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Impacts of climate change-induced extreme weather events on carbon dynamics in soil

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Abstract

Soil organic carbon (SOC) content is an important indicator of soil health, agricultural productivity, and ecosystem service. Soil carbon sustains a number of ecosystem processes including water holding capacity and availability to plants, nutrient cycling, soil structure and microbial diversity. Carbon dynamics in soil is highly complex, and depending on the land management practices, soil carbon can serve as a significant source or sink for greenhouse gas (GHG) emissions, thereby contributing to climate change. Soil carbon storage can be promoted as part of a greater suite of nature-based climate change mitigation strategies that can simultaneously render natural capital ecosystem benefits and environmental outcomes, and diversify livelihoods. In regard to soil carbon sequestration and its function in mitigating climate change, this study offers a thorough bibliometric analysis of critical discussions on the effects of extreme weather events such as floods, wildfires and drought. Floods, droughts, and wildfires are among the extreme weather events that are becoming more frequent and intense due to climate change. These extreme weather events due to climate change can influence soil carbon dynamics by affecting soil carbon input and the microbial breakdown of soil organic matter. Drought promotes more root biomass than shoot biomass as a drought adaptation strategy by plants, thereby impacting the root-derived carbon input to soil. Flooding can mobilize dissolved organic carbon in soil, thereby facilitating the leaching losses of soil carbon. Wildfires can lead to the loss of above ground biomass, thereby impacting carbon input to soil. All these major extreme weather events can also impact soil carbon by influencing soil microbial activity and function, and soil erosion.

Highlights

- Climate change-induced extreme weather events impact C dynamics in soil.
- Drought reduces plant biomass production, soil C inputs and alters microbial activity.
- Soil heterotrophic respiration declines under drought stress conditions.
- Prolonged waterlogging promotes Fe oxyhydroxides reduction and DOC release.
- Wildfires under dry conditions reduce C sequestration potential in peat and wetland.

Keywords Carbon dynamics, Climate change, Extreme weather, Drought, Flood, Wildfire

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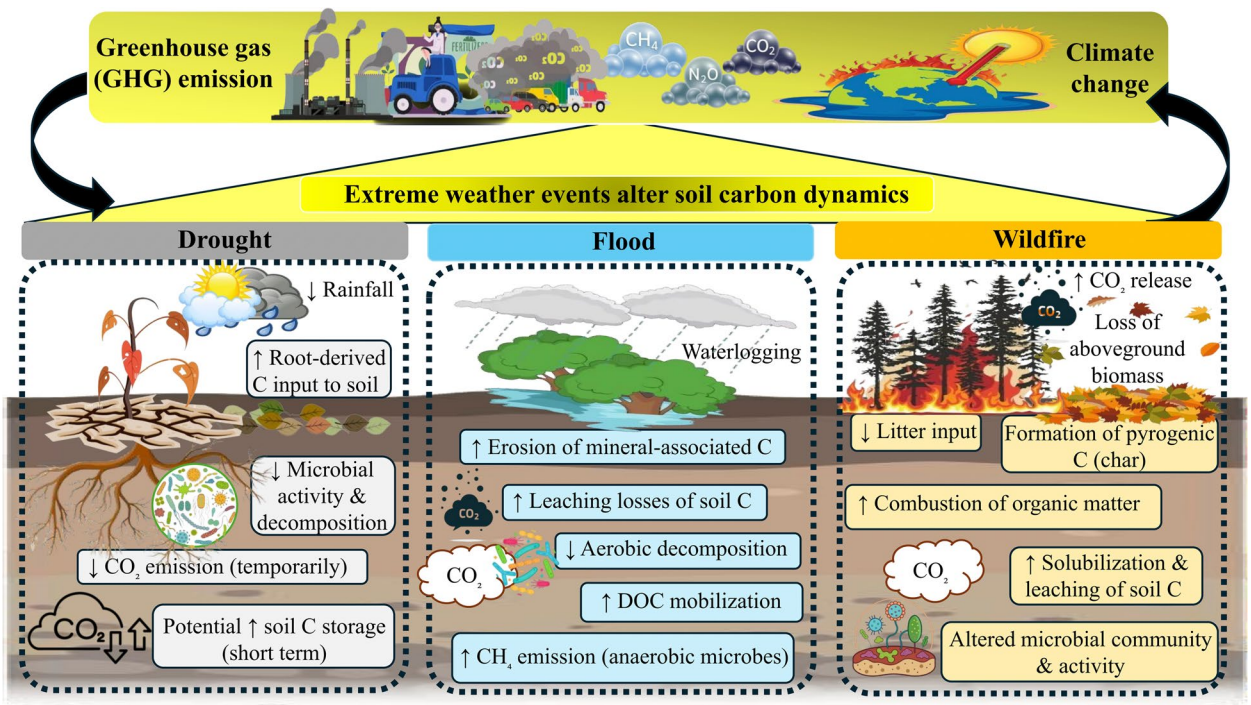
Graphical Abstract



1 Introduction

There are increasing concerns about the rising concentration of greenhouse gases (GHGs) that include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Ritchie et al. 2020; WMO 2023; US EPA 2025). These GHGs are derived primarily from industrial activities including coal-fired power stations, transport and agricultural activities (IPCC 2022; US EPA 2025). The rising concentration of GHGs in the atmosphere is attributed to climate change which can lead to increasing intensity and frequency of drought, flood and wildfire (extreme weather events) (Seneviratne et al. 2021; Williams et al. 2022).

According to the Intergovernmental Panel on Climate Change (IPCC 2021a, b), "an extreme weather event is one that is uncommon for a specific location and time of year". These events stand out from the typical patterns we expect based on historical climate data for that region. Statistically, events typically qualify as extreme when they fall at or beyond the 10th percentile (for cold extremes) or the 90th percentile (for heat extremes) of the historical distribution. This means that extreme events are those that occur less frequently than 10% of the time at either end of the temperature or precipitation spectrum. Some researchers use even stricter thresholds. Events exceeding the 95th or 99th percentile-occurring only 5% or 1% of the time represent increasingly severe extremes" (IPCC 2021a, b; Radović et al. 2019).

Initiatives to sequester carbon (C) in soils as one of the strategies to mitigate climate change are gaining momentum globally (Lal 2004; Paustian et al. 2019; White 2022). Increasing soil C storage not only contributes to reducing greenhouse gas emissions but also enhances soil health, thereby contributing to increased capture of CO_2 through improved biomass production. Therefore, it is important to emphasize the greater role of C on soil health and subsequent biomass production compared to the role of soil C-sequestration in mitigating climate change (Don et al. 2024; Moinet et al. 2023; Paltineanu et al. 2024).

Extreme weather events are important in altering soil C dynamics in various ways. For example, drought promotes more root biomass than shoot biomass as a drought adaptation strategy by plants, thereby impacting the root-derived C input to soil (Zhou et al. 2018; Wang et al. 2021; Guasconi et al. 2023). Flooding can mobilize dissolved organic C (DOC) in soil, thereby facilitating soil C losses through leaching (Sánchez-Rodríguez et al. 2019; Nakhavali et al. 2020). Wildfires can lead to the loss of above ground biomass, thereby impacting C input to

soil (Cheng et al. 2023; Li et al. 2023a). All these major extreme weather events also impact soil C by influencing soil microbial activity and function, and soil erosion (Wang et al. 2019; Nottingham et al. 2022; Furtak and Wolińska 2023).

Most reports have focussed on the effect of individual climate change-induced extreme weather events on soil C dynamics in relation to C input and C release through microbial decomposition (drought -Deng et al. 2021; flood - Bai et al. 2020; wildfire -Cheng et al. 2023). The specific knowledge gaps relating to the effects of change-induced extreme weather events on soil C dynamics include: (i) lack of knowledge on the transformation and mobilization of soil C as impacted by extreme weather events; and (ii) lack of effort in linking C dynamics to C sequestration and long-term preservation in relation to soil health as impacted by climate change-induced extreme weather events. The specific objectives of this critical review are: (i) investigate the mobilization and redistribution of C in soil in response to climate change-driven extreme weather events, such as flooding, droughts, and wildfires; (ii) examine the soil microbial response to extreme weather events; (iii) explore the mobility of soil C pools as impacted by extreme weather events, considering their potential transport from terrestrial (i.e., soil) to aquatic environment (i.e., groundwater); and (iv) predict C sequestration as impacted by extreme weather events.

2 Methodology

On January 14, 2026, screening of literature was performed with the following search keywords in Google Scholar, PubMed and Web of Science database: Topic Search (TS) = ("Climate change" OR "Global warming" OR "Climate shift" OR "Radiative forcing") AND TS = ("Extreme weather events" OR "drought" OR "flood" OR "wildfire" OR "bushfire") AND TS = ("carbon" OR "soil carbon" OR "carbon sequestration" OR "soil organic matter") AND TS = ("microbial activity" OR "decomposition" OR "mineralization") AND TS = ("Soil erosion" OR "dissolved organic matter" OR "leaching").

