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 changeinfluence 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 (CO_2) 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 (CH_4) and nitrous oxide (N_2O) are primarily linked to agriculture, soil serves as both a sink and a source for one of the most important greenhouse gases, carbon dioxide" (CO_2) (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 CO_2-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 CO_2efflux to the atmosphere. This pool of carbon, on the other hand, is critical for 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 docontribute to overall carbon fixation.

"Carbon sequestration is the process of absorbing CO_2 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 = 10^{15} 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.

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 ^{13}C 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 390 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 CO_2 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

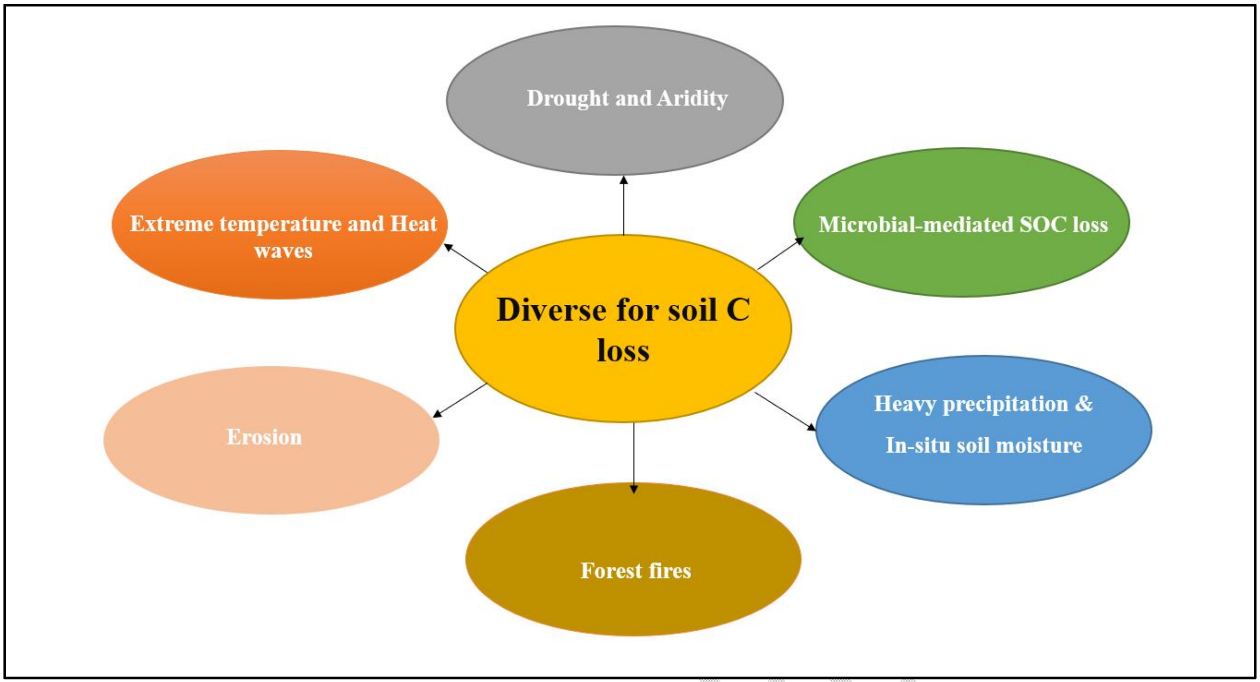

Fig 1: Different divers for climate-induced Soil carbon loss.

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.

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 CO_2 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 CO_2. 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 Kpomblekou-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 CO_2 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 andin 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).

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; Prein*et al*., 2017). "Extreme rainfall impacts soil CO_2 fluxes and CO_2 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 CO_2. 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*., 2016201.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 *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.

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 CO_2 emissions are strongly influenced by temporal variability of environmental conditions such as initial soil moisture, location, soil management, and rainfall (Wang *et al*., 2014). 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, Q_{10}, 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.

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” (Sergaki*et 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*. (20172002) 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*., 2018). As shown by a recent 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). 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 ^{0}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 CO_2 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 CO_2 reflux. This could be due to moisture-induced diffusion restrictions, which limit enzyme contact with their respective substratesand slow down decomposition. Enzymes may also be 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.*, 20142016). 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.* (20142016) found that increased CO_2 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). It will be vital to have a better quantitative understanding of soil ecosystem processes in order to forecast future land–climate feedback interactions.

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*., 2015). 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 CO_2 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 (William*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 (Kolb*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 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 CO_2e (Chambers *et al.,* 2007), and tropical cyclones had a net effect of a small carbon source overforests 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 (Poeplau*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 CO_2 and N_2O 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 CO_2 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 (; 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).

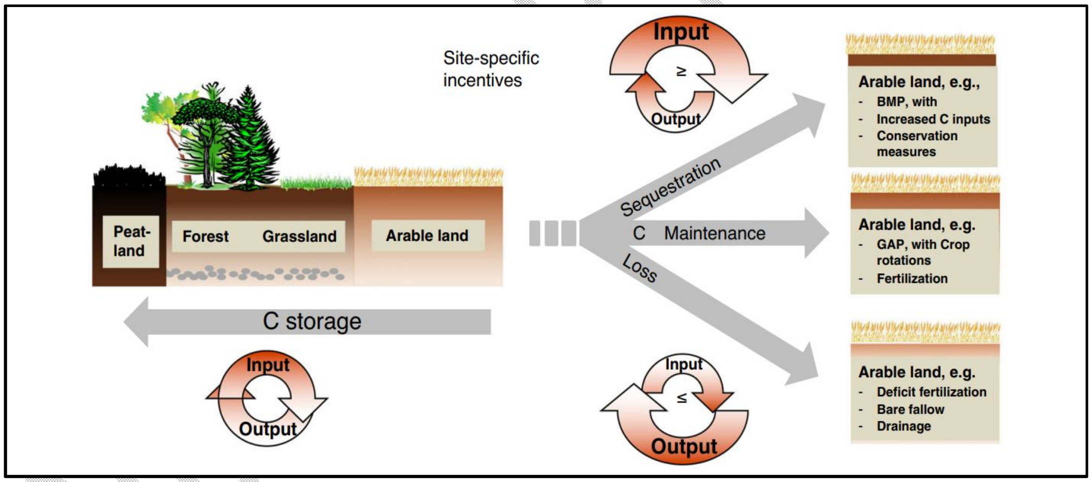

Fig2:The loss of C after conversion of native ecosystems i.e. peat land, forest, and grassland to arable land{adopted from Amelung *et al.* (2020) 11:5427 | https://doi.org/10.1038/s41467-020-18887-7}

