitation events can increase microbial activity as substrate diffusion is increased, resulting in greater CO₂ fluxes. However, due to a lack of oxygen, intense or longer precipitation events might reduce microbial respiration. Extracellular enzymes control the organic matter and nutrient cycle in the soil. Extracellular enzyme activity decreased under drought, which was consistent with the results of soil CO₂ reflux. This could be due to moisture-induced diffusion restrictions, which limit enzyme contact with their respective substrates and slow down decomposition. Enzymes may also be

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more securely adsorbed to clay minerals when soils dry, making them more resistant to proteolytic degradation.

5.1.2 Plants/ organic matter inputs by plants

Increased SOC buildup has been found in some litter addition trials (Lajtha *et al.*, 2014b), whereas minor SOC responses have been observed in others (Lajtha *et al.*, 2014a; van Groenigen *et al.*, 2014). Microbial dynamics are thought to play a key role in the complicated reactions to carbon additions. Through priming effects, the addition of new organic material can speed up microbial development and SOM decomposition. SOM cycling is dominated by 'hot zones,' such as the rhizosphere and areas near fresh debris (moderate evidence, high agreement) (Kuzyakov and Blagodatskaya, 2015). This complicates estimates of SOC responses to increased plant production since higher carbon inputs may encourage higher SOC storage, but they may also deplete SOC reserves by encouraging faster decomposition. Van Groenigen *et al.* (2014) found that increased CO₂ accelerated SOC turnover rates across many biomes in a meta-analysis. These impacts have been documented in the tropics as well as high-latitude regions where soils have high organic matter content and plant production is growing. Along with biological breakdown, stabilization via interactions with mineral particles (high confidence) is another source of uncertainty in estimating SOC responses to climate change (Kleber *et al.*, 2011; Schmidt *et al.*, 2011). Historically, the significance of chemical recalcitrance in SOC cycling has been centered on the premise that long-lived SOC components are produced from organic molecules that are innately resistant to breakdown. Stable SOC is generated predominantly by the bonding of microbially-processed organic material to mineral particles, which limits the accessibility of organic material to microbial decomposers (Kallenbach *et al.*, 2016). By being contained in soil pores too small for microorganisms to access (Six *et al.*, 2004), SOC in soil aggregates can be preserved from the microbial breakdown (Keiluweit *et al.*, 2016). Although the sensitivity of mineral-associated organic matter to changes in temperature, moisture, fire, and carbon inputs is highly uncertain, some new models are incorporating these mineral protection processes into SOC cycling projections (Wang *et al.*, 2017^a). It will be vital to have a better quantitative understanding of soil ecosystem processes in order to forecast future land–climate feedback interactions.

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5.2 Indirect impacts

Plant phenology and microbe dispersion are both affected by climate change, so plant species distribution is affected as well (Classen *et al.*, 2015). Many studies have failed to explain how soil-associated bacteria might adjust their ranges to maintain a negative or positive interaction between the soil microbiome and the plant. Because soil microorganisms are poor dispersers, they adapt to climate change at different rates than plants (Chen *et al.*, 2015a). However, we know that microorganisms and plants have distinct dispersal abilities, which can affect plant productivity and the establishment of new plant species, as well as their interactions. Plants that successfully establish themselves in new ranges are known to produce increased quantities of plant defense chemicals such as polyphenols (Agrawal and Weber, 2015). Agricultural species, insect pests, weeds, and crop diseases are all affected by rising global temperatures or expected climate change. Weeds are thought to be responsible for 34% of crop losses, with 18% due to insects and 16% owing to diseases. Climate change looks to have the potential to exacerbate the already significant negative effects of insects, weeds, and disease on agricultural systems. Several weed species benefit more than crops from elevated temperatures and CO₂ levels, which is one of the predicted effects.