The initial search of online literature databases yielded 14,218 entries. The dataset included a variety of resources, including non-English articles, research that did not fully match the desired keywords, and non-peer-reviewed sources (book chapters, conference proceedings, and editorials). Mendeley (version v2.142.0) was used to remove duplicate entries, and the remaining articles were selected to include only relevant English-language peer-reviewed research and review publications, yielding 10,897 suitable records. These records were then subjected to full-text eligibility screening, with 6,956 articles eliminated based on preset inclusion criteria linked to climate change-induced extreme weather events, soil C dynamics, and microbiological activities.

The complete PRISMA-based article selection process and bibliometric analysis are presented in SI Figs. 1 and 2. Following full-text screening, 3,754 articles were retained for bibliometric and qualitative analysis. VOSviewer (version 1.6.20) was used for the bibliometric analysis to determine keyword co-occurrence patterns (with a minimum threshold of ≥ 4) to identify major research themes related to the study. A selection of 187 papers was chosen for extensive qualitative synthesis based on relevance, methodological robustness, and availability of major findings and these studies were utilised for the preparation of tables and in-depth discussion.

3 Climate change and extreme weather events

Drought, floods, and wildfires are among the extreme weather events that are becoming more frequent and intense due to climate change. When these occurrences deviate substantially from 90% or 95% of past weather events in the same region, they are known as "extreme"(Coumou and Rahmstorf 2012).

3.1 Drought

Global climate change can increase the frequency and severity of drought periods, raising severe concerns among environmentalists (Kizildeniz 2025). Drought events affect stream, lake, and groundwater flow (i.e., hydrologic drought), soil moisture content (i.e., ecological or agricultural drought), and the quality and volume of water resources for human and animal consumption (i.e., socio-economic drought) (IPCC 2022; OECD 2025). Globally, climate change has resulted in the expansion of the area susceptible to drought by 1.2×10^5 km^2 (Li et al. 2024a). In Europe, 2003, 2010, 2015, 2018, and 2022 are comprehensively described as the years in the twenty-first century during which Europe experienced extreme drought events (Ionita et al. 2017; Sutanto et al. 2020, 2025). In western North America, increased duration of drought severity resulting from rising temperatures has been observed in recent decades (King et al. 2024). In Africa, a trend of increasing drought events with a significant rise in the Sahara region has been reported from 1960 to 2018 (Ogunrinde et al. 2025).

Several reasons could be attributed to the effect of climate change resulting from elevated levels of GHGs emission on increased environmental risks of drought. First, the rise in atmosphere temperature resulting from global warming is likely to result in an overall increase

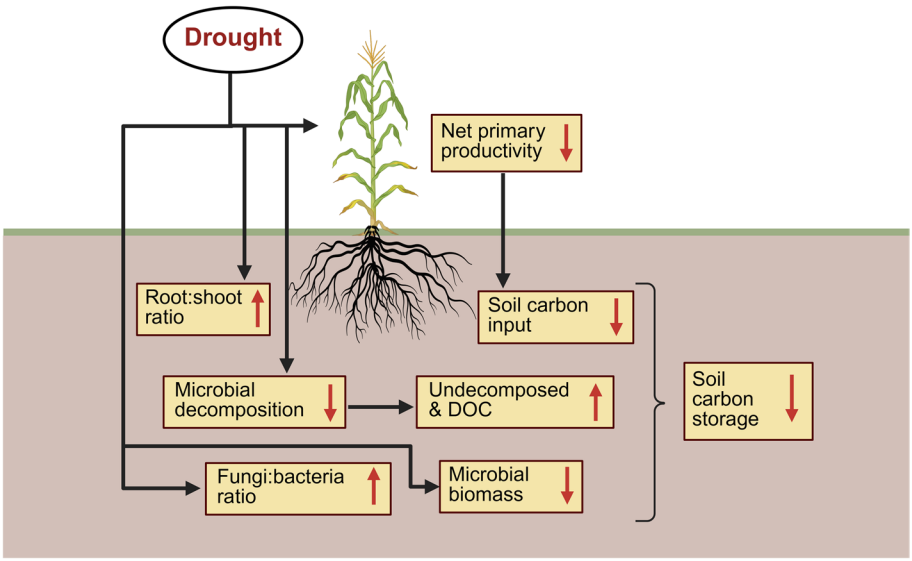


Fig. 1 Schematic diagram of the effects of drought on soil C input, microbial decomposition, and overall change in soil carbon storage. The red arrows indicate an increase (upward arrow) or a decrease (downward arrow) in each pool

in potential evapotranspiration in soil and aquatic systems (Pan et al. 2015; Woolway et al. 2022). Secondly, the increased level of one of the major GHGs, CO_2, is likely to promote photosynthesis in higher plants (i.e., CO_2 fertilization effect) thereby increasing water loss and consequent soil temperature (Boretti and Florentine 2019; Zhu et al. 2023). Thirdly, climate change-induced reductions in snowpack areas can also lead to an increase in land surface temperatures, thereby exacerbating drought due to the snow's reflective properties (Hao et al. 2023; Kosolapova and Altshuler 2024).

3.2 Flooding

Climate change-induced flooding risk is attributed primarily to increased rainfall intensity resulting from elevated atmospheric moisture content (Zhang et al. 2023). This increase in moisture content can result in short, intense downpours that can overwhelm drainage systems and increase the risk of flash flooding (Kendon et al. 2014; Debortoli et al. 2017). Moreover, increased atmospheric temperatures resulting from global warming can also result in tropical cyclones and hurricanes, thereby leading to higher frequency and intensity of flooding (Li et al. 2023a).

The extra heat in the atmosphere represents a supply of energy for weather systems to generate intense precipitation (Giannakopoulos et al. 2009), and heavier precipitation is a key factor in the increase of flooding risk. Areas that experience a higher proportion of rainfall to snowfall witness higher stream flow and, consequently, heightened flood hazards (Jennings and Jones 2015; Mallakpour and Villarini 2015).

3.3 Wildfires

Various factors, such as increased drought conditions, longer fire seasons, rising ambient temperatures, inappropriate fire suppression techniques, and changes in land use practices, are linked to the increased frequency of wildfires (Jones et al. 2022; Wang et al. 2022a; Kim et al. 2025). Similarly, a modelling study tested two high GHG and aerosols scenarios and showed a 25% rise in the risk of extreme fires in New South Wales by 2050 (Pitman et al. 2007). Fire activity and spread of fire depend on fuel characteristics such as amount, type, structure and moisture content, weather conditions such as temperature and wind characteristics, and human activities (Santos et al. 2021; Cruz et al. 2022).

4 Soil carbon

In general, both organic and inorganic types of soil C occur in the natural environment. C is primarily found in organic forms in most soils and regions, although it can also be found in inorganic forms in calcareous soils and dry and semiarid regions.

4.1 Soil organic carbon

The main source of fresh organic matter in the soil is the decomposition of plant matter. Carboxylates are organic molecules that plants directly release into the soil through their roots. An important source of organic matter is derived from the addition of compost, green manure, and animal manure. One way to improve soil characteristics and sequester C is to pyrolyze agricultural leftovers into biochar and add it to the soil.

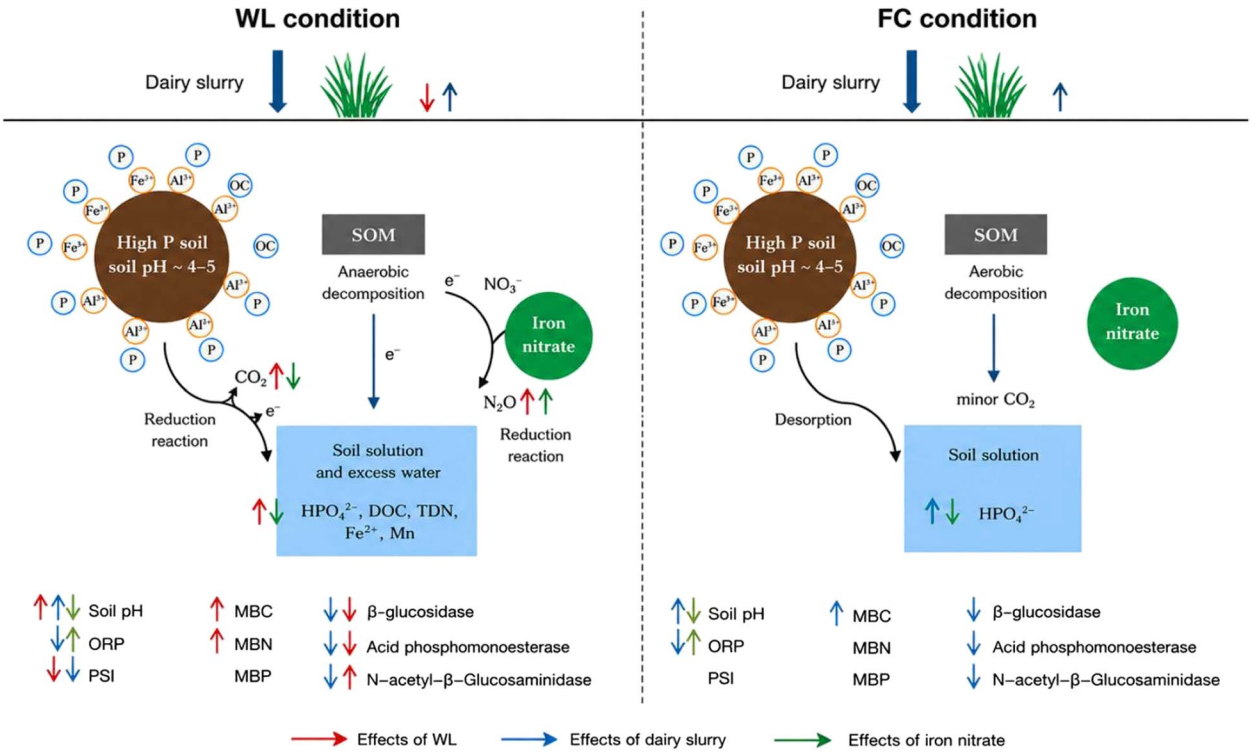


Fig. 2 Schematic representation of chemical, biological, and physical reactions in the acidic soils under flooded conditions. WL = waterlogging and FC = field capacity. (Source: Rupngam and Messiga 2024)

During the breakdown of labile (easily decomposable) organic matter, microbes like bacteria and fungi emit CO_2 through respiration. Both plants and microorganisms can absorb nutrients that are released from organic matter via microbial breakdown. Both stabilization of C and its release through SOM decomposition depend heavily on the community structure and activity of the microbial populations (Wang et al. 2023). Microbial respiration, erosion, and leaching are the prime processes that play a role in the release of SOC.