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 CO_2 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 CO_2, 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, CO_2 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&Gifford2002; Don*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

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 km^2 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*., 2011). 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, 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).

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 CO_2 yr^{-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 (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, 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 CO_2 emissions by 0.08–5.7 Gt CO_2 yr^{-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 CO_2 yr^{-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-

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).

- 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, fertilization, 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 CO_2 yr^{-1} (Lal, 2004) to a sink of 0.44–3.67 Gt CO_2 yr^{-1} (Hoffmann *et al.*, 2013).

8. Conclusion

The impact of major drivers of climate change and management approaches on SOC dynamics, which including SOC quality, soil aggregation, and CO_2 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 CO_2 emissions and, as a consequence, global warming. Increasing SOC sequestration and reducing CO_2 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 CO_2 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 CO_2 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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References

Agrawal AA, WeberMG (2015) On the study of plant defence and herbivory using comparative approaches: how important are secondary plant compounds. Ecol Lett 18:985–991. https ://doi.org/10.1111/ ele.12482

Amelung, W., Bossio, D., de Vries, W. *et al.* (2020). Towards a global-scale soil climate mitigation strategy. *Nat Commun* **11**, 5427 https://doi.org/10.1038/s41467-020-18887-7

Amundson R (2001) 'The carbon budget in soils', Annual Review of Earth Planetary Sciences 29: 535-62.

Andela N(2017) A human-driven decline in global burned area. Science 356, 1356–1362. doi: 10.1126/ science.aal4108; pmid: 28663495

Anderegg WRL, TrugmanAT, Badgley G, AndersonCM, Bartuska A, CiaisP, et al (2020) Climate-driven risks to the climate mitigation potential of forests. Science, 368(6497), eaaz7005. https://doi.org/10.1126/science.aaz7005

Auffret MD, Karhu K, Khachane A et al (2016) The role of microbial community composition in control-ling soil respiration responses to temperature. PLoS ONE 11:e0165448. https ://doi.org/10.1371/journ al.pone.01654 48

BalchJK, BradleyBA, D'AntonioCM and Gómez-DansJ (2013) Introduced annual grass increases regional fire activity across the arid western USA (1980–2009). Glob. Chang. Biol., 19, 173–183, doi:10.1111/gcb.12046.

Balesdent, J, Basile-DoelschI, ChadoeufJl, Cornu S, Fekiacova Z, FontaineSb, Guenet B, Hatté C (2017)Renouvellement du carboneprofond des sols cultivés: une estimation par compilation de donnéesisotopiques. Biotechnol. Agron. Soc. Environ. 1–12.

Barre P, Fernandez-Ugalde O, Virto I, Velde B, Chenu C (2014) Impact ofphyllosilicate mineralogy on organic carbon stabilization in soils: incomplete knowledge and exciting prospects. Geoderma 235, 382–395.

Bagri DS, Upadhyaya DC, Kumar A, Upadhyaya CP (2018) Overexpression of PDX-II gene in potato (Sola- num tuberosum L.) leads to the enhanced accumulation of vitamin B6 in tuber tissues and tolerance to abiotic stresses. Plant Sci 272:267–275. https ://doi.org/10.1016/j.plant sci.2018.04.024

Batjes NH (1996)Total carbon and nitrogen in the soils of the world. Eur J Soil Sci47(2), 151–163. doi:10.1111/j.1365-2389.1996.tb01386.x

Baveye PC (2017) Quantification of ecosystem services: Beyond all the "guesstimates", how do we get real data? EcosystServ 24, 47–49, doi:10.1016/J.ECOSER.2017.02.006

BeerC, ReichsteinM, Tomelleri E, Ciais P, Jung M, et al (2010) Terrestrial gross carbon dioxide uptake: global distribution and covariation with climate. Sci329(5993):834–38

Bintanja R (2018) The impact of Arctic warming on increased rainfall. Sci Rep. https://doi.org/10.1038/ s4159 8-018-34450-3

Bojko O, Kabala C (2017) Organic carbon pools in mountain soils-sources of variability and predicted changes in relation to climate and land use changes. Catena. https://doi.org/10.1016/j.caten a.2016.09.022.

Bronick CJ, Lal R (2005) Manuring and rotation effects on soil organic carbon concentration for different aggregate size fractions on two soils in northeastern Ohio, USA. Soil Tillage Res. 81 (2), 239–252.