Many biotic disturbance agents, such as insects and viruses, are affected by climate change, resulting in significant tree mortality around the world. Warmer weather increases winter survival and increases life stage–development rates in bark beetles (Kautz *et al.*, 2017). Defoliators eat leaves and can destroy trees after causing severe damage for several years. Defoliators have caused widespread tree death in temperate and boreal forests, in both coniferous and broad-leaved forests (Williamet *et al.*, 2020). Non-native invasive biotic disturbance agents, in addition to these native biotic agents, are responsible for the death of many trees around the world. Drought stresses host trees, lowering their defenses, changing the quality of their foliage, and making them more vulnerable to attack (Kolbet *et al.*, 2016). Moisture in the air can affect pathogen survival and spread (Dymond *et al.*, 2010).

5.3 Other disturbances

Storms and wind-driven events, as well as snow and ice events and lightning, can all have an impact on forest ecosystem carbon cycling (Seidl *et al.*, 2017). These disturbance events can

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have a significant impact on local to regional carbon cycling in some locations, but their global impact is estimated to be low to modest (Zscheischler *et al.*, 2014). Hurricanes wreak havoc on coastal forests and have a significant influence on carbon budgets. Hurricane Katrina, for example, destroyed 320 million large trees containing 385 Tg CO₂e (Chambers *et al.*, 2007), and tropical cyclones had a net effect of a small carbon source over forests in the twentieth century.

6. SOC loss in different ecosystems with changing climate

6.1 Agro-ecosystem

Soil carbon levels are depleted as a result of forest land conversion for agricultural uses due to soil erosion, site disturbance associated with rapid SOC decomposition, and changes in the quantity and quality of organic wastes supplied to the soil (Guo and Gifford, 2002; Kasel and Bennett, 2007) as shown in Fig2. Natural forest changes raise maximum soil temperature and decrease soil moisture storage, especially if drainage systems are installed (Lal, 2008). Nutrients produced by the mineralization of labile SOC accumulate in forest vegetation for a few years, helping to preserve agricultural productivity. Tillage, drainage, weeding, the addition of mineral fertilizers, and liming, on the other hand, exacerbate the breakdown of SOC and the release of carbon into the atmosphere (Poepplau *et al.*, 2011). Over the previous two centuries, forest conversion to farmland has been estimated to account for 40% (180–200 Pg C) of all anthropogenic carbon emissions (Marland *et al.*, 2000).

Agricultural soil management is a key approach for increasing their C pool. Cropland soils cover roughly 1.5 billion hectares and have a substantial C sink capacity due to prior SOC depletion. Agricultural soils, if not maintained properly, can be a significant source of CO₂ and N₂O in the atmosphere. When forest systems are converted to agricultural land, the SOC drops rapidly, owing to smaller amounts of insoluble material in quickly digested crop residues. Soil tillage promotes SOC mineralization while also releasing CO₂ into the environment (Sandeep and Manjaiah, 2014). Tillage breaks aggregates and exposes carbon compounds that would otherwise be unavailable to bacteria, in addition to churning and mixing the soil. In agriculture, residue burning is an essential management tool, particularly in the tropics. This process releases a variety of gases into the environment while leaving charcoal, a passive component, as a byproduct. Skjemstad *et al.* (2002) estimated that in fire-prone ecosystems, incomplete biomass combustion charcoal might account for up to 35 percent of total SOC. According to studies, the

refractory charcoal fraction occupies a large amount of the total organic carbon pool in soils as the SOC pool is depleted by agriculture and degradation (Skjemstad *et al.*, 2001).

Heavy rain and flooding in agricultural systems can cause crop losses due to anoxia and root infections, as well as delayed sowing and increased soil compaction (Posthumus *et al.*, 2009). Flooding caused by tropical cyclones can cause crop failure in tropical areas due to both rainfall and storm surges. Surface flooding and soil saturation frequently result in decreased soil quality due to nutrient loss, reduced plant productivity, stimulated microbial growth and microbial community composition, negatively impacted soil redox, and increased GHG emissions (Barnes *et al.*, 2018; Sánchez-Rodríguez *et al.*, 2019). Management systems that may minimize or worsen the impact of flooding on soil quality have an impact on the impact of flooding on soil quality. Although soils recover quickly after flooding, the influence of recurrent high flood events on soil quality and function over longer durations is unknown (Sánchez-Rodríguez *et al.*, 2017).