4.2 Soil inorganic carbon

In general, different forms of soil inorganic carbon (SIC) such as dissolved ionic solutes (carbonates/CO_3^{2-}, bicarbonates/HCO_3^-), calcite ($CaCO_3$), and dissolve CO_2 are found in nature. In salt-affected and alkaline soil, CO_3^{2-} and HCO_3^- ions predominate, whereas $CaCO_3$ predominates in calcareous soil. It has been reported that due to the release of CO_2 during microbial and root respiration process, soil porewater often contains a higher concentration of dissolved CO_2 than the atmosphere (Kuzyakov and Larionova 2006; Zamanian 2024). When silicate minerals such as basalt are subjected to natural weathering, atmospheric CO_2 is consumed, which helps to sequester CO_2 and releases CO_3^{2-} and HCO_3^- ions. Agricultural management techniques, such as adding ground silicate rock, can speed up the natural weathering process, which is typically a rather sluggish process (i.e., increased weathering). Particularly in dry and semi-arid areas, dissolved inorganic carbon (DIC), such as CO_3^{2-} and HCO_3^- ions and dissolved CO_2 in soil porewater, becomes a crucial part of the soil C cycle.

4.3 Organic carbon and soil health

SOC, a part of SOM, offers essential benefits to both human and the natural ecosystems. In order to maintain sustainable food production and prevent an irreversible climate catastrophe, protection and sequestration of SOC are essential in terms of environmental perspectives. SOM can be categorized into particulate organic matter (POM) and mineral-associated organic matter (MAOM), respectively. Although the amounts of plant and microbial components in these SOM fractions differ, MAOM consisted of comparatively more microbial components. Microbial activity, as measured by C consumption efficiency, and microbial access limitations, mostly because of connection to minerals and occlusions in micro-aggregates, will determine the persistence behaviour of SOM.

5 Extreme weather events and soil carbon dynamics

It is important to emphasize that some of these climate change-induced extreme weather events can occur simultaneously, thereby exerting 'compound-effects' on soil C dynamics (Hao et al. 2022; Tripathy et al. 2023). For example, extreme heat resulting from climate change can result in both drought and wildfire simultaneously, thereby impacting soil C dynamics (Table 1). The consequences of flood events on soil carbon dynamics have also been summarized in Table 1.

5.1 Drought and carbon dynamics

Drought is a critical abiotic stress that threatens natural ecosystems and food security by limiting plant growth and productivity. Soil moisture deficits hinder nutrient uptake, growth, and physiological functions of plants. However, different parts of the plant can react differently to drought (Eziz et al. 2017). Similarly, the response to drought can differ across natural and managed ecosystems (Liu et al. 2021; Ye et al. 2023). While natural woody plants can survive prolonged extreme drought, arable crops may not (Liu et al. 2021; Cao et al. 2022). These contrasting responses influence ecosystem contributions to soil C.

Drought not only reduces plant biomass production and soil C inputs but also alters microbial activity through shifts in soil microclimate. These effects can slow SOM decomposition, change turnover rates, and ultimately reshape soil C storage (Ferreira et al. 2023). However, this response varies depending on ecosystems. For example, the natural woody ecosystems may have a greater impact on overall C storage compared to arable croplands (Zhou et al. 2016). Similarly, perennial cropping systems may differ in their response to drought compared to annual crops (Wang et al. 2023).

5.1.1 Drought effects on soil carbon flux

Soil moisture limitation restricts plant growth in both natural and agricultural systems. As a compensatory strategy, many plants allocate more C to roots, enabling deeper soil exploration for water (Li et al. 2024b). However, prolonged drought can reduce overall net productivity and terrestrial C input (Deng et al. 2021; Qiao et al. 2024). Due to a decline in net primary productivity (NPP), drought reduces C input to soil by approximately 3.3% in natural ecosystems, mainly through reduced plant litter input and litter decomposition (Deng et al. 2021). However, this response can be lower in arable croplands due to the increase in the root-to-shoot ratio (Zhou et al. 2016). For example, moderate drought in maize increases root biomass by around 34–46% while reducing leaf biomass by around 1–8% (Yan et al. 2023). Such shifts help plants survive short-term deficits, but lower canopy photosynthesis and NPP during the drought episode (Figueroa-Bustos et al. 2020). A meta-analysis of 164 studies found that drought decreases stem mass fraction by 5.55%, leaf mass fraction by 2.29%, and reproductive mass fraction by 7.54%, but increases the root matter fraction by 9.1% (Eziz et al. 2017). However, prolonged or repeated droughts, spanning multiple weeks or growing seasons, cause cumulative declines in both above- and below-ground biomass (Table 2) (Qu et al. 2023; Deribe 2025). As soil moisture deficits deepen, carbohydrate reserves are depleted, and even previously enhanced root growth slows or reverses (Ullah et al. 2019). Severe long-term drought can reduce total biomass by 50% or more, with shoots suffering greater reductions than roots, maintaining an elevated root-to-shoot ratio (Eziz et al. 2017; Abu-Ria et al. 2024). Therefore, an overall decline of plant C input to soil is expected. Soares et al. (2023) reported this decline to be around −1.4% in arable croplands across different cropping systems.

Under drought stress, the fraction of plant-derived C entering soil via roots (root turnover and exudation) becomes relatively larger, whereas aboveground litter inputs decline. Roots and shoots also differ in how their C persists in soil, altering the balance of labile vs. stable C fractions. Crop roots typically have a greater C:N ratio than shoots, which makes them resistant to microbial breakdown process (Eziz et al. 2017; Ordóñez et al. 2020). Therefore, while drought reduces total C inputs, the C that does enter the soil may be inherently more protected and persistent in the soil.

Forage and pasture systems like perennial grasses or forage legumes like alfalfa respond differently to drought from annual grain crops. Perennial forages frequently develop extensive root systems and can go dormant during drought, then recover when soil moisture is restored (Upton et al. 2018; Schärer et al. 2025). This strategy can stabilize soil C to a degree because the plant cover is not entirely lost. On the other hand, annual crops are more susceptible to extreme drought and may suffer a loss of biomass and yield (Cui et al. 2024; Qiao et al. 2024). Therefore, although the overall biomass is declining across ecosystems in response to drought, forests and grasslands may still experience an increase in soil C pools, while it declines in arable croplands (Zhou et al. 2016; Li et al. 2024c).

5.1.2 Drought effects on microbial decomposition and soil carbon stock

Soil moisture stress can significantly alter soil microbial activity, community structure, and SOM mineralization

Table 1 Effects of climate change-induced extreme weather events on soil carbon dynamics

Carbon dynamics	Impacts of climate change-induced extreme weather events			
	Drought	**Flood**	**Wildfire**	**Compound event (drought and wildfire)**
Carbon input	• Decreases total biomass-derived carbon input • Increases root-derived carbon input	• Increases total biomass-derived carbon input	• Decreases total biomass-derived carbon input • Increases root-derived carbon input	• Decreases total biomass-derived carbon input • Increases root-derived carbon input
Carbon output	• Increases wind erosion loss of soil carbon • Decreases leaching loss of dissolved carbon	• Increases run-off loss of soil carbon • Increases the leaching of dissolved organic carbon	• Increases wind erosion loss of soil carbon	• Increases wind erosion loss of soil carbon • Decreases leaching loss of dissolved carbon
Carbon transformation	• Decreases microbial aerobic/anaerobic mineralisation/immobilisation of soil carbon • Enhances solubilization of soil carbon thereby increasing dissolved organic carbon	• Decreases microbial aerobic mineralisation/immobilisation of soil carbon • Facilitates anaerobic mineralisation of soil carbon	• Decreases microbial aerobic/anaerobic mineralisation/immobilisation of soil carbon • Enhances solubilization of soil carbon thereby increasing dissolved organic carbon	• Decreases microbial aerobic/anaerobic mineralisation/immobilisation of soil carbon • Enhances solubilization of soil carbon thereby increasing dissolved organic carbon

dynamics. Global meta-analyses suggest a decline in overall microbial biomass due to prolonged effects of drought event (Wang et al. 2017; Ren et al. 2018). However, it increases the fungal community and the fungi-to-bacteria ratio (Ren et al. 2018; Leyrer et al. 2025). Due to filamentous growth of fungi, they generally tolerate dry conditions better than many bacteria, so droughts often lead to shifts towards fungal-dominated communities (Canarini et al. 2024; Leyrer et al. 2025). A meta-analysis by Deng et al. (2021) noted that drought reduced litter decomposition rates by around 13% across natural and arable ecosystems. As a result, soil heterotrophic respiration declines under drought stress, and the overall soil respiration is dominated by the autotrophic plant respiration (Zheng et al. 2021). Due to reduced decomposition rates, DOC in soil can increase due to undecomposed SOM in drought conditions (Abdalla et al. 2024).