Carvalhais N. et al.(2014)Global covariation of carbon turnover times with climate in terrestrial ecosystems. Nature 514, 213–217

ChamberJQ, FisherSI, ZengeliseH, Chapman EL, David BBand George CH(2007)Hurricane Katrina's Carbon Footprint on U.S. Gulf Coast Forests. Science 318.5853. 1107. DOI: 10.1126/science.1148913

ChazdonRL,Broadbent EN,RozendaalDMA,BongersF, Zambrano AMA et al. (2016) Carbon sequestration potential of second-growth forest regeneration in the Latin American tropics. SciAdv 2(5):e1501639

Chen D, Cheng J, Chu P et al (2015) Regional-scale patterns of soil microbes and nematodes across grasslands on the Mongolian plateau: relationships with climate, soil, and plants. Ecography (Cop) 38:622–631. https://doi.org/10.1111/ecog.01226

ChoatB, Brodribb TJ, BrodersenCR, DuursmaRA, LópezR,&MedlynBE (2018) Triggers of tree mortality under drought. Nature 558,31–539

ChuviecoE, YueC, HeilA, MouillotF, Alonso-Canas I, PadillaM, Pereira JM, Oom D and TanseyK (2016) A new global burned area product for climate assessment of fire impacts. Glob. Ecol. Biogeogr. 25, 619–629.doi: 10.1111/geb.12440

ClarkeH, and EvansJP (2018) Exploring the future change space for fire weather in Southeast Australia. Theor. Appl. Climatol.136, 513–527, doi:10.1007/s00704-018-2507-4

Classen AT, Sundqvist MK, Henning JA et al (2015) Direct and indirect effects of climate change on soil microbial and soil microbial–plant interactions: what lies ahead? Ecosphere. https ://doi. org/10.1890/ES15-00217

Coffield SR, HemesK S, Koven CD, GouldenML& RandersonJT (2021)Climate-driven limits to future carbon storage in California's wildland ecosystems. AGU Advances, 2, e2021AV000384. https://doi. org/10.1029/2021AV000384

ColeJJ, PrairieYT, Caraco NF, McDowellWH, Tranvik LJ, Striegl RG, DuarteCM, Kortelainen P, DowningJA, MiddelburgJJ, MelackJ (2007) Plumbing the Global Carbon Cycle: Integrating Inland Waters into the Terrestrial Carbon Budget. Ecosystems 10, 172-185.

ColeRJ, SelmantsP, Khan S & ChazdonR(2020) Litter dynamics recover faster than arthropod biodiversity during tropical forest succession. Biotropica 52, 22–33

ConantRT, Ryan MG, Agren GI, BirgeHE, Davidson EA, EliassonPE, Evans SE, Frey SD, Giardina CP, Hopkins FM, HyvonenR, Kirschbaum MUF, Lavallee JM, Leifeld J, Parton WJ, SteinwegJM, WallensteinMD,WetterstedtJAM, Bradford MA (2011) Temperature and soil organic matter decomposition rates - synthesis of current knowledge and a way forward. Glob. Change Biol. 17, 3392-3404.)

Conant RT, CerriCEP, OsborneB, PaustianK (2017) Grassland management impacts on soil carbon stocks: a new synthesis. Ecol. Appl. 27, 662–668. https://doi.org/ 10.1002/eap.1473.

Crews TE, and RumseyBE (2017) What agriculture can learn from native ecosystems in building soil organic matter: A review. Sustain., 9, 1–18, doi:10.3390/su9040578.

DaiA (2011) Drought under global warming: A review. WIREs Clim. Change 2, 45–65. doi: 10.1002/wcc.81.

DavidsonEA, Janssens I (2006) Temperature sensitivity ofsoil carbon decomposition and feedbacks to climate change. Nature 440, 165–173.

DeAngelis KM, Pold G, Topçuoğlu BD et al (2015) Long-term Forest soil warming alters microbial communities in temperate forest soils. Front Microbiol.https://doi.org/10.3389/fmicb .2015.00104.

DonA, SchumacherJ & FreibauerA (2011) Impact of tropical land-use change on soil organic carbon stocks - a meta-analysis. Glob. Change Biol. 17, 1658–1670.

Dubey A, Ahmad MallaM, Khan F, ChowdharyK, Yadav S, KumarA, Sharma S, KhareP K, Khan K L (2019) Soil microbiome: a key player for conservation of soil health under changing climate Biodiversity and Conservation https://doi.org/10.1007/s10531-019-01760-5.

DungaitJA, Hopkins DW, Gregory AS and Whitmore AP(2012) Soil organic matter turnover is governed by accessibility not recalcitrance, Glob. Change Biol., 18, 1781–1796.

Dymond CC et al (2010) Future spruce budworm outbreak maycreate a carbon source in eastern Canadian forests. Ecosystems13, 917–931. doi: 10.1007/s10021-010-9364-z.

Eglin T, CiaisP, Piao SL, Barre P, BellassenV, Cadule P, Chenu C, GasserT, KovenC, Reichstein, M. & Smith P (2010) Historical and future perspectives of global soil carbon response to climate and land-use changes, Tellus B: Chemical and Physical Meteorology, 62:5, 700-718, DOI: 10.1111/j.1600-0889.2010.00499.

FAO (2015) Global Soil Status, Processes and Trends. Food and Agriculture Organization of the United Nations, Rome, Italy, 605.

Field JPet al (2010) The ecology of dust. Front. Ecol. Environ., 8, 423–430, doi:10.1890/090050

Fontaine S, BarreP, BdiouiN, MaryB, and RumpelC (2007) Stability of organic carbon in deep soil layers. Nature, 450, 277–281. doi:10.1038/ nature06275

EnforsEI and Gordon LJ (2008) Dealing with drought: The challenge of using water system technologies to break Dryland poverty traps. Glob. Environ. Chang., 18, 607–616, doi:10.1016/J.GLOENVCHA.2008.07.006.

FrankDet al (2015) Effects of climate extremes on the terrestrial carbon cycle: Concepts, processes and potential future impacts. Glob. Chang. Biol., 21, 2861–2880, doi:10.1111/gcb.12916.

Fuss, S. et al. Negative emissions - Part 2: Costs, potentials and side effects. *Environ. Res. Lett*. **13**, 063002 (2018).

García-RuizJM, BegueríaC, Nadal-RomeroE, González-HidalgoJC, Lana-RenaultNand Sanjuán V (2015) A meta-analysis of soil erosion rates across the world. Geomorphology, 239, 160–173, doi:10.1016/j.geomorph.2015.03.008.

