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Amplifying feedback loop between drought, soil desiccation cracking, and greenhouse gas emissions

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The continuous escalation of carbon dioxide (CO_2) emissions into the atmosphere is recognized as the primary catalyst for anthropogenic climate change. In 2021, CO_2 emerged as the predominant contributor to the warming effect of all human-made greenhouse gases (GHGs), accounting for two-thirds of their global heating impact [1]. While the primary anthropogenic source of increased atmospheric CO_2 concentration is the combustion of fossil fuels, the largest terrestrial source of CO_2 emissions is soil [2] where 80% of the total terrestrial carbon is stored. Approximately 62% of soil carbon is in organic form and readily released as CO_2, while the remaining is made up of inorganic carbon (soil inorganic carbon (SIC)) [3]. Here, we postulate that there is an amplifying feedback loop between drought, soil desiccation cracking, and CO_2 emission in a warming climate (figure 1)—a critical aspect that has been overlooked in the existing literature. Further, we argue that the postulated feedback loop affects the emissions of other GHGs, such as methane (CH_4) and nitrous oxide (N_2O), from soils. The urgent need to recognize and characterize this exacerbating feedback loop is twofold. Firstly, it is widely acknowledged that drought accelerates the oxidation of soil organic carbon (SOC) and, thus, increases CO_2 emissions into the atmosphere. Drought-induced soil moisture deficits differentially affect plant processes; while photosynthesis rates may be reduced in plants, leading to decreased carbon uptake, respiration rates can vary. Initially, drought may cause a slight increase in respiration, despite a decline in photosynthesis, leading to increased carbon emissions from the soil. These effects can differ based on ecosystem types, highlighting the complex interplay between drought, photosynthesis, and respiration. Secondly, drought triggers soil desiccation cracking, substantially increasing the permeability of the soil and the interfacial exchange area between the atmosphere and the soil, which, in turn, can considerably increase CO_2 efflux in soil by exposing deeper and older stores of soil carbon. Desiccation cracking threatens earthen infrastructure systems and the natural environment. The problems associated with desiccation cracks are becoming more prevalent as anthropogenic climate change exacerbates the severity and frequency of droughts, heatwaves, and drought-heavy precipitation cycles [4]. As the warming trends continue, more (and possibly older) CO_2 is released from the soil, which can further contribute to global warming. Thus, a chain of events happens in a cascading manner. Failure to consider the hypothesized feedback loop can result in significant inaccuracies when modeling and predicting GHG emissions from soil. It may also lead to underestimating the overall impact of climate change on critical aspects such as soil health, crop production, and the structural integrity of earthen infrastructure.

1. Drought and soil desiccation cracking

Drought is recognized among the main causes of soil desiccation cracking—a common phenomenon observed on the surface of fine-grained soils, predominantly clay. These cracks can potentially extend to considerable depths, reaching several meters below the surface. Soil desiccation cracking is driven by

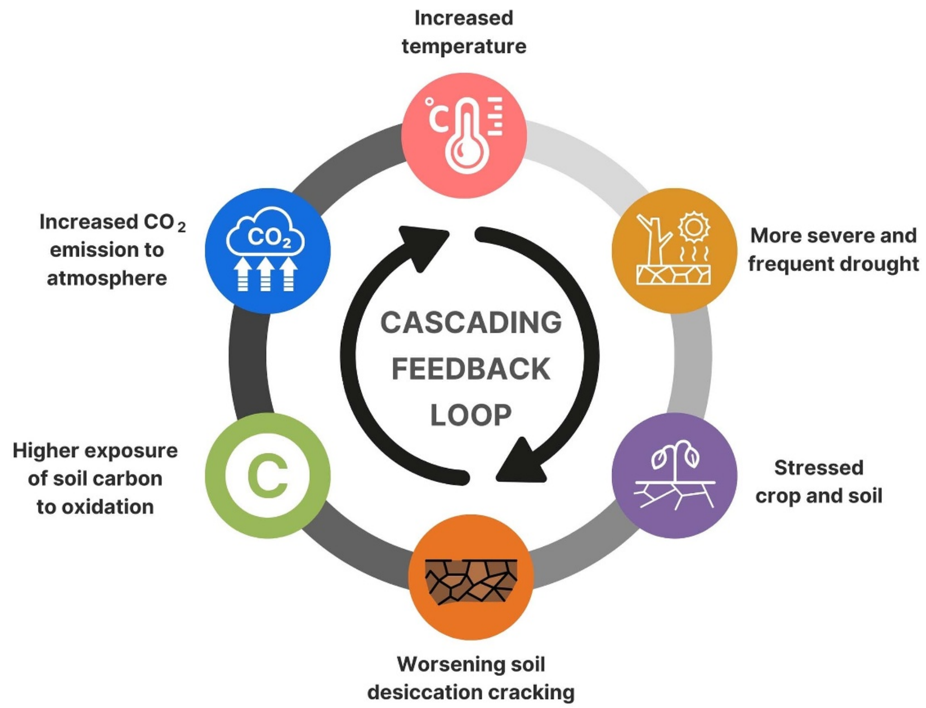

Figure 1. Feedback loop describing drought, soil desiccation cracking, and CO_2 emission relationships in a warming climate.