Drought also increases readily oxidizable and particulate organic C (POC) (Li et al. 2023b). However, this response varies across ecosystems. On the other hand, Qu et al. (2023) reported about 30% and 36% decline in MBC and microbial biomass nitrogen (MBN), respectively, in arable croplands, which were much greater than those observed in any natural ecosystem. They also reported an overall decrease in SOC in response to drought across natural and arable cropping systems (Qu et al. 2023). Interestingly, they found a slight increase in N cycling genes in soils in response to drought. The dynamics of drought (drying and rewetting) also significantly influence the rates of SOM decomposition. During a prolonged dry spell, SOM accumulates in a semi-decomposed state (Deng et al. 2021; Tiwari et al. 2022). When moisture is reintroduced to the soil, microbes rapidly proliferate and consume these available substrates, leading to a flush of CO_2 (Lazicki et al. 2023; Na et al. 2025). This pulse can offset some of the C saved during the drought (Schimel 2018). In agricultural contexts, the rewetting after drought might correspond to the first substantial rain or irrigation. Thus, over a full dry-wet cycle, the soil may end up losing a flush of C that effectively cancels out the temporary storage that occurred during the dry period (Deng et al. 2021). Repeated cycles of drought and rewetting can therefore lead to net C loss and increased C volatility in the system (Soares et al. 2023).

Overall, multiyear and repeated drought, as expected in future climate scenarios, can significantly reduce SOC storage across ecosystems. The extent of SOC decline is more pronounced in grassland (−8.7%) than in forests and shrubs (Deng et al. 2021). The arable croplands showed similar responses to grasslands, with around 8% decline in SOC across different cropping systems (Qu et al. 2023). A schematic diagram of the overall effect of drought on soil C pools is presented in Fig. 1. A summary of published studies reporting changes in soil C across different ecosystems is also presented in Table 3. SOM can be stored and become more drought-resistant with the application of sustainable management techniques (Palm et al. 2014; Poeplau and Don 2015).

5.1.3 Factors affecting carbon cycling during drought

Plant development, water flows, and the biogeochemical cycles of all elements are among the essential functions of terrestrial ecosystems that are impacted by drought. In addition to decreased photosynthesis and growth,

Table 2 Typical impacts of drought on aboveground vs. belowground biomass in major crops under short-term and long-term scenarios. Short-term refers to an episodic within-season drought; long-term refers to a prolonged or repeated drought

*Crops	*Short-Term Drought Effects (within one season)	*Long-Term/Severe Drought Effects (prolonged or multi-season)
Maize (corn)	Noticeable shoot growth reduction; e.g. mid-season drought caused leaf biomass to drop 1–8%, while root biomass increased around 34–46% as the plant allocated more to roots. Minor droughts can still reduce grain yield significantly (a few weeks of stress around flowering often cause > 20% yield loss)	Drastic aboveground biomass loss in severe drought. Extended water stress can cut total maize biomass by around 50–60%, with pronounced yield failure. Root growth also slows and fine roots may die, but shoot losses are greater, so root:shoot ratio remains elevated
Wheat	Moderate early-season drought curbs shoot and leaf growth modestly; plants often respond by increasing root length and root:shoot ratio. Drought before flowering may only cause a small yield dip (< 10–20%). If drought strikes later, effects intensify - one study noted only around 10% yield drop from an early drought vs > 30% from a late-season drought	Terminal drought (during grain fill) severely reduces wheat biomass and yield. Grain yields can drop by > 50% in a severe late drought. For instance, in experiments two cultivars lost 67% and 80% of yield under terminal drought. Shoots senesce early; roots extract deep soil water but ultimately also decline. Multi-year drought and heat can stunt wheat growth and reduce yields by 50% or more, with cumulative soil moisture depletion
Rice	Extremely sensitive to water stress. Even mild drought causes large aboveground impacts: minor droughts in rainfed rice can cut yields by 10–30% due to reduced tillering and panicle formation. Rice has shallow roots, so it has limited ability to compensate via root growth (breeding for deeper roots is ongoing). Some drought-tolerant varieties show slight increases in root length under moderate stress, but generally rice struggles to maintain biomass in any dry spell	Sustained drought is devastating for rice. Severe drought across the growing season can decimate rice biomass, often causing 70–90% yield loss if irrigation fails. Plants exhibit almost complete aboveground senescence (dried leaves, empty panicles). Belowground, roots do not proliferate enough to find moisture and may desiccate in hardened soil. Long-term drought in paddy regions can leave fields fallow and significantly reduce soil organic matter due to minimal residue returns
Soybean	Moderate drought (1–2 weeks during vegetative or early reproductive stages) causes moderate shoot biomass declines (e.g. around 20% less shoot mass after 15 days of stress). Leaves may droop and some flowers abort, but soybean often responds by expanding its root system. Drought-stressed soybeans commonly show increased root dry mass and deeper rooting as an adaptive strategy. Short droughts can thus raise the root:shoot ratio slightly while trimming shoot growth	Prolonged drought (≥ 4–6 weeks) greatly impairs soybean growth and yield. In one study, continuous water stress from flowering onward led to a ~ 48% reduction in shoot biomass by 45 days into the drought. Pod number and seed size plummet under extended drought, often resulting in > 50% yield losses if dry conditions persist through pod-filling. Root biomass may plateau or decline under long stress (as soil moisture becomes critically low), but shoot losses are more pronounced, maintaining a higher relative allocation belowground. Repeated seasonal droughts can also reduce nodule activity (N fixation), impacting long-term productivity and soil N contributions
Sorghum	Sorghum is notably drought-resistant. Under short dry spells, sorghum maintains a higher fraction of its growth than other cereals. For example, in field tests without biostimulants, moderate drought (80% field capacity) reduced sorghum biomass by around 21%, much less than the around 37% loss seen in maize. Sorghum's deep, fibrous roots and waxy leaves help sustain aboveground biomass longer; mild drought might cause only slight leaf area reduction and a modest boost in root length as plants mine deeper moisture	In severe or long droughts, sorghum still outperforms most crops, though yield and biomass do decline. Under a higher drought level (around 60% field capacity), sorghum's total biomass dropped by around 32% (versus nearly 59% in maize) in the same comparative study. Extended drought causes some leaf rolling and premature leaf death in sorghum, and grain yield can fall (e.g. drought during grain fill may cut yields around 30–50%). Nonetheless, sorghum often continues minimal growth where other crops fail, owing to its efficient water use and the ability of its roots to tap deep soil layers. The root: shoot ratio remains high, indicating sorghum prioritizes root maintenance during extreme drought
Cotton	Cotton tolerates drought better than many annual crops. Short-term drought (e.g. a few dry weeks) may cause only moderate reductions in aboveground growth – often on the order of 20–30% less shoot biomass or yield, depending on timing. Plants respond by extending roots deeper; water stress trials show cotton increases its root:shoot ratio under drought as roots elongate to find moisture. Visible symptoms include reduced leaf expansion and some flower/boll shed, but the perennial nature of cotton (often grown as an annual) allows it to endure brief droughts with manageable yield losses	Prolonged drought significantly curtails cotton biomass and lint yield. Under severe season-long drought, cotton yields have been observed to drop by up to around 67%. Plants cut off many fruiting positions and may drop leaves to conserve water, leading to much lower aboveground biomass. Cotton's deep taproot helps the plant survive (it can access deeper moisture to stay alive), so complete crop failure is less common than in shallow-rooted crops. However, fiber quality and boll count suffer greatly. Extended multi-season droughts can even reduce cotton plant stand or vigor in subsequent years. Overall, cotton under chronic drought shows a marked decline in shoot mass (stunted, fewer bolls) while maintaining substantial root biomass relative to shoots (high root:shoot ratio) as a survival mechanism

Table 2 (continued)