Gao D, Hagedorn F, Zhang L et al (2018) Small and transient response of winter soil respiration and microbial communities to altered snow depth in a mid-temperate forest. Appl Soil Ecol 130:40– 49. https ://doi.org/10.1016/j.apsoi l.2018.05.010.

GinouxP, ProsperoJM, GillTE, HsuNC and ZhaoM (2012) Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. Rev. Geophys., 50, doi:10.1029/2012RG000388.

GMD(2017)Global Monitoring Division, Earth System Research Laboratory. https://www. esrl.noaa.gov/gmd/.

González-Jaramillo V et al (2016) Assessment of deforestation during the last decades in Ecuador using NOAA-AVHRR satellite data.Erdkunde, 70, 217–235, doi:10.3112/erdkunde.2016.03.02.

Gonzalez-MartinC, Teigell-Perez,N,ValladaresB and GriffinDW (2014) The global dispersion of pathogenic microorganisms by dust storms andits relevance to agriculture. Adv. Agron., 127, 1–41, doi:10.1016/B978-0-12-800131-8.00001-7.

GuanXK, Turner NC, Song L, GuYJ, WangTC and LiFM (2016) Soil carbon sequestration by three perennial legume pastures is greater in deeper soil layers than in the surface soil, Biogeosciences, 13, 527-534, 10.5194/bg-13-527-2016.

GuoLB and Gifford RM (2002) Soil carbon stocks and land use change: a meta-analysis. Global Change Biology 8, 345-360.

HansenMC, PotapovPV, MooreR, Hancher, M, Turubanova SA, Tyukavina A et al (2013) High-Resolution Global Maps of 21st-Century Forest Cover Change. Science, 342, 850–853.

Harden J, TrumboreSE, Stocks BJ, Hirsch AI, Gower ST, NeillKPO, Kasischke E (2000) The role of fire in the boreal carbon budget. Glob. Chang. Biol. 6, 174–184.

Henry B, MurphyB and CowieA (2018) Sustainable Land Management for Environmental Benefits and Food Security. A synthesis report for the GEF. Washington DC, USA, 127 pp.

Hicks Pries CE, CastanhaC, PorrasRCand TornMS (2017) The whole-soil carbon fluxin response to warming. Science, 355, 1420 LP-1423.

Hawkes CV, WaringBG, RoccaJD& KivlinS N(2017)Historical climate controls soil respiration responses to current soil moisture. PNAS 114, 6322–6327.

Hoffmann T, MuddSM, van Oost K, VerstraetenG, Erkens G, Lang A, MiddelkoopH, Boyle J, Kaplan JO, Willenbring Jand AaltoR (2013)Short Communication: Humans and the missing C-sink: erosion and burial of soil carbon through time. Earth Surf. Dynam. Discuss., 1, 1–20.

Hurteau MD, HungateBA & Koch GW(2009) Accounting for risk in valuing forest carbon offsets. Carbon Balance Management. 4, 1.doi: 10.1186/1750-0680-4-1; pmid: 19149889.

IPCC (2006) IPCC Guidelines for National Greenhouse Gas Inventories. IGES, Japan.

IPCC (2019)Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial. (In press)

JassalRS, Black TA, NovakMD, Gaumont-Guay D, Nesic Z (2008) Effect of soil water stress on soil respiration and its temperature sensitivity in an 18-year-old temperate Douglas-fir stand. Glob. Chang. Biol. 14, 1305–1318.

Jia B, Zhou G, Yuan W. Modeling and coupling of soil respiration and soil water content in fenced Leymuschinensis steppe, Inner Mongolia. Ecol Model. 2007;201(2):157–62.

KallenbachC M, Frey SD and GrandyAS(2016)Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. Nat. Commun. 7:13630.

Karhu K, Auffret MD, Dungait JA et al (2014) Temperature sensitivity of soil respiration rates enhanced by microbial community response. Nature 513:81–84. https://doi.org/10.1038/nature13604.

KaselS and BennettLT (2007) Land-use history, forest conversion, and soil organic carbon in pine plantations and native forests of south eastern Australia. Geoderma 137, 401–413.

Kautz M, Meddens A J H, HalRJ and ArnethA (2017) Biotic disturbances in Northern Hemisphere forests – a synthesis of recent data, uncertainties and implications for forest monitoring and modelling. Global Ecology and Biogeography, 26, 533–552.

Keiluweit M, Nico PS, Kleber M, Fendorf S (2016) Are oxygen limitations under recognized regulators of organic carbon turnover in upland soils? Biogeochemistry 127(2–3):157–71.

Kleber M, NicoPS, PlanteAF,FilleyT, KramerM, SwanstonC et al (2011) Old and stable soil organic matter is not necessarily chemically recalcitrant: implications for modelling concepts and temperature sensitivity. Glob. Change Biol. 17:1097–1107.

Klingmüller KA,Pozzer S, Metzger GL,Stenchikov and LelieveldJ(2016) Aerosol Optical Depth trend over the Middle East. Atmos. Chem. Phys.16, 5063–5073, doi:10.5194/acp-16-5063-2016.

Kogel-KnabnerI (2002) The macromolecular organic composition of plant and microbial residues as inputs to soil organic matter. Soil Biol. Biochem. 34, 139–162.

Kolb TE, Fettig CJ, Ayres MP, BentzBJ, Hicke JA, MathiasenR, StewartJE, Aaron SW (2016) Observed and anticipated impacts of drought on forest insects and diseases in the United States. For. Ecol. Manage. 380, 321–334 (2016).doi: 10.1016/ j. foreco.2016.04.051

Knorr W, Prentice IC, House JI, Holland EA(2005)Long- term sensitivity of soil carbon turnover to warming. Nature 433: 298–301.