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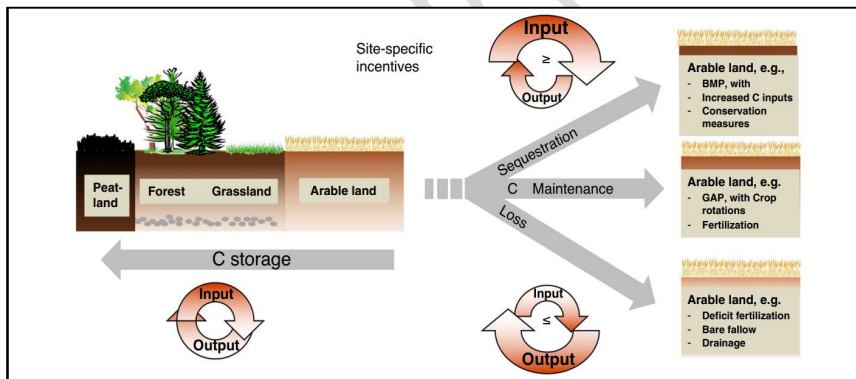


Fig2: The loss of C after conversion of native ecosystems i.e. peat land, forest, and grassland to arable land {adopted from Amelunget *et al.*, (2020) 11:5427 | <https://doi.org/10.1038/s41467-020-18887-7>}

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6.2 Forest ecosystem

Forest ecosystems are critical to global carbon cycling and ecological service provision (Seddon *et al.*, 2016). As a result of present climate change and related drought and heat stress (Choat *et al.*, 2018), there has been evidence of changes in forest composition, structure, and

function. The predicted shift in precipitation and temperature patterns in the twenty-first century, as well as rising CO₂ levels, are likely to have a significant impact on forest ecosystems (Seneviratne *et al.*, 2012, Senf *et al.*, 2016). As a result, for policymakers and stakeholders to effectively plan adaptation measures to cope with the future climate scenario, understanding the likely consequences of climate change, particularly connected drought and CO₂, on forests and their functions is crucial. Forest ecosystems have long been recognized as the most effective carbon sinks, capable of lowering atmospheric emissions both directly and indirectly by sequestering carbon in soil and plant biomass (Tokimatsu *et al.*, 2017).

Nearly 70% of all organic carbon in soil is sequestered by forest ecosystems (Hurteau *et al.*, 2009). Climate-induced Forest die-off has been observed all over the world, posing a catastrophic carbon cycle feedback by releasing enormous amounts of carbon stored in forest ecosystems into the atmosphere while also reducing the size of the future forest carbon sink. Climate-related concerns in the twenty-first century may jeopardize forest carbon sinks and stocks. Climate change affects forests in both positive and negative ways (Trumbore *et al.*, 2015), and vegetation responses will differ regionally and over time. Warming, changes in precipitation and water balance, CO₂ fertilization, and nutrient cycling are just a few of the climate-change-related drivers that interact in complex ways, making estimating future net impacts problematic.

Deforestation and regeneration can alter dynamic soil properties significantly, impacting a variety of soil functional processes both directly and indirectly (Kurniawan *et al.*, 2018). For example, deforestation is linked to lower soil organic carbon (SOC) stocks (Guo & Gifford 2002; Donet *et al.*, 2011), higher soil bulk density and pH changes (Veldkamp *et al.*, 2020). Changes in dynamic soil properties occur most quickly in organic-matter-rich topsoils with the highest biological activity (van Straaten *et al.*, 2015). Deeper soil strata (>50 cm) are affected by deforestation and reforestation, albeit changes are more gradual and often take decades to show. In order to quantify impacts on the atmosphere, net emissions, or the balance of gross emissions and gross carbon removals from the atmosphere through forest regrowth, must be estimated during forest harvesting for lumber and fuelwood, as well as land-use change (deforestation) (Poorter *et al.*, 2016). SOC is a collection of fractions with varying residency periods (from a few months to decades or millennia (Amundson, 2001) and responses to land-use change. Changes in

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SOC stocks during deforestation and restoration have been intensively studied due to the critical role that land-use dynamics play in the present global C budget.