*Crops	*Short-Term Drought Effects (within one season)	*Long-Term/Severe Drought Effects (prolonged or multi-season)
Alfalfa	Alfalfa (a perennial forage legume) can withstand short dry periods by going semi-dormant. A single-cycle moderate drought (weeks of reduced irrigation between cuttings) will decrease aboveground forage yield noticeably, often by 30–50% in the affected growth cycle, as the plant diverts energy to persistence rather than new shoot growth. During a brief drought, alfalfa taps into its deep roots and large root carbohydrate reserves; root biomass may even increase in length as the plant mines water, though root *weight* might not change drastically over such a short interval. Once water is restored, alfalfa can regrow from crown buds, but with yield lagging behind fully irrigated crops	Under prolonged or repeated drought cycles, alfalfa's aboveground production drops precipitously. In a two-year study, withholding 50% of irrigation over successive regrowth cycles led to 65–80% reductions in shoot biomass (hay yield) compared to normal conditions. Plants under chronic drought allocate resources to survival (maintaining root tissues and crown buds) over producing foliage. Alfalfa stands will thin out if drought is extreme, as some plants die back, and those surviving remain short with few leaves. The deep root system allows alfalfa to endure drought longer than shallow-rooted annuals, but extended drought ultimately depletes root energy reserves too root biomass can decline after multiple stress cycles, though some resilient varieties with extensive roots fare better. From a soil carbon perspective, repeated drought in alfalfa reduces residue returns (fewer fallen leaves and sloughed roots), potentially slowing soil carbon accumulation
Sunflower	Sunflower's extensive taproot grants it moderate drought tolerance. Short-term drought results in reduced leaf area and slower stem growth. Studies on cultivated sunflower report about a 24% decline in total biomass under drought stress for a few weeks. Aboveground, the plant may have smaller heads and fewer leaves; belowground, sunflower often extends its taproot further. Drought tends to increase sunflower's root:shoot ratio by causing a smaller drop in root biomass than in shoot biomass. In fact, mild drought can stimulate deeper rooting at the expense of shoot growth. Overall, a brief drought leads to moderately lower shoot biomass (e.g. leaves may wilt and some flower abortion can occur) while root systems remain robust relative to shoot size	During sustained drought, sunflower's growth and yield are sharply curtailed. Severe water stress can shrink head diameter, seed fill, and plant height dramatically.Some inbred lines showed up to 90% reductions in key growth parameters under extreme drought. Root growth in deep soil continues until moisture is exhausted, but drought-induced root mortality eventually occurs (fine roots desiccate). Still, the loss in root biomass is less pronounced than the loss in shoot biomass, so the root:shoot ratio rises under long drought. Sunflowers in long-term drought will often produce very small, poorly filled seed heads or none at all. If drought persists over multiple seasons, soil structure (hardpan formation) can restrict root penetration and further limit growth. Wild sunflower relatives, however, exhibit higher genetic drought tolerance, for instance, wild types had negligible biomass loss under drought compared to around 24% in cultivated types, hinting at breeding opportunities for improving drought resilience

* Sources: Specific percentage changes are drawn from experimental studies where available. These illustrate general trends but actual impacts vary with drought timing, intensity, and cultivar

early plant senescence during dry summers also results in decreased plant C inputs.

Soil carbon pool Drought generally affects the soil C cycle, which includes: i) plant-based C inputs, including rhizodeposits and biomass from above- and belowground plants; ii) soil C pools; and iii) soil CO_2 emissions. Deng et al. (2021) showed that drought increased DOC concentration (59.2%), which might be a significant factor in contributing to SOC pools and enhanced microbial CO_2 up to 15.8%, respectively. Furthermore, drought effect on DOC concentration was found to be more significant for grasslands and forests compared to the shrub ecosystem. In grasslands, drought caused a significant drop in SOC concentration (−8.7%); in contrast, it had little effect on forests or shrubs (Jiang et al. 2023). The microbial CO_2 in grasslands and forests rose by 19.9% and 15.5%, respectively, whereas it dropped in shrubs after the drought event (Xue et al. 2017; Deng et al. 2021).

Plant litter and root biomass production rates are reduced by drought events. The reduction can be explained by two primary processes: i) NPP reduction under water limitation, followed by a decline in plant C input into the soil from aboveground litter and roots; ii) reduction of litter decomposition and decreased water availability for microorganisms, which in turn reduce litter inputs into the soils, particularly in grasslands, the aforementioned activities lower plant C inputs, which in turn decrease SOC concentration. Martí et al. (2011) have discussed that the slow rise in SOC concentration in Mediterranean shrubs caused by drought, delayed SOC breakdown, and therefore reduced soil C losses. Drought decreased DOC transport from plant residues by decreasing root formation and plant litter breakdown. Furthermore, drought reduced the amount of DOC that leached into the deeper soil layer, which in turn raised its concentration in the topsoil. But drought may also cause more root-borne organic chemicals, such as rhizodeposits and root exudates, to be released into the soil (Preece and Peñuelas 2016). Patra et al. (2021) reported that a larger percentage of photosynthates were deposited in the roots than in the shoots. Root-borne organic

compounds are important factors contributing to DOC. Particularly for fungus; the high DOC content provides available C, which in turn raises the fungal/bacteria ratio.

Soil microbial responses The microbial functional groups of soil microorganisms associated with the C cycle reacted differently to drought, which resulted in various C turnover processes such as changes in enzymes production, soil respiration status, C use efficiency and altered plant-microbes interactions (Daunoras et al. 2024; Peng et al. 2024; Jayaramaiah et al. 2025). Although heterotrophic bacteria play a major role in soil C turnover, the net amount of C losses will depend on how drastically plant inputs have decreased as drought effects become prominent. Drought frequently lowers plant production and can have long term impacts, but its effects on soil C balance are less clear (Guan et al. 2017; De Silva et al. 2025). Moreover, symbiotic bacteria in the phyllosphere and rhizosphere may respond to drought in different ways that benefit their hosts (plants), thereby enhancing the drought resistance of soil microbiomes and plant inputs concurrently (De Silva et al. 2025; Ullah et al. 2021). Two variables, such as the duration and intensity of the drought, affects how much soil C is lost through microbial respiration. According to Canarini et al. (2017), the decreases in the frequency and volume of precipitation event was responsible for the drop in soil CO_2 outflow. Soil CO_2 emissions increase rapidly during the early drought as a response of plants and microorganisms to environmental stress (Guan et al. 2017). Steady rises of DOC and DON are observed with soil dryness due to: i) increased soluble organic matter as a result of decreased microbial absorption of DOC and DON and sustained high extracellular enzyme activity; ii) extracellular polymeric substances (EPS) generated by soil microbes. Soil moisture plays a vital role in C cycling by supporting healthy microbial communities. Rapid moisture changes, particularly frequent wet and dry cycles, probably disintegrate soil aggregates while exposing the occluded organic matter to microbial access. This leads to the loss of labile C that is vulnerable to microbial breakdown.

5.2 Flood and carbon dynamics

5.2.1 Flood effects on soil carbon flux

Flooded ecosystems, including floodplains and areas susceptible to flooding, demonstrate important C sequestration capacity (Rupngam and Messiga 2024). High SOM accumulation in flooded areas is generally explained by conditions favorable for plant material accrual and limitation of plant decomposition (Sutfin et al. 2016). It is estimated that flooded ecosystems bury 218 g C m^{-2} yr^{-1}, while burial rates of forests and grasslands are 5.5 g C m^{-2} yr^{-1}only (Macreadie et al. 2019). The frequency and duration of flooding affect soil C flux (Table 4). Flooding triggers anaerobic conditions as a result of reduced oxygen in the soil, with changes on microbial activity and nutrient cycling. The primary sources of C in flooded systems include plant litter, root exudates, surface runoff, and allochthonous inputs such as organic materials transported by water. The quantity and quality of these inputs are influenced by vegetation type, land use practices, and hydrological connectivity. Coastal vegetated habitats have substantial C storage and contribute about 20–30% of global soil C (Lal 2008) despite covering only 5–8% of the world's land (Mitsch et al. 2013). Wetlands sequester approximately 830 teragrams of C annually, with an average retention rate of 118 g C m^{-2} yr^{-1}, most of which occurs in tropical and subtropical regions. According to (Mitsch et al. 2013), wetland creation and restoration can enhance C storage and deliver additional ecosystem services without significantly increasing climate warming from methane emissions.

C inputs in flooded ecosystems originate from terrestrial and aquatic sources. The terrestrial C is derived from litter decomposition. Its main forms are particulate, mineral-associated, and DOC (Chenu et al. 2024; Rupngam and Messiga 2024). Every year, it is estimated that on average, 250 Tg of DOC are moved to coastal systems (Nakayama 2020).

Aquatic ecosystems encompass wetlands, marine, and freshwater environments such as rivers and lakes. The C sink of wetlands accounts for 20–30% of the world's C pool (Deng et al. 2022). The source of C in wetlands depends to a large extent on their geographical location. In tropical peatland, woody remains, roots, and litterfall deposited on the ground are the primary sources of organic C (Chave et al. 2010). In contrast, in temperate and arctic wetlands, moss and herbaceous plant remains are the primary sources of organic C (Tveit et al. 2019). In freshwater environments, the main inputs of organic C in rivers consist of terrestrial surface runoff, littoral, planktonic, and bacterial sources (Verrone et al. 2024), while in eutrophic lakes with inputs of N and phosphorus (P) from surrounding farm lands, algal activity and primary production by aquatic plants control organic C inputs (Dianto et al. 2020). In marine environments, organic C incorporated in phytoplankton and marine plants becomes part of the food web and is deposited in sediments at the bottom of oceans (Bauer et al. 2013). Marine sediments represent more than 70% of the land surface and harbor significant amounts of C (Hoshino et al. 2020).