KurniawanS et al(2018) Conversion of tropical forests to smallholder rubber and oil palm plantations impacts nutrient leaching losses and nutrient retention efficiency in highly weathered soils. Biogeosciences15, 5131–5154.

Kuzyakov Y and Blagodatskaya E (2015) Microbial hotspots and hot moments in soil: concept and review. Soil Biol. Biochem. 83:184–99

Lajtha K, Bowden RD and Nadelhoffer K. (2014a) Litter and root manipulations provide insights into soil organic matter dynamics and stability. Soil Sci. Soc. Am. J. 78:S261.

Lajtha K, Townsend KL, Kramer MG, Swanston C, Bowden RD, Nadelhoffer K (2014b) Changes to par- ticulate versus mineral-associated soil carbon after 50 years of litter manipulation in forest and prairie experimental ecosystems. Biogeochemistry 119(1–3):341–60.

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627.

LalR (2008) Sequestration ofatmospheric CO_2 into global carbon pool. Energy Environ. Sci. 1, 86–100.

LalR (2009) Sequestering carbon in soils of arid ecosystems. L. Degrad. Dev., 20, 441–454, doi:10.1002/ldr.934.

Lal R (2014) Soil carbon management and climate change. In: Hartemink AE, McSweeney, K(Eds.), Soil Carbon. Springer, Cham, Switzerland, pp. 339–361.

LeskCP, Rowhaniand NRamankutty (2016) Influence of extreme weather disasters on global crop production. Nature, 529, 84. doi:10.1038/ nature16467.

LiuY, Wang P, Ding Y, Lu H, Li L, ChengK, Zheng J, FilleyT, ZhangX, Zheng Jand Pan G(2016)Microbial activity promoted with organic carbon accumulation in macroaggregates of paddy soils under long-term rice cultivation. Biogeosciences, 13, 6565–6586. doi:10.5194/bg-13-6565-2016.

Liu, Z., & Wimberly, M. C. (2016). Direct and indirect effects of climate change on projected future fire regimes in the western United States. *Science of the*

TotalEnvironment, **542**, 65-75. https://doi.org/10.1016/J.SCITOTENV.2015.10.093

Liu Z, Ballantyne AP, Poulter B, Anderegg WRL, Li W, Bastos A, et al (2018) Precipitation thresholds regulate net carbon exchange at the continental scale. Nat Commun.;9(1):3596.

MajeedA and MuhammadZ (2019) Salinity: A major agricultural problem – Causes, impacts on crop productivity and management strategies. In: Plant Abiotic Stress Tolerance [Hasanuzzaman, M., K.R. Hakeem, K. Nahar and H. Alharby (eds.)]. Springer International Publishing, Cham, Switzerland, pp. 83–99.

Majumder B, MandalB, BandyopadhyayPK (2008) Soil organic carbon pools and productivity in relation to nutrient management in a 20-year-old rice berseem agroecosystem. Biol. Fertil. Soils 44, 451–461.

ManolaI B, Van Den Hurk H, De Moel and AertsJCJH (2018) Future extreme precipitation intensities based on a historic event. Hydrol. Earth Syst. Sci., 22, 3777–3788, doi:10.5194/hess-22-3777-2018.

MarlandG, BodenTA, Ndres RJ (2000) Global, regional, and national CO_2 emissions. In: Trends: A Compendium of Data on Global Change. U.S. Department of Energy, Oak Ridge, Tenn., USA.

MathieuJA, Hatté C, BalesdentJ, ParentÉ (2015) Deep soil carbon dynamics are driven more by soil type than by climate: a worldwide meta-analysis of radiocarbon profiles. Glob. Change Biol. 21, 4278–4292.

MelilloJM, SteudlerPA, Aber JD, NewkirkK, LuxH, BowlesFP, Catricala C, MagillA, AhrensT, Morrisseau S (2002) Soil warming and carbon -cycle feedbacks to the climate system. Science 298, 2173-2176.

Middleton NJ (2017) Desert dust hazards: A global review. Aeolian Res., 24, 53–63, doi:10.1016/J.AEOLIA.2016.12.001.

Mohan TS and RajeevanM (2017) Past and future trends of hydroclimatic intensity over the Indian monsoon region. J. Geophys. Res. Atmos., 122, 896–909, doi:10.1002/2016JD025301.

Montanarella LR, Scholes and BrainicA (2018) The IPBES Assessment Report on Land Degradation and Restoration. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany. 744. doi: 10.5281/zenodo.3237392.

MulderVL, Lacoste M, Martin MP, Richer□de□Forges A &Arrouays D(2015)Understanding large□extent controls of soil organic carbon storage in relation to soil depth andsoil□landscape systems. Global Biogeochemical Cycles, 29, 1210–1229. https://doi.org/10.1002/2015gb005178.

Nath AJ, Bhattacharyya T, Ray SK, DekaJ, Das AK & DeviH(2016) Assessment of rice farming management practices based on soil organic carbon pool analysis. Tropical Ecology 57(3): 607-611.

Nearing MA, UnkrichCL, GoodrichDC, NicholsMHand KeeferTO (2015) Temporal and elevation trends in rainfall erosivity on a 149 km^2 watershed in a semi-arid region of the American Southwest. Int. Soil Water Conserv. Res. 3, 77–85, doi:10.1016/j.iswcr.2015.06.008.

NishinaK, Ito A, BeerlingDJ, Cadule P, Ciais P, Clark DB, Falloon P, FriendAD, KahanaR, Kato E, Keribin R, LuchtW, Lomas M, RademacherTT,Pavlick R, SchaphoffS, Vuichard N, Warszawaski L, YokohataT (2014) Quantifying uncertainties in soil carbon responses to changes in global mean temperature and precipitation. Earth Syst. Dyn. 5, 197–209.

