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Effects of Soil Salinity on Soil Carbon Stocks, Microbial Activity and Greenhouse Gas Emissions

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Introduction

Soil salinity is one of the most widespread threats to land degradation, affecting agricultural productivity, ecosystem functioning, and environmental sustainability worldwide. It occurs when soluble salts accumulate in the soil profile to levels that negatively affect plant growth, soil structure, and biological activity. According to the Food and Agriculture Organization (FAO), more than one billion hectares of land are affected by salinity globally, and the extent of salt-affected soils is expected to increase due to climate change, sea-level rise, intensive irrigation practices, and inadequate drainage infrastructure systems (FAO, 2021).

Salinity imposes both osmotic stress and ionic toxicity on plants and soil organisms. Elevated concentrations of salt minerals reduce water availability, impair nutrient uptake, and alter soil physical properties. Consequently, salt-affected soils often exhibit lower crop productivity, reduced vegetation cover, and increased susceptibility to desertification (Rengasamy, 2010).

Beyond its impacts on agriculture, soil salinity has emerged as an important factor influencing global carbon cycling and climate change. Soil serves as the largest terrestrial carbon reservoir, storing more carbon than the atmosphere and vegetation combined. Therefore, any factor affecting soil carbon storage has significant implications for greenhouse gas emissions and climate regulation (Lal, 2004).

Recent studies have demonstrated that salinity alters soil microbial communities, enzymatic activities, carbon sequestration processes, and greenhouse gas fluxes. These changes directly influence soil carbon stocks and determine whether soils function as carbon sinks or carbon sources. Understanding the interactions among salinity, microbial processes, carbon stocks, and greenhouse gas emissions is therefore critical for sustainable land management and climate change mitigation.

Effects of Soil Salinity on Soil Carbon Stocks

Sequestering atmospheric CO_2 in soils is one of the most effective nature-based strategies for mitigating global warming while simultaneously improving soil health and enhancing agricultural sustainability. By quantifying soil carbon stocks, the carbon storage capacity of soils can be monitored, enabling the assessment of temporal changes and the implementation of appropriate management practices to enhance long-term carbon sequestration.

Soil carbon stocks refer to the total amount of carbon stored in the soil. Soil carbon is generally divided into two major pools: Soil organic and inorganic carbon pools. The primary source of soil carbon is vegetation. Through photosynthesis, plants capture atmospheric CO_2 and transfer carbon into the soil through roots, litter, and crop residues. Soil inorganic carbon consists primarily of carbonates such as Calcium carbonate ($CaCO_3$) and Magnesium carbonate ($MgCO_3$). In arid and semi-arid regions, inorganic carbon may constitute a substantial proportion of total soil carbon storage.

Globally, soils represent the largest terrestrial carbon reservoir, storing approximately 1500–2400 Pg C as soil organic carbon (SOC) and 700–1000 Pg C as soil inorganic carbon (SIC) (Lal, 2004). More recent estimates indicate SOC stocks of approximately 1500–1600 Pg C in the upper 1 m of soil (Lin et al., 2024), while global SIC stocks are estimated at 2305 ± 636 Pg C in the upper 2 m (Huang et al., 2024). These findings highlight the substantial contribution of both organic and inorganic carbon pools to global soil carbon storage.

The standard formula to calculate Soil Organic Carbon (SOC) stock in tons per hectare (t/ha) is:

$$\text{SOC Stock (t/ha)} = \text{SOC(\%)} \times \text{BD (g/cm}^3) \times \text{Depth(cm)} \times 100$$

SOC (%): The organic carbon concentration of the soil by weight (from laboratory analysis).
BD: The soil bulk density

Depth: The thickness of the sampled soil layer in centimeters

100: The conversion factor used to scale the units from (g/cm^2) to (tons/ha)

As soil salinity increases, the capacity of soils to store carbon declines. High salinity adversely affects soil microbial activity, plant growth, and organic matter inputs, resulting in reduced soil organic carbon accumulation and long-term carbon storage (Photo 1). Consequently, increasing soil salinity not only degrades soil quality and agricultural productivity but also diminishes the role of soils as an effective carbon sink, thereby limiting their contribution to climate change mitigation.

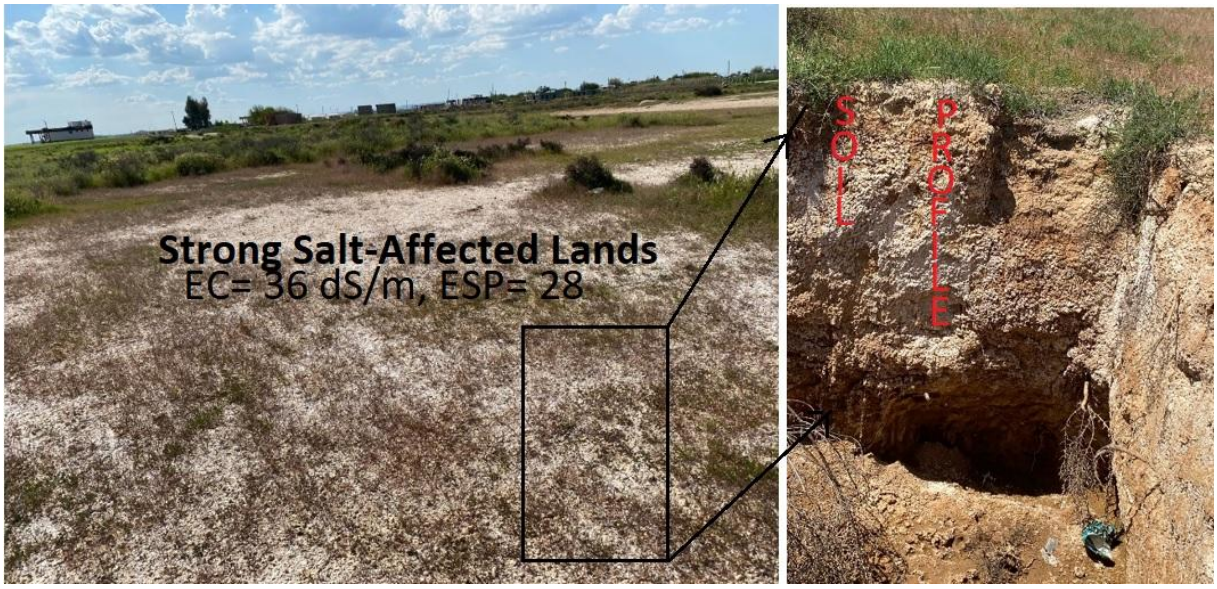