Table 3 Summary of published studies reporting changes in soil carbon (C) in response to drought across natural and arable ecosystems

Country	Climate	Ecosystem types	Soil depth (cm)	Change in soil C	References
Global	Various (arid to mesic)	Grasslands & shrublands	0–15	Drought reduced SOC by 7.9% in areas with an aridity index > 0.65	Shi et al. (2024)
Global	Various	Various	Various	Drought decreased SOC by 8.7% in grasslands but had no impact on forests and shrubs	Deng et al. (2021)
France	Csa (Mediterranean)	Natural woody	0–10	74% lower litter input in pine under reduced precipitation	Santonja et al. (2022)
Germany	Cfb (Temperate)	Natural woody	0–30	An 80% increase in SOC stocks at a depth of 0–5 cm. No effect at depths of 5–15 cm	Brunn et al. (2023)
China	BSk (Cold semi-arid)	Grassland	0–10	Chronic and intense drought decreased SOC content by 9–14% in topsoil; losses were strongest at arid sites	Jaman et al. (2024)
South Africa	BSh (Hot semi-arid)	Grassland	0–30	Soil C stocks increased by 12% under the 5-year extreme drought	Munjonji et al. (2020)
USA	Cfa (Humid subtropical)	Arable cropland (soybean)	0–30	Drought raised extractable and microbial biomass C	Singh et al. (2021)
China	Cfa/Cwa (Humid subtropical)	Natural woody	0–10	Topsoil SOC increased after 5 years of reduced throughfall	Yang et al. (2021)
China	Cwa (Humid subtropical)	Natural woody	0–10	Throughfall reduction can increase living fine root biomass without any effect on soil carbon pools	Lu et al. (2017)
Sweden	Dfb (Humid continental)	Grassland	0–45	Experimental drought did not affect SOC stocks	Guasconi et al. (2025)
China	BSk (Cold semi-arid)	Grassland	0–20	Soil labile C increased with higher rainfall	Song et al. (2012)
China	Various (arid to semi-arid)	Heterogeneous	0–50	Drought promotes soil inorganic carbon loss	Li et al. (2024b)
China	Cwa (Humid subtropical)	Natural woody	0–60	Drought decreased SOC by 6.7–19.1%	Ge et al. (2024)
India	BSh (Hot semi-arid)	Arable cropland (rice)	0–30	Drought reduced SOC by 3.94%	Nunna and Balachandar (2024)
China	Cwa (Humid subtropical)	Grassland	0–50	Drought increased particulate organic C	Wang et al. (2024)
China	Cwa (Humid subtropical)	Natural woody	0–50	Drought reduced SOC by 12.4% and 11.9% at 0–10 and 10–20 cm depths, respectively	Yu-lin et al. (2022)
China	Cwa (Humid subtropical)	Natural woody	0–10	Drought did not affect SOC	Wang et al. (2022b)
China	Dwb (Cold semi-arid)	Grassland	0–50	Drought increased particulate organic C, but did not affect SOC	Li et al. (2023b)

5.2.2 Flood effects on microbial decomposition and soil carbon stock

Floods significantly impact microbial decomposition and soil C stock through various mechanisms including changes in microbial community structure and function, thereby altering soil respiration and enzymatic degradation rates. When flooding occurs, too much water can drastically limit the diffusion of O_2 in the soil's water-saturated pore spaces (Drew 1990). O_2 depletion can happen quickly and frequently in less than a day, in warm soil conditions

when microbial respiration is stimulated. As a result, soil ecosystems experience an O_2 shortage as fully aerobic environment are converted to anaerobic ones (Erdmann et al. 1988). Anaerobic bacteria, which consume oxygen along with roots and other soil fauna, are more likely to survive when the soil is wet (Chakraborty et al. 2023).

In general, in wetland environments, anaerobic bacteria produce greenhouse gasses such CO_2, N_2O, and CH_4 (Burgin et al. 2012; Oh et al. 2023). Enzyme activity, which is necessary for the breakdown of SOM and the cycling of nutrients, is necessary for soil microbes to function properly (Dick et al. 1997). By changing the activity of soil enzymes, O_2 availability has a significant impact on the building up of microbial communities (Burns and Ryder 2001). Increased microbial biomass up to 18% was found in a recent meta-analysis under high-precipitation events (Xu et al. 2020a, b), suggesting that increased soil water controls overall microbial development. Wagner et al. (2015) found that fungal biomass drastically increased after the natural flood event, whereas the proportion of Gram-negative bacteria decreased. Fungi's higher capacity to break down low-quality dead organic material, which enables them to adapt to low O_2 conditions, may be the reason for the rise in the population of fungi (Berg and McClaugherty 2008; Zhou et al. 2010).

5.2.3 Factors affecting carbon cycling during floods

As organic C reaches floodplains and areas susceptible to flooding, several factors influence the residence time and accumulation (Pei et al. 2024).

Environmental stressors The main environmental stressors affecting C cycling in flooded areas include the frequency and duration of floods (Rupngam et al. 2023; Rupngam and Messiga 2024) as well as salt stress (Brown et al. 2022). The frequency and duration of flooding favor waterlogging, reduced oxygen concentration, and buildup of partially decomposed OM. Prolonged waterlogging promotes the reduction of Fe oxyhydroxides and the release of DOC. Flooding alters C dynamics in flooded areas, but there is no finite direction on the outputs of the process. A study conducted in Canada showed that in frequently flooded soils, organic C decreases compared with non-flooded zones (Saint-Laurent and Arsenault-Boucher 2020).

Increased salinity reduces the decomposition and mineralization of SOM (Weston et al. 2010), resulting in buildup and stabilization (Wu et al. 2024). Under elevated salinity conditions, clay particles flocculate and form aggregates, rendering substrates less available to microorganisms (Wong et al. 2010). The occurrence of aggregates enhances the bonds between SOM and soil particles and increases their stability through cation bridging (Hassani et al. 2024; Wu et al. 2024). Salinity affects organic C dynamics in flooded areas by altering the community of soil microorganisms (Yan et al. 2015). Under salinity conditions, plant residues accumulate as partially decomposed SOM because plant communities are less adaptable and have a high turnover rate (Brown et al. 2022).

Substrate quality The quality of SOM substrate in flooded areas has profound effects on organic C cycling. Dissolved organic C is the major substrate of SOM in flooded areas, and it modulates aquatic basal food webs (Lau and Del Giorgio 2020). High levels of DOC and fluorescent humic substances of soil origin were measured during high discharge flow in the Heihe River Basin in northwestern China (Hu et al. 2016).

Microbial community composition Microbial communities promote a wide range of C metabolic pathways and enhance the efficiency of C sequestration in soils (Kästner and Miltner 2016). In flooded areas and areas susceptible to flooding, microbial metabolism follows the anaerobic pathways, and up to 50% of the mineralization of SOM is controlled by sulfate reduction (Luo et al. 2016). Cycles of drying-wetting events in flooded areas affect the diversity of micro-organisms, their processes and functions (Zhang et al. 2020 and 2023). In Switzerland, a survey of aquatic habitats highlighted significant spatial and seasonal dynamics among microbial communities (Doering et al. 2021). However, the authors did not detect pelagic bacteria in the floodplain habitats after the flood, suggesting a transient impact. The shift in community structures following flooding is also directly linked to increased contribution of microbial necromass to organic C (Zhang et al. 2024). It has been shown that microbial CUE promotes SOC storage in terrestrial ecosystems (Sokol and Bradford 2019). The formation of stable and labile SOC storage in terrestrial ecosystems depends on microbial necromass C (MNC) and POC (Wu et al. 2024). However, less is known about the effects in aquatic environments, including flooded areas and areas prone to flooding. Precipitation also plays a pivotal role in regulating MNC formation, indicating that future changes in precipitation regimes may strongly affect SOC sequestration in alpine meadows (Sheng et al. 2025). Continuous P addition in paddy soils increases POC more than MNC indicating a greater key role for plant-derived SOC in C sequestration in these ecosystems (Chen et al. 2025).