Oades JM, WatersAG, VassalloAM, WilsonMAand JonesJP (1988) Influence of management on the com- position of organic matter in red-brown earth as shown by 13C nuclear magnetic resonance. Aust. J. Soil Res. 26: 289-299.

OkunoMand NakamuraT (2003) Radiocarbon dating of tephra layers: recent progress in Japan. Quat. Int., 105, 49–56, doi:10.1016/S1040-6182(02)00150-7.

PanGX, Smith P, PanWN (2009) The role of soil organic matter in maintaining the productivity and yield stability of cereals in China. Agric. Ecosyst. Environ. 129, 344–348.

PfahlS, O'GormanPA and FischerEM (2017) Understanding the regional pattern of projected future changes in extreme precipitation. Nat. Clim. Chang., 7, 423–427, doi:10.1038/nclimate3287.

Philben M et al (2015) Temperature, oxygen, and vegetation controls on decomposition in a James Bay peatland. Global Biogeochem. Cycles, 29, 729–743, doi:10.1002/2014GB004989.

PoeplauC, DonA, VesterdalL, Leifeld J, Van WesemaelBAS, Schumacher J, Gensior A, (2011) Temporal dynamics of soil organic carbon after land-use change in the temperate zone–carbon response functions as a model approach. Glob. Chang. Biol. 17 (7), 2415–2427.

PoorterLet al (2016) Biomass resilience of neotropical secondary forests. Nature, 530, 211–214, doi:10.1038/nature16512.

Post WM and Kwon KC (2000) Soil carbon sequestration and land-use change: processes and potential. Glob. Chang. Biol. 6, 317–327.

Posthumus Het al (2009) Impacts of the summer 2007 floods on agriculture in England. J. Flood Risk Manag., 2, 182–189, doi:10.1111/j.1753-318X.2009.01031.

PreinAFet al (2017) The future intensification of hourly precipitation extremes. Nat. Clim. Chang., 7, 48–52, doi:10.1038/nclimate3168.

PughTAMet al(2019)Role of forest regrowth in global carbon sink dynamics. Proc. Natl. Acad. Sci. U.S.A. 116, 4382–4387.doi: 10.1073/pnas.1810512116; pmid: 30782807.

Quan Q, Tian D, Luo Y, Zhang F (2019) Water scaling of ecosystem carbon cycle feedback to climate warming. Sci Adv.5:1131.

Reichstein M et al (2013) Climate extremes and the carbon cycle. Nature 500, 287–295. doi: 10.1038/nature12350; pmid: 23955228.

RenW, TianHQ, TaoB, HuangY and PanSF (2012) China's crop productivity and soil carbon storage as influenced by multifactor global change. Glob. Chang. Biol. 18, 2945–2957.

ReynoldsJF (2011) Scientific concepts for an integrated analysis of desertification. L. Degrad. Dev., 22, 166–183, doi:10.1002/ldr.1104.

RumpelC and Kögel-KnaberI (2011) Deep soil organic matter-A key but poorly understood component of terrestrial C cycle. Plant Soil 338:143– 158. doi:10.1007/s11104-010-0391-5.

RumpelCet al (2018) Put more carbon in soils to meet Paris climate pledges. Nature, 564, 32–34, doi:10.1038/d41586-018-07587-4.

Ryan MG and LawBE (2005) Interpreting, measuring, and modelling soil respiration. Biogeochemistry 73, 3–27.

Samuel HB, AndrewH, SimonJ, MarielaSB, AndrewSD, Trung HN (2020)A satellite data driven approach to monitoring and reporting fire disturbance and recovery across boreal and temperate forests. Int J Appl Earth ObsGeoinformation 87,102034.

Sandeep S andManjaiah KM (2014) Thermal stability oforganic carbon in soil aggregates of maize-wheat system in semiarid. India. J. Soil Sci. Plant Nutr. 14 (3), 111–124.

Sánchez-RodríguezAR, HillPW, ChadwickDR and JonesDL (2017) Crop residues exacerbate the negative effects of extreme flooding on soil quality. Biol. Fertil. Soils, 53, 751–765, doi:10.1007/s00374-017-1214-0.

Sánchez-Rodríguez AR, NieC, HillPW, ChadwickDRand JonesDL (2019) Extreme flood events at higher temperatures exacerbate the loss of soil functionality and trace gas emissions in grassland. Soil Biol.Biochem.,130,227–236, doi:10.1016/j.soilbio.2018.12.021.

Sasaki N, Asner GP, PanY, KnorrW, DurstPB, Ma H, Abe I, Lowe AJ, Koh LPand PutzFE(2016) Sustainable Management of Tropical Forests Can Reduce Carbon Emissions and Stabilize Timber Production. Front. Environ. Sci. 4:50. doi:10.3389/fenvs.2016.00050.

SchimelJP and Schaeffer SM(2012) Microbial control over carbon cycling in soil. Front Microbiol. https ://doi. org/10.3389/fmicb .2012.00348.

SchlesingerWHet al (2016) Forest biogeochemistry in response to drought. Glob. Chang. Biol., 22, 2318–2328, doi:10.1111/gcb.13105.

SchimelDS, HouseJI, Hibbard KA, BousquetP, CiaisP, PeylinP, BraswellBH, AppsMJ, BakerD, BondeauA, Canadell J (2001) Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. Nature 414 (6860), 169.

SchindlbacherA, Wunderlich S, Borken W, Kitzler B, ZechmeisterBoltenstern S, Jandl R, Soil SchlesingerWHet al (2016) Forest biogeochemistry in response to drought. Glob. Chang. Biol., 22, 2318–2328, doi:10.1111/gcb.13105.

Schmidt MWI, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Kleber M, Kögel- Knabner I, Lehmann J, Manning DAC, Nannipieri P, Rasse DP, Weiner S, Trumbore SE (2011) Persistence of soil organic matter as an ecosystem property. Nature 478:49–56.