soil shrinkage potential and is highly sensitive to climatic conditions such as relative humidity, temperature, and wetting–drying cycles. Elevated temperature can reduce the soil's tensile strength [5], which is the primary factor in resisting desiccation cracking. At higher temperatures, surface tensile stresses develop at a higher rate causing desiccation cracks to form faster [6]. Further, low relative humidity under drought conditions causes a faster cracking rate, resulting in the formation of a longer total crack length at the end of evaporation [7].

The formation and propagation of desiccation cracks can significantly impact the mechanical and hydraulic characteristics of soils. Drought-induced changes in soil properties and near-surface processes trigger a number of weakening mechanisms that, in conjunction with other factors, have the potential to give rise to various geotechnical, geoenvironmental, hydrological, and environmental issues. For instance, drought-induced desiccation cracks can accelerate desertification by increasing the soil evaporation rate and decreasing the soil water retention capacity [6]. Further, increased soil hydraulic conductivity creates preferential flow pathways for the migration of fluids and contaminants and accelerates soil weathering and erosion. These effects collectively pose a threat to the structural integrity of foundations, levees, earthen dams, landfill covers, and roads and trigger a suite of natural hazards such as landslides.

2. Desiccation cracking and soil carbon dynamics

The impacts of desiccation cracking on soil carbon dynamics can vary depending on factors such as climate, soil type, vegetation cover, and land management practices. Desiccation cracking can have significant impacts on SOC and SIC through several mechanisms (figure 2).

SOC plays a crucial role in the agroecosystem as the basis of plant nutrient availability, soil structure (i.e. aggregation), water retention and availability, and biological health (i.e. soil fauna and flora). It can also serve as an indicator of soil quality for accessing yield potential. Desiccation cracking creates open fissures and fractures in the soil surface, which can lead to increased soil aeration and enhanced microbial activity. This accelerated microbial decomposition can result in the rapid breakdown of organic matter, leading to carbon loss from the soil system. Further, soil desiccation cracking significantly affects microbial and macrofauna diversity and function by altering habitat structures and introducing more aerobic conditions. These changes can expose soil biota to environmental stress, impacting microbial communities responsible for nutrient cycling and soil structure maintenance [8, 9]. As cracks allow deeper oxygen penetration, aerobic microbial activity increases, potentially altering microbial composition and functions, which can affect soil carbon

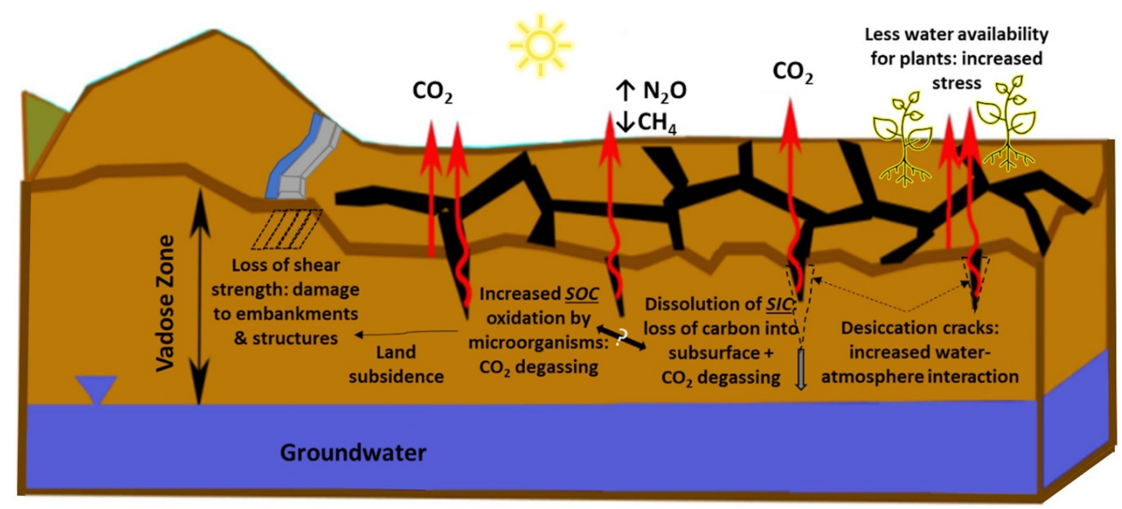

Figure 2. Consequences of drought-induced desiccation cracks on emissions of greenhouse gases, including CO_2, CH_4, and N_2O, from soils.

dynamics and nutrient availability. The changes in microbial and macrofauna diversity due to soil desiccation cracking and the resulting more aerobic conditions can thus have cascading effects on soil health, affecting its ability to support plant life, sequester carbon, and regulate GHG emissions.