6.3 Grasslands

Grasslands cover 26% of the global land area (Conant *et al.*, 2017), and their use for grazing farm animals across 34 million km² contributes significantly to food security in order to meet the needs of a growing population (Soussana *et al.*, 2010). The carbon preserved as soil organic matter (SOM) contributes about 20% of global carbon shares to a depth of 1 m due to the widespread presence of grasslands (Stockmann *et al.*, 2013). Improved grassland management to increase carbon stocks (Conant *et al.*, 2017) could help reduce agricultural greenhouse gas emissions (Smith *et al.*, 2016), improve soil fertility (Lal, 2004), and make agricultural systems more resilient to extreme weather events (Pan *et al.*, 2009). According to Zomer *et al.* (2017), global farmland soils could store 26–53 percent of the 4 per 1,000 initiative's objective carbon storage (Soussana *et al.*, 2017). However, because of the complex interactions between climate and soil types (Conant *et al.*, 2017), as well as management practices such as grazing intensity, frequency, and duration (Zhou *et al.*, 2017), irrigation, fertilizer addition, and plant species mixes, predicting the impacts of management on grassland soil stocks is difficult. Through the elimination of biomass and the return of carbon in dung, as well as high nitrogen concentrations in urine patches, grazing animals disconnect the stoichiometric links between carbon and nitrogen cycling in soils (Soussana and Lemaire, 2014).

6.4 Drylands

The variables that produce desertification are known as desertification drivers. Early studies of desertification in the early to mid-twentieth century ascribed it largely to human activity. The validity of such a uni-causal perspective on desertification, on the other hand, was proven (Reynolds *et al.*, 2007). The primary ecosystem services (provisioning, regulating, sustaining, and cultural functions) in drylands are vulnerable to the effects of climate change due to significant variability in temperature, precipitation, and soil fertility (Enfors and Gordon, 2008). Dryland ecosystem services, particularly food and fodder production, have been impeded by desertification processes such as soil erosion, secondary salinization, and overgrazing (Majeed and Muhammad, 2019). Desertification impacts the albedo and water balance of the soil surface (Gonzalez-Martin *et al.*, 2014). Because erosive winds have no hurdles to overcome,

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wind erosion and dust storms are more likely to occur in such environments. Mineral aerosols have a large impact on soil nutrient distribution and contribute to soil property changes (Middleton, 2017). Soil formation as a supporting ecosystem service suffers as a result. By eliminating fine soil particles (silt and clay), wind erosion limits the ability of soil to absorb carbon (Wiesmeier *et al.*, 2015). In some dryland settings, SOC is also lost due to soil erosion, resulting in SOC reduction and carbon (C) transfer from soil to the atmosphere (Lal, 2009). Dust storms also have an impact on crop yields by exposing crop roots, burying crop seeds under sand deposits, and causing nutrient and fertilizer losses from topsoil owing to sandblasting leading to plant leaf loss and thus lower photosynthetic activity (Field *et al.*, 2010).

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7. Mitigation potential of soil C loss through different management practices under changing climate

- The importance of enhancing and sustaining the global soil C pool (both SOC and SIC) is growing for a range of ecosystem services, but most notably to mitigate climate change and improve food security. In the context of climate change, understanding the climatic variable sensitivity of SOM breakdown and its impact on the global SOC pool is equally important (Zhang, 2010). Soil and other terrestrial ecosystems sequester carbon, which has consequences for both mitigation and adaptation. The adaptation benefits of better soils and crop management systems are reliant on limiting the negative effects of climate change. However, there are significant roadblocks to realizing the mitigation and adaptation benefits of management innovations. Though the full literature range is larger, raising soil organic matter stocks in mineral soils is predicted to have a worldwide mitigation potential of 1.3–5.1 Gt CO₂yr⁻¹ (Fuss *et al.*, 2018; Smith, 2019).
- Sustainable land management (SLM) strives to replenish soil carbon, which is particularly important in the face of climate change (Rumpel *et al.*, 2018; Montanarella *et al.*, 2018; Rumpel *et al.*, 2018). The loss of 20–60 percent of the soil carbon they contained under natural ecosystem conditions is due to frequent disturbance from tillage and harvesting, as well as the change from deep-rooted perennial plants to shallow-rooted annual plants in agricultural soils (Crews and Rumsey, 2017). Increasing soil organic matter intake or limiting SOM decomposition are two methods for increasing soil carbon. Agronomic operations can substantially impact the carbon balance by increasing organic inputs from litter and roots into the soil. SOM can be improved by retaining residues,

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using locally suited cultivars, intercropping, crop rotations, cover crops, and green manure crops, among other things (Henry *et al.*, 2018). Reduced tillage (sometimes called no-tillage) is another important approach for reducing soil erosion and nutrient loss caused by wind and water (Van Pelt *et al.*, 2017).