Flooding also affects soil enzyme activity. Flooding reduces the energy available for enzymes to complete their metabolic reactions. In high copper-flooded soils,

Table 4 Selected references on the effect of flooding on soil carbon dynamics

Soil types	Flooding treatment	Properties monitored	Observations	References
Eutric Cambisol (Typic Hapludalf)	Coastal grassland ecosystem; sea and brackish water flooding; relationship between plant/microbial growth and CUE; natural salinity gradient. Low (ambient) and high (growth stimulation) levels of 14C-labelled glucose	Soil microbial activity, carbon use efficiency, and 16S amplicon sequencing	Reduced plant growth with flooding; increased soil C content, increased microbial C use efficiency with low glucose-C; alpha diversity increased with salinity; beta diversity shifted with high saline conditions	Brown et al. (2022)
Well-established soil profile databases: LUCAS and WoSIS	>40, 000 mineral soil; varying land covers	Soil Salinity; SOC	Decreased SOC in vegetation/cropland mosaics; decreased SOC in evergreen needle-leaved trees/ noncroplands	Hassani et al. (2024)
Nanji Wetland, Southern region of Poyang Lake, China	Quantification and evaluation of soil microbial metabolic; flooding duration (FD) gradient; three-year study	Soil water content; pH and EC; nutrients; DOM; β-glucosidase;phenoloxidase; β-N-acetyl-glucosaminidase; acid phosphatase	Decreased microbial carbon and phosphorus limitations with FD;	Huang et al. (2023)
Three lakes: Caohai Lake; Hongfeng Lake; Wujiangdu Lake;; Southwestern Plateau, China	Sediment cores	DOM;spectral analysis; DOM biodegradation test	Increased terrestrial DOM in CaohaiLake; enriched autochthonous DOM in Hongfeng and Wujiangdu Lake;	Jiang et al. (2017)
Yangtze River, China	Combination of ultraviolet and fluorescent spectroscopy; ultrahigh-resolution mass spectrometry; DOM	DOM, aromaticity, humic-like fluorescent components, polyphenols, unsaturated compounds	High DOM concentration during high discharge; detection of unique molecular formulae (up to 4927) during high discharge	Pang et al. (2021)
Anthrosols, Luvisols, and Regosols, China	Stratified sampling design following water level elevation	Water-stable aggregate fractions;soil organic carbon forms	Increased particulate organic matter with flooding intensity in Regosols; Organic carbon fractions in Anthrosols and Luvisols are found to respond similarly to flooding regimes	Ran et al. (2023)
Typic Dystroxerepts, Canada	Soil columns and lysimeters; combinations treatments of moisture regimes and dairy slurry P rates;	Soil pH; total carbon; total nitrogen; carbon-to-nitrogen ratio; Fe^{3+}, Fe^{2+}	Decreased Fe^{3+} concentrations with waterlogging; increased Fe^{2+} concentrations with waterlogging; increased soil pH in the topsoil with waterlogging	Rupngam et al. (2023)
Typic Dystroxerept, Canada	Soil moisture regimes; phosphorus rates (0, 15, 30, 45 kg available P ha^{-1})	Soil enzymes; microbial biomass carbon; microbial biomass nitrogen; microbial biomass P; dissolved organic carbon; total dissolved nitrogen	Decreased extracellular enzymes with waterlogging and additions of slurry; adequate supply of C, N, and P; restricted enzyme activities and microbial biomass in the upper soil layer	Rupngam and Messiga (2024)
South central Québec watershed, Canada	Flood frequency (0 to 20 years; 20 to 100 years)	Total organic carbon; total nitrogen	Low total organic carbon and total nitrogen in frequent flood zones	Saint-Laurent and Arsenault-Boucher (2020)
Duliujian River estuary wetland ecosystem, China	Soil sampling at different depth; multiple locations	Bulk SOM;POM; MAOM; SOC; TN; MBC; SWC; BD; SOC	MAOM controlled by soil water content; MAOM and POM controlled by salinity and soil water content	Wu et al. (2024)
Drawdown areas; Chongqing and Hubei Provinces, China	Soil sampling at different elevations based on flooding duration	Soil chemical, biological and physical properties	Increased proportion of easily degradable DOM with the duration of flooding; decreased proportion of refractory DOM; increased microbial authigenic DOM with periodic flooding and drying; decreased stability and aromaticity of soil DOM	Zhang et al. (2025)

cellular activity is suppressed, and extracellular enzymes are inactivated due to the decrease of invertase and urease in the soil (Kunito et al. 2001). Rupngam and Messiga (2024) suggested a conceptual representation that encapsulates the several soil reactions and processes in acidic soils under waterlogging conditions (Fig. 2). According to the authors, reduction reactions occur under waterlogging conditions and are controlled by anaerobic microorganisms using nitrate and Fe as electron acceptors. The by-products of these reactions are organic C and greenhouse gases (Rupngam and Messiga 2024). In flooded soils, metals affect the activity of polyphenol oxidase and peroxidase (Huang et al. 2023).

Fungi, particularly arbuscular mycorrhizal fungi (AMF), contribute significantly to C cycling, including under flooded conditions (Hodge et al. 2001; VanDerWal et al. 2013). AMF enhances nutrient uptake and modulates root exudation, which in turn influences microbial activity and C dynamics (Wahab et al. 2023). Fungi generally prefer relatively dry, low-pH environments (VanDerWal et al. 2013). Microbial interactions with root exudates are especially important in flooded ecosystems, where plant roots release organic acids, amino acids, and phenolics that serve as substrates or signalling molecules for soil microbes (Ma et al. 2022). These rhizodeposits shape microbial community composition and metabolic pathways, influencing the balance between CO_2 and CH_4 emissions (Li et al. 2024d).

5.3 Wildfire and carbon dynamics

Wildfires can lead to the loss of above-ground biomass, thereby impacting C input to the soil. Wildfires also heat the soil surface, convert the protective layer of litter and vegetation to ash, and may make the soil surface water repellent (Zavala et al. 2010; Eldridge et al. 2023). These processes have flow-on effects on soil chemical and biological processes, and run-off and erosion, thereby impacting soil C dynamics. The nature and magnitude of these effects will vary with soil type and moisture content, but also depend on fire intensity and landscape context.

Wildfires, intensified by climate change, profoundly alter soil C dynamics through direct combustion, indirect ecosystem disruptions, and long-term shifts in biogeochemical processes (Hantson et al. 2024). These events consume above-ground biomass and SOM, leading to immediate C losses via emissions and erosion, while also influencing subsequent C inputs and microbial activities. For instance, high-severity fires can volatilize up to 50–80% of surface SOC, depending on fire intensity and soil moisture conditions (Li et al. 2023c). This section examines the impacts on C input and microbial decomposition, drawing from recent studies to highlight mechanisms and variability across ecosystems.

5.3.1 Wildfire effects on soil carbon flux

Wildfires directly reduce C inputs to soil by combusting vegetation and litter, which diminishes the supply of plant-derived SOM. Above-ground biomass loss during fires interrupts the flow of C from photosynthesis to roots and exudates, often resulting in a temporary decline in rhizodeposition, a primary pathway for fresh C entering soils. In boreal forests, for example, post-fire vegetation recovery can take decades, leading to reduced litterfall and root biomass in the initial years following a burn (Mekonnen et al. 2022). Similarly, in temperate grasslands, wildfire-induced degradation following afforestation has been linked to a 20–30% reduction in soil C stocks due to decreased plant productivity and increased exposure to erosive forces (Pellegrini et al. 2018). However, wildfires can also indirectly enhance C inputs in certain contexts. Charred residues (pyrogenic C (PyC, or black C) from incomplete combustion are highly recalcitrant and can persist in soils for centuries, acting as a long-term C sink. Meta-analyses indicate that PyC contributes 5–15% to total SOC in fire-affected soils, with its stability influenced by soil texture and mineral associations (Santín et al. 2015). In mountainous terrains, post-wildfire erosion redistributes SOC down slope, potentially increasing inputs in depositional areas while depleting upslope zones (Abney and Berhe 2018). Vegetation succession post-fire further modulates inputs; pioneer species like N-fixing plants can accelerate recovery, boosting root exudates and litter quality. Research in the Eastern Cascades, Oregon, demonstrates that low-severity fires promote rapid regrowth, maintaining C inputs at 70–90% of pre-fire levels within 5 years, whereas high-severity burns delay recovery by 10–20 years (Meigs et al. 2009).

Fuel structure and drought preconditions exacerbate these effects. In peatlands and wetlands, wildfires under dry conditions consume deep organic layers, reducing future C sequestration potential (Turetsky et al. 2015). A global meta-analysis on fire effects reveals that ecosystems with high fuel loads, such as dense pine forests, lose more C inputs due to complete biomass combustion (Cheng et al. 2023). Table 5summarizes wildfire severity impacts on C input mechanisms across ecosystems. Overall, while immediate losses dominate, long-term inputs depend on fire regime, climate, and land management, with potential for enhanced stability through pyrogenic materials.

5.3.2 Wildfire effects on microbial decomposition and soil carbon stock

Wildfires alter microbial communities and processes, accelerating or inhibiting the decomposition of SOM. Heat from fires sterilizes surface soils, killing microbes and reducing enzymatic activity initially, which can temporarily slow decomposition and preserve C (Dooley and Treseder 2012). However, post-fire inputs of labile C from ash and dead roots stimulate surviving microbes, leading to a "priming effect" where decomposition rates increase by 20–50% in the first few months(Soong and Cotrufo 2015). In northern Eurasia, wildfires from 2003–2016 altered soil thermal regimes, thawing permafrost and enhancing microbial access to previously frozen C, resulting in net C releases of up to 1–2 kg C m^{-2} yr^{-1} (Xu et al. 2024).

Molecular changes of SOM induced by fires, such as increased aromaticity in SOM, make C more resistant to microbial breakdown (Certini 2005). Yet, shifts in microbial life history traits favouring fast-growing opportunists over slow-growing specialists can enhance short-term decomposition (Dooley and Treseder 2012). In semiarid agroecosystems, prescribed fires in grasslands increase decomposition rates by altering soil stability and nutrient availability (Soong and Cotrufo 2015). Erosion following high-severity fires exposes deeper C layers to microbes, amplifying losses in dynamic landscapes.