Inversely, micro and macrofaunal behavior have been shown to directly affect soil crack morphology and intensity through bioturbation and biocompaction, respectively [10]. Additionally, these changes in crack morphology can result in significant increases in CO_2 flux in soils by affecting the soil moisture, temperature, and respiration dynamics through the creation of preferential pathways for fluid flow [11]. Soil macrofauna, like earthworms and millipedes, play an important role in regulating CO_2 and N_2O [12]. Drought has been shown to negatively affect the density, biomass, and richness of macrofauna [13]. The cyclic interplay between drought, desiccation crack introduced aeration, micro and macrofaunal abundance and activity, and its overall effect on GHGs warrants further attention. The increased exposure of organic materials to the atmosphere through cracks provides an avenue for microbial decomposition and the release of CO_2 into the atmosphere. Further, desiccation cracking undermines the physical structure of the soil, which can result in the loss of soil aggregation and pore connectivity, leading to reduced soil organic matter retention. As a consequence, the stabilization of organic carbon in soil aggregates becomes compromised, increasing the vulnerability of soil carbon to further degradation. In turn, further degradation of SOC can destabilize soil macroaggregates, which further drives soil cracking and exacerbates the carbon loss cycle [14]. The enhanced water flow due to the presence of cracks can lead to increased erosion and sediment transport, resulting in the displacement of organic matter-rich topsoil layers. The loss of these carbon-rich soil horizons further contributes to carbon depletion in the affected areas.

Desiccation cracking reduces the soil's water-holding capacity by creating gaps and openings that allow rapid water infiltration and drainage. This leads to drier soil conditions, which can limit microbial activity and organic matter decomposition rates. Consequently, the slower breakdown of organic matter results in reduced carbon mineralization and sequestration in the soil. It is shown that more cracking leads to decreased SOC content [15]. However, the interplay between soil cracking and CO_2 is poorly understood and has not been examined in long-term field studies. It is not only important to understand the total CO_2 efflux increase due to desiccation cracking but also the age of the carbon that is being emitted. The stability and age of SOC increase with soil depth regardless of vegetation, soil type, and land use [16]. It is expected that as global warming trends continue, desiccation cracking will propagate deeper into the soil, exposing deep, previously stable SOC to oxidation.

Another potentially significant, yet largely unexplored consequence of desiccation cracking is its potential impact on SIC dynamics. SIC constitutes a significant portion, accounting for approximately 30%–40% of the total soil carbon pool. It is particularly abundant in semi-arid and arid regions, surpassing SOC levels by 1.4 times [17]. Soils rich in SIC, which occupy approximately 54% of the world's land surface, play an important role in carbon sequestration, primarily in the form of carbonate minerals and transiently in the form of dissolved carbonate and bicarbonate ions in soil moisture [17]. However, there is limited knowledge regarding the potential changes in stored carbon when SIC-rich soils are exposed to prolonged drought and the resulting desiccation cracks. In areas dominated by carbonate rocks, rainfall introduces CO_2-rich moisture into the soil, in turn promoting carbonate mineral dissolution and generation of soil CO_2 [18]. Temperature changes affect soil pH in arid soil, leading to degassing of CO_2. Experiments have shown that as the drought period increases, soil CO_2 degassing will also increase [19]. Drought is suggested as one of the processes that could decrease SIC stocks globally [20]. The development of cracks would allow water to penetrate further into the soil and dissolve carbonate minerals, thus removing the stored, older carbon to deeper portions of the subsurface. Experimental, field, or modeling studies of the variables controlling these complex processes are limited, thus warranting more attention to these vulnerable soil systems.

3. Effects on the emissions of other GHGs

The feedback loop between drought-soil desiccation cracking can alter the emissions of other GHGs from soils (figure 2). It is shown that the emissions of GHGs, such as CO_2, methane (CH_4), and nitrous oxide (N_2O), from intact soils are sensitive to climatic variables, with the most significant factors being moisture and temperature [21, 22]. The interplay of drought and soil desiccation cracking can significantly impact CH_4 emissions from soil to the atmosphere. Several studies have observed decreased CH_4 emissions from soils during drought periods [23]. This phenomenon has been attributed to the combined effects of reduced microbial activity in aerobic conditions and increased methane oxidation. Typically, CH_4 production occurs in anaerobic environments, where oxygen is limited. However, the presence of soil desiccation cracking can introduce increased aeration into the soil, altering the conditions for CH_4 production and emissions. Under aerobic environments, the microbial processes that produce CH_4 are suppressed, reducing CH_4 emissions. Additionally, the increased aeration associated with soil desiccation cracking promotes organic carbon oxidation. As a result, organic carbon is more likely to be converted to CO_2 rather than methane. The oxidation of CH_4 to CO_2 can further contribute to the decrease in CH_4 emissions under drought conditions. However, the specific impact of drought and soil desiccation cracking on CH_4 emissions can vary depending on soil type, vegetation cover, and microbial community composition.