- Using legumes, feed legumes, and cover crops in combination with conservation tillage methods could help to minimize desertification. These methods can be used as part of a broader crop management strategy aimed at increasing vegetation coverage and lowering wind erosion losses. Desertification control techniques give considerable benefits in dryland areas by stabilizing soils, as the transition from grassland to annual crop production increases erosion and soil loss. In a perennial agroecosystem, the biogeochemical controls on SOC accumulation shift dramatically and begin to mirror the controls that govern wild ecosystems (Baveye, 2017). SOC levels are expected to rise if erosion is reduced or eliminated, crop allocation to roots is increased by 100–200%, and soil aggregates are not disturbed, resulting in reduced microbial respiration (Crews and Rumsey, 2017).
- Agroforestry is a method of land management that combines crops and/or livestock with woody biomass (such as trees or shrubs). Agroforestry can cut CO₂ emissions by 0.08–5.7 Gt CO₂yr⁻¹ (Coffield *et al.*, 2021). Agroforestry can assist in achieving sustainable intensification by allowing for higher productivity output on the same unit of land while maintaining agricultural yields (Nath *et al.*, 2016). Agroforestry has been linked to increased carbon sequestration in soils and biomass, improved water and nutrient efficiency, and the creation of a favourable microclimate for crop development (Sonwa *et al.*, 2017). Importantly, agroforestry can avoid deforestation by preventing shifting agriculture (Cole *et al.*, 2020; Veldkamp *et al.*, 2020).
- On a worldwide basis, forest management may be able to contribute to modest mitigation advantages of up to 2 Gt CO₂yr⁻¹. By increasing biomass production, the most effective forest carbon mitigation approach for managed forests is one that maximizes carbon stocks (in forests and long-lived products) and wood substitution effects for a particular time frame (Anderegg *et al.*, 2020). If forest management mitigation approaches are integrated into the community and ecological adaptation mechanisms, such as landscape management, they are more likely to be long-lasting (Terry and Dominic, 2019). Low-

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impact logging and wood processing technology, paired with financial incentives, can reduce forest fires, forest degradation, timber production, and carbon stocks (Sasaki *et al.*, 2016).

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- Afforestation, replanting, and forest restoration are some of the land management alternatives for averting desertification. Forests help to safeguard water and soil quality by restricting runoff and storing sediments and nutrients (Smith *et al.*, 2019). Afforestation and reforestation programs can be performed throughout broad swaths of the planet, resulting in synergies in areas prone to desertification (Coffield *et al.*, 2021). Natural regeneration of second-growth forests boosts carbon sinks in the global carbon budget (Chazdon *et al.*, 2016).
- Integrated soil fertility management (ISFM) is a long-term nutrient management technique that combines chemical and organic supplements (manure, compost, biosolids, biochar), rhizobial nitrogen fixation, and liming materials to address soil chemical limits (Henry *et al.*, 2018). Grazing pressure reduction, fertilisation, and diverse plants like legumes and perennial grasses can all help to avoid erosion and boost soil carbon in pasture systems (Viglizzo *et al.*, 2019).
- Integrated water management strategies, such as water conservation and irrigation, improve soil health by increasing soil organic matter content, which helps to prevent or reverse desertification (Stephen *et al.*, 2019). Existing demands on water supply and agricultural systems will be exacerbated by climate change, particularly in semi-arid regions (IPCC, 2019).
- Erosion control and management may aid in the prevention of organic carbon losses in sediments transported by water or wind. At the global level, however, the overall impact of erosion control on mitigation is context-specific and ambiguous, ranging from a source of 1.36–3.67 Gt CO₂yr⁻¹ (Lal, 2004) to a sink of 0.44–3.67 Gt CO₂yr⁻¹ (Hoffmann *et al.*, 2013).