SeddonAWR, Macias-FauriaM, LongPR, BenzDand WillisKJ (2016) Sensitivity of global terrestrial ecosystems to climate variability. Nature, 531, 229–232, doi:10.1038/nature16986.

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D. , Petr, M., Honkaniemi, J., Lexer, M. J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T. A., Reyer, C. P. O.

Forest disturbances under climate change. *Nat. Clim. Chang.* **7**, 395–402 (2017). 10.1038/nclimate3303

Seneviratne SI, Nicholls N, Easterling D, Goodess CM, Kanae S et al (2012) Changes in climate extremes and their impacts on the natural physical environment. In Managing the Risks ofExtreme Events and Disasters to Advance Climate Change Adaptation: Special Report ofthe Intergovernmental Panel on Climate Change, ed. CB Field,109–230. Cambridge, UK: Cambridge Univ. Press.

SenfC, Wulder MA, Campbell EM& HostertP(2016) Using Landsat to Assess the Relationship Between Spatiotemporal Patterns of Western Spruce Budworm Outbreaks and Regional-Scale Weather Variability, Can. J. Remote Sens. 42:6, 706-718, DOI: 10.1080/07038992.2016.1220828.

Sergaki C, Lagunas B, Lidbury I et al (2018) Challenges and approaches in microbiome research: from fundamental to applied. Front Plant Sci. https ://doi.org/10.3389/fpls.2018.01205.

SinghM, SarkarB, BiswasB, BolanNS, ChurchmanGJ (2017) Relationship between soil clay mineralogy and carbon protection capacity as influenced by temperature and moisture. Soil Biol. Biochem. 109, 95–106.

SinghM, SarkarB, SarkarS, ChurchmanJ, BolanN, Mandal S, MenonM, Purakayastha TJ, BeerlingDJ (2018) Stabilization of soil organic carbon as influenced by clay mineralogy. Adv. Agron. 148, 33–84. https://doi.org/10.1016/bs.agron.2017.11.001.

Sissoko A and KpomblekouAK (2010) Carbon decomposition in broiler litter-amended soils. Soil Biol. Biochem. 42, 543–550.

SixJ, BossuytH, DegryzeSand DenefK (2004) A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil Tillage Res. 79(1): 7–31.

SkjemstadJO, DalalRC, JanikLJ and McGowanJA (2001) Changes in chemical nature ofsoil organic carbon in Vertisols under wheat in southeastern Queensland. Aust. J. Soil Res. 39, 343–359.

Skjemstad JO, ReicoskyDC, WiltsAR and McGowan JA (2002) Charcoal carbon in U.S. agricultural soils. Soil Sci. Soc. Am. J. 66, 1255–1949.

Smith, P. Soil carbon sequestration and biochar as negative emission technologies. Glob. Chang. Biol. 22, 1315–1324 (2016).

SmithP, Adams J, BeerlingDJ, Beringer T, Calvin KV, Fuss S,Keesstra S(2019)Impacts of land-based greenhouse gas removal options on ecosystem services and the United Nations Sustainable Development Goals. Annual Review of Environment and Resources, 44(1), 255–286. https://doi.org/10.1146/annurev-envir on-101718-033129.

SonwaDJ, WeiseSF, Nkongmeneck BA, TchatatM& JanssensMJJ (2017)Structure and composition of cocoa agroforests in thehumid forest zone of southern Cameroon. Agroforestry Systems,91,451–470.

SoussanaJFand LemaireG(2014) Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems. Agric. Ecosyst. Environ. 190, 9–17. doi: 10.1016/j.agee.2013.10.012.

SoussanaJF, Tallec T &BlanfortV(2010)Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. Animal 4, 334–350.

Soussana JF, Lutfalla S, Ehrhardt F, RosenstockT, LamannaC, Havlík P, RichardsM, WollenbergE, ChotteJL, Torquebiau E, CiaisP, SmithP&Lal R (2017) Matching policy and science: rationale for the ‘4 per 1000 - soils for food security and climate’ initiative. Soil Till. Res.

Spaccini R, Piccolo A, Conte P, HaberhauerG&Gerzabek MH (2002) Increased soil organic carbon sequestration through hydrophobic protection by humic substances. Soil Biol. Biochem. 34 (12), 1839–1851.

StahlC, FontaineS, KlumppK, Picon-Cochard C, GriseMM, DezecacheC, PonchantL, Freycon V, BlancL, BonalD, BurbanB., Soussana JFand BlanfortV (2017) Continuous soil carbon storage of old permanent pastures in Amazonia, Global Change Biology, 23, 3382-3392, doi:10.1111/gcb.13573.

Stephen MO, Cody A, Jeff B, Martial B, Breidt FJ, McConkey B, Regina K& Gabriel G. Vazquez-Amabile (2019) Adoption climate and Soil characteristics Determine Where no-till Management can Store carbon in Soils and Mitigate Greenhouse Gas emissions. Scientific Report 9:11665https://doi.org/10.1038/s41598-019-47861-7.

StevensonFJ (1994) Humus Chemistry: Genesis, Composition, Reactions. John Wiley & Sons.

StockmannU, Adams MA, Crawford JW, FieldDJet al (2013) The knowns, known unknowns and unknowns of sequestration of soil organic carbon. AgricEcosyst Environ 164:80–99.

TanZ, Lal R, Owens L andIzaurraldeRC (2007) Distribution oflight and heavy fractions of soil organic carbon as related to land use and tillage practice. Soil Tillage Res. 92, 53–59.

Terry CHS and Dominic R (2019)Forests, Land Use, and Challenges to Climate Stability and Food Security. Sustainable Food and Agriculture. 95-116.