The N_2O emission is another significant GHG emission, mainly from agricultural lands, which can be affected by the feedback loop between drought-soil desiccation cracking. Over 50% of total N_2O emissions to the atmosphere are from soils [21]. It is shown that N_2O emissions from soil increase after a prolonged drought followed by rewetting [24]. The interplay of drought and soil desiccation cracking can lead to increased N_2O emissions through enhanced nitrification in oxygenated soil microsites, intensified denitrification in moisture-rich pockets within cracks, and accelerated organic matter decomposition. Drought-included desiccation cracks provide preferential pathways for oxygen to penetrate deeper into the soil, creating microsites with increased oxygen availability. Consequently, this oxygen-rich environment can promote the activity of nitrifying bacteria, which convert ammonium (NH_4^+) to nitrate (NO_3^-) through nitrification. Increased nitrification rates can lead to higher levels of nitrate in the soil. In addition, the presence of desiccation cracks can affect soil moisture distribution, leading to spatial heterogeneity in moisture availability. In regions with intermittent moisture, desiccation cracks can trap water during wet periods and create isolated moisture pockets. These moist pockets can become hotspots for microbial activity, including denitrification, which converts nitrate to N_2O and other nitrogen gases. Therefore, desiccation cracks can promote denitrification and subsequent N_2O emissions.

4. Future steps

The amplifying feedback loop between drought, soil desiccation cracking, and GHG emissions is indeed a significant concern with potentially adverse effects on the natural and built environment. Mitigating the impact of this feedback loop requires collaborative efforts and actions from various stakeholders. There is a need for more interdisciplinary research that combines knowledge from fields such as soil science, hydrology, atmospheric science, civil and geotechnical engineering, agriculture, and ecology to better understand the complex interplay between drought, soil desiccation cracking, and GHG emissions in a changing climate. Outstanding research gaps to be filled to unravel this interplay and mitigate its long-term effects include [1]: quantifying the interdependences between soil carbon and cracking [2], understanding the fraction of SOC being oxidized and the age of that fraction, along with estimating SIC losses [3], identifying how the postulated feedback loop can affect the emissions of the other primary GHGs, such as CH_4 and N_2O, from soils, and [4] identifying nature-based solutions and best land management practices for soil moisture conservation and management in drought-prone areas to reduce soil desiccation cracking and its associated emissions. Accurately modeling this feedback loop in a changing climate poses a complex and challenging problem that requires understanding multi-physics processes at different scales that are need fully understood yet. As a possible solution, we propose to invest in developing data-driven models and employ the Digital Twin concept, which offers unprecedented opportunities to address challenging problems in science and engineering. Environmental, biological, chemical, and physical interactions that cause GHG emissions from cracked soil to the atmosphere present an example of such challenging problems that cannot be adequately addressed using traditional modeling methods. Further, long-term experiments are needed to develop, validate, and refine data-driven models for linking soil cracking patterns, GHG emissions, and climate change scenarios.

Government agencies and policymakers need to allocate research funding to support studies on the relationship between drought, soil cracking, and GHG emissions. Further, they need to establish regulations and guidelines that promote sustainable land management practices, particularly in areas susceptible to drought and soil desiccation. Incentives need to be offered for the adoption of precision irrigation techniques and water conservation practices to minimize soil desiccation and subsequent emissions. We must investigate the socio-economic effects of different land management practices, such as tillage and crop rotation, on soil cracking and GHG emissions under various climate change scenarios. This will nurture the development of decision-support tools to help policymakers, land managers, and other stakeholders identify the most effective mitigation and adaptation strategies.

The agricultural and land management sector needs to implement drought-resistant agricultural practices, such as crop rotation and the use of drought-tolerant crop varieties, to mitigate the impacts of drought and reduce soil cracking. Utilizing soil conservation techniques, including cover cropping, mulching, and reduced tillage, can enable the agricultural and land management sector to improve soil moisture retention and decrease GHG emissions. Further, the use of organic fertilizers and compost enhances soil organic matter content and improves soil water-holding capacity.

Data availability statement

No new data were created or analyzed in this study.

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