Long-term effects of wildfires on microbial activity and C dynamics can vary; in boreal chronosequences, microbial communities recover within 10–50 years, but altered C quality sustains lower decomposition rates (Mekonnen et al. 2022). Fire frequency also plays a role: recurrent burns in the Northwestern Himalayas reduce microbial biomass by 15–25%, slowing decomposition but increasing vulnerability to further losses. Table 6 outlines post-wildfire changes in microbial parameters affecting decomposition. Wildfires disrupt microbial decomposition through heat, substrate changes, and environmental shifts, often leading to net C losses that feed back into climate change. Integrating fire management with C farming strategies could mitigate these impacts (Santín et al. 2015).

5.3.3 Factors affecting carbon cycling during wildfire

Several environmental conditions, such as tree species, soil layers, and fire patterns, influence the soil C pools. This finding suggests that controlled fires might increase soil C storage by promoting plant litter breakdown and soil microbial activities. Prescribed fire may be a useful strategy to prevent wildfires and preserve healthy soils, since wildfire types can also influence how C moves through the soil, particularly in forests.

Soil organic matter (SOM) and carbon cycling pools Researchers have found that the effects of low-intensity wildfires on total C and SOC were more substantial than those of moderate and high-intensity wildfires (Simanský 2015; Cheng et al. 2023). This impact could arise from the fact that low-intensity wildfires frequently induce extensive soil heating and modifications to nearby mineral soil characteristics. In subtropical areas and evergreen broadleaf forest ecosystems, wildfires had a stronger effect on soil C cycling pools. This implies that deeper active soil layers and warmer soils promote microbial mineralization, which in turn affects surface energy fluxes, the C cycle, and ecosystem functions (Naylor et al. 2022; Azevedo et al. 2024).

Wildfire has diverse effects on soil C pools; nonetheless, over time, these pools gradually reach equilibrium. Furthermore, wildfires have long-lasting impacts on SOM and microbial composition, which in turn affects the soil C dynamics. The distinct production method and characteristics of PyC may explain why wildfire has a greater effect on PyC than on other soil C fractions. PyC is one of the most organic C pools that resist degradation due to its strong resistance to biodegradation. PyC is essential for N cycling, which usually prolongs the duration of wildfire-impacted soil processes, and assists in the recovery of ecosystems with little inputs of OM (Nelson et al. 2024)

Soil enzymes and microbial activities Various studies have demonstrated that wildfires can negatively impact soil microbial biomass and consequently, it is believed that wildfire may cause a general decrease in soil extracellular enzyme activity (EEAs) of about 20–40% (Dooley and Treseder 2012; Zhou et al. 2022; Pei et al. 2023). In addition to influencing soil microbial biomass, wildfires may also alter EEAs reactions and associated microbial activities. Wildfire can change the types of OM inputs and reduce the quantity of SOM, which can have an impact on soil EEAs. Larger amounts of SOM are occasionally transformed by catastrophic fires, which results in a persistent substrate that may create constraints for microbial populations, resulting in a decrease in soil EEAs in the post fire environment (Barreiro and Díaz-Raviña 2021; Cheng et al. 2023).Wildfire regularly increases the amount of phosphorus that is accessible in the soil by causing organic phosphorus to mineralize due to heat (García-Oliva et al. 2018; Hrelja et al. 2020). Pei et al. (2023) showed that fire would cause a general decrease in soil EEAs, mainly as a result of fire-induced reductions in OM substrates and soil microbial biomass. They also highlighted that compared to a single wildfire event; repeated wildfires often result in larger reductions in soil microbial biomass and OM substrates.

Table 5 Impacts of wildfire severity on soil carbon inputs in selected ecosystems

Wildfire severity	Ecosystem types	Primary impact on carbon input	Estimated change (%)	References
Low	Temperate Deciduous Forest (Eastern North American Oak Forest)	Reduced litterfall, but quick regrowth	−10 to −20	Meigs et al. (2009)
	Temperate Coniferous Forest (West Coast Pine Forest)	Reduced litterfall, but rapid recovery	−10 to −20	Meigs et al. (2009)
Moderate	Boreal Coniferous Forest (Siberian Spruce Forest)	Erosion and pyrogenic C addition	−30 to + 5 (net)	Mekonnen et al. (2022); Li et al. (2023c)
	Boreal Coniferous Forest (Canadian Black Spruce Forest)	Erosion and pyrogenic C addition	−30 to + 5 (net)	Mekonnen et al. (2022); Li et al. (2023c)
High	Temperate Grassland (North American Great Plains)	Biomass loss and degradation	−40 to −60	Pellegrini et al. (2018)
	Mediterranean Shrubland (California Chaparral)	Biomass loss and degradation	−40 to −60	Pellegrini et al. (2018)
Variable	Montane Coniferous Forest (Rocky Mountains)	Redistribution via erosion	−50 upslope, + 20 downslope	Abney and Berhe (2018)
	Montane Shrubland (Andes Mountains)	Redistribution via erosion	−50 upslope, + 20 downslope	Abney and Berhe (2018)

Table 6 Wildfire-induced changes in microbial factors influencing soil carbon decomposition

Parameter	Pre-fire baseline	Post-fire change (Short-term)	Post-fire change (Long-term)	References
Microbial Biomass	High diversity	−30 to −70% (sterilization)	Recovery to 80–100%	Dooley and Treseder (2012)
Decomposition Rate	Stable	+ 20 to + 50% (priming)	−10 to −20% (recalcitrant C)	Certini (2005); Soong and Cotrufo (2015)
Enzyme Activity	Balanced	Reduced initially	Increased with nutrient flux	Cheng et al. (2023)
Community Composition	Specialist-dominated	Opportunist shift	Succession to resilient taxa	Mekonnen et al. (2022)
Soil Respiration Rate	Moderate and stable	+ 30 to + 60% (increased labile C)	−15 to −25% (reduced substrate availability)	Hart et al. (2005); Knicker (2007)
Microbial Carbon Use Efficiency (CUE)	High efficiency	−10 to −20% (labile C dominance)	Recovery to near pre-fire levels	Blagodatskaya et al. (2014)
Fungal to Bacterial Ratio	Balanced (fungal dominated in forests)	Shift to bacterial dominance (−20 to −40%)	Partial fungal recovery (+ 10 to + 20%)	Grandy et al. (2016)

6 Conclusions

Climate change-induced extreme weather events, including drought, flood, and wildfire, impact C dynamics in soils by influencing C input and microbial decomposition of SOM. This review stresses the role of drought on root biomass production rather than shoot biomass as a drought adaptation strategy by plants, thereby impacting the root-derived C input to soil. Flooding can cause a decrease in soil C through erosion of mineral-associated organic C, mobilization and leaching of DOC. There is a body of recent studies showing that waterlogging can increase MNC and POC in alpine meadow soils. Wildfires can both reduce C input to soil through the burning of aboveground biomass and increase the loss of C from soil through leaching of solubilised soil C. All these major extreme weather events can also impact soil C by influencing soil microbial activity and function. Future research needs to focus on:

- Quantifying the effects of climate change-induced extreme weather events on the redistribution of SOM under various land use systems, soil types, and environments, including terrestrials and aquatics.
- Examining the microbial response in terms of genomic and functional diversity to extreme weather events in relation to SOM dynamics using advanced molecular techniques.
- Monitoring the changes in elemental stoichiometry of SOM as impacted by extreme weather events using advanced spectroscopic techniques.
- Using advanced technologies including high-resolution remote sensing and ground-based observations

coupled with integrated modelling to bridge the gaps in our understanding of climate change-induced extreme weather events on SOC dynamics at various time and spatial scales.
- Measuring the long-term impact of extreme weather events on the storage and loss of SOC as influenced by changes in microbial communities and structure in relation to C sequestration.
- Assessing the interactions and timing of extreme weather events, including successions/alternations of floods and droughts, and of wildfires and droughts on changes in SOC.
- Investigate the effects of climate change-induced extreme weather events on physico-chemical mechanisms and interactions involving Fe/Al oxy-hydroxides and clay minerals on the storage and loss risks of SOC.

Abbreviations

GHGs	Greenhouse Gases
SOM	Soil Organic Matter
DOC	Dissolved Organic Carbon
NPP	Net Primary Productivity
POC	Particulate Organic Carbon
MBC	Microbial Biomass Carbon
SOC	Soil Organic Carbon
MBN	Microbial Biomass Nitrogen
PyC	Pyrogenic Carbon
DON	Dissolved Organic Nitrogen
EPS	Extracellular Polymeric Substances
EEAs	Extracellular Enzyme Activities
CUE	Carbon Use Efficiency
MNC	Microbial Necromass Carbon
AMF	Arbuscular Mycorrhizal fungi
MAP	Mean Annual Precipitation
MAOM	Mineral Associated Organic Matter
SWC	Soil water content

Supplementary Information

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Supplementary Material 1.

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Declarations

Declaration of Generative AI and AI-assisted technologies in the manuscript preparation process
During the preparation of this work the author(s) used Generative AI and AI-assisted technologies (e.g., Copilot) in order to increase readability. After using this tool/ service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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