TianH, Chen G, ZhangC, Melillo JM& Hall CA (2010) Pattern and variation ofC: N: P ratios in China's soils: a synthesis of observational data. Biogeochemistry 98, 139–151.

TokimatsuK, YasuokaR & NishioM (2017) Global zero emissions scenarios: The role of biomass energy with carbon capture and storage by forested land use. Appl. Energy 185, 1899–1906. doi: 10.1016/j.apenergy.2015.11.077.

Trumbore S, Brando P&Hartmann H (2015) Forest health and global change. Science 349(6250):814–18.

Tylor, P. G. Cleveland, C. C., Wieder, W. R. Sullivan, B. W. Doughty, C. E., Dobrowrki, S. Z., And Townsend, A. R. (2017). Temperature and rainfall interact to control carbon cycling in tropical forests. Ecology Letter, 20: 779-788

van Groenigen KJ, Osenberg CW, Terrer C, Carrillo Y, DijkstraF, Heath J et al (2016) 2014 Faster turnover of new soil carboninputs under increased atmospheric CO2. Glob ChangeBiol 23:4420–4429. https://doi.org/10.1111/gcb.13752.

Van Oost, K., Quine, T.A., Govers, G., De Gryze, S., Six, J., Harden, J.W., Ritchie, J.C., McCarty, G.W., Heckrath, G., Kosmas, C., Giraldez, J.V., da Silva, J.R.M., Merckx, R., (2007)The impact of agricultural soil erosion on the global carbon cycle. Science 318, 626-629.

Van Pelt R.S. *et al.* (2017) The reduction of partitioned wind and water erosion by conservation agriculture. Catena

Van Straaten Oet al(2015)Conversion of lowland tropical forests to tree cash crop plantations loses up to one-half of stored soil organic carbon. Proc. Natl Acad. Sci. USA 112, 9956–9960.

Veldkamp E, Schmidt M, Powers JS and Corre MD (2020) Deforestation and reforestation impacts on soils in the tropics.Nature Reviews, 1, 590-605.

VermaBC, DattaSP, RattanRK, SinghAK (2010) Monitoring changes in soil organic carbon pools, nitrogen, phosphorus, and sulfur under different agricultural management practices in the tropics. Environ. Monit. Assess. 171, 579–593.

ViglizzoEF, RicardMF,TaboadaMAand Vázquez-AmábileG(2019) Reassessing the role of grazing lands in carbon-balance estimations: Meta-analysis and review. Science of the Total Environment 661, 531–542.

Wan S, Norby RJ, Ledford J, Weltzin JF. Responses of soil respiration to elevated CO2, air warming, and changing soil water availability in a model old-field grassland. Glob Change Biol. 2007;13(11):2411–24.

Wang QJ, Lu CY, Li HW, He J, Sarker KK, Rasaily RGet al (2014) The effects of no-tillage with subsoiling on soil properties and maize yield: 12-year experiment on alkaline soils of Northeast China. Soil Till Res; 137:43-49.

WangX, Butterly CR, Baldock JA, TangC (2017) Long-term stabilization ofcrop residues and soil organic carbon affected by residue quality and initial soil pH. Sci. Total Environ. 587, 502–509.

WangX, Tang C, Baldock J, Butterly C, Gazey C (2016) Long-term effect of lime application on the chemical composition of soil organic carbon in acid soils varying in texture and liming history. Biol. Fertil. Soils 52, 295–306.

Wiesmeier M, MunroS, BartholdF, SteffensM, SchadP and Kögel-KnabnerI (2015) Carbon storage capacity of semi-arid grassland soils and sequestration potentials in northern China. Glob. Chang. Biol., 21, 3836–3845, doi:10.1111/gcb.12957.

William RLA, AnnaTT &Grayson Bet al(2020) Climate-driven risks to the climate mitigation potential of forests. Science 368, eaaz7005.DOI: 10.1126/science. Aaz 7005.

Wolters V (2000) Invertebrate control of Soil organic matter stability. BiolFertile Soils 31. 1-19

Zhang L, Xie Z, Zhao R, Zhang Y (2018) Plant, microbial community and soil property responses to an experimental precipitation gradient in a desert grassland. Appl Soil Ecol 127:87–95https ://doi. org/10.1016/j.apsoi l.2018.02.005.

Zhou L et al (2014) Widespread decline of Congo rainforest greenness in the past decade. Nature 508, 86-90 doi:10.1038/nature13265.

Zhang J (2010) Temperature sensitivity of soil organic matter decomposition and the influence of soil carbon and attributes. [Graduate Theses and Dissertations], Iowa State University, Paper 11234.

Zhou G, Zhou X, He Y, Shoa J, Hu Z, LiuRet al(2017) Grazing intensity significantly affects belowground carbon and nitrogen cycling in grassland ecosystems: a meta-analysis. Glob Change Biol 23, 1167–1179. doi: 10.1111/gcb.13431.

Zomer RJ, BossioDA, SommerR and VerchotLV(2017)Global sequestration potential of increased organic carbon in cropland soils. Sci. Rep. 7:15554.doi: 10.1038/s41598-017-15794-8.

ZscheischlerJ et al (2014) A few extreme events dominate global interannual variability in gross primary production. Environ. Res. Lett. **9**,035001.doi:10.1088/17489326/9/3/035001.

Garcia-Franco N, Wiesmeier M, Buness V, Berauer BJ, Schuchardt MA, Jentsch A, Schlingmann M, Andrade-Linares D, Wolf B, Kiese R, Dannenmann M. Rapid loss of organic carbon and soil structure in mountainous grassland topsoils induced by simulated climate change. Geoderma. 2024 Feb 1;442:116807.

Dash PK, Bhattacharyya P, Roy KS, Neogi S, Nayak AK. Environmental constraints' sensitivity of soil organic carbon decomposition to temperature, management practices and climate change. Ecological indicators. 2019 Dec 1;107:105644.