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8. Conclusion

The impact of major drivers of climate change and management approaches on SOC dynamics, which including SOC quality, soil aggregation, and CO₂ outflow, has been highlighted in this chapter. SOC is essential for the survival of all terrestrial life and the conservation of natural resources. Climate change is posing hurdles to global

agriculture by affecting CO₂ emissions and, as a consequence, global warming. Increasing SOC sequestration and reducing CO₂ emissions to the atmosphere are crucial for mitigating global warming. Regardless of land uses, management approaches, climate, or soil types, temperature and moisture are the two most important drivers that govern SOC dynamics. SOC stocks, fractions, and CO₂ outflow are all highly associated with temperature and moisture. The pace at which organic carbon accumulates in soil varies by location and is influenced by temperature, soil characteristics, and plant type. Carbon can be sequestered in soil by converting degraded or barren regions to forests or permanent plants. Many studies have shown that conservation management practises like no-tillage, residue incorporation, manure application, cover crop use, erosion control and integrated nutrient management practises increase SOC storage and improve agro-ecosystem sustainability by aggregating soil and protecting SOC from microbial attack. It is critical to identify appropriate land use and management strategies in order to prevent climate change by increasing carbon sequestration in soil. Climate change and warming have both direct and indirect effects on soil microbial populations due to changes in multiple parameters at the same time. Such drastic changes can have a significant impact on the soil microbiota, plants, and ultimately the carbon balance of the soil. Although several ecosystems, particularly the agriculture sector, where production is highly dependent on soil microbial activity, have been anticipated to mitigate the negative effects of climate change so far, this position may alter in the near future. This necessitates the development of appropriate measures to address the issues of climate change and its consequences on soil microbiomes. Further, despite the abundance of solutions for combatting desertification, climate change adaptation, and mitigation, there is a risk of unintended consequences. Because of their negative environmental consequences, several activities that promote agricultural intensification in dryland environments might become maladaptive. However, estimates of future changes in SOC stocks are highly unpredictable because to the complex mechanisms underpinning SOC responses to moisture regimes, carbon addition, and warming.

9. Policy interventions and future research needs

- Implementation of best management practices to boost carbon absorption in soils and vegetation, practices and conversion to restorative land use are necessary. Crop residues

as surface mulch, complicated crop rotations and agricultural systems, INM techniques for recycling biosolids and other co-products, and other practices are examples of these methods. Crop waste can be used for cellulosic ethanol production, biofuel co-combustion with coal or wood, animal feed, and industrial raw materials, among other things. As a result, policies promoting the use of crop wastes, animal dung, and other by-products as soil additions are necessary.

- Farmers should be compensated for sustaining ecological services by cultivating carbon credits and exchanging them. Small-scale farmers must be organised into associations or producer cooperatives to reduce the transaction costs of C trading, monitoring, and accounting. Contract farming can also successfully connect small-scale farmers with larger farm enterprises, cutting transaction costs.
- SOC dynamics have a larger impact on soil health than SIC dynamics in general. Secondary carbonate formation, bicarbonate transfer into shallow groundwater, and silicate weathering, on the other hand, can all affect atmospheric CO₂ levels and global climate change. The effects of various management practises with both SOC and SIC pools should be the focus of future research.
- There is a lack of understanding of the adaptive limits to the combined effects of climate change and desertification. Furthermore, due to methodological limitations, reliable indicators for attributing desertification to climatic and/or human causes are still insufficient, despite several relevant studies.
- Previous research has concentrated on the broad characteristics of previous and existing desertification climatic feedbacks. However, knowledge of future climate and desertification interactions (beyond changes in the aridity index) is scarce. At both the global and local levels, understanding of projected climate change consequences on desertification processes such soil erosion, salinization, and nutrient depletion as well as [its](#) impact on soil carbon stock is lacking. Filling these gaps will necessitate significant research and data collection efforts. Overall, better assessment and mapping of desertification areas is required, which will include a combination of rapidly rising sources of remotely sensed data.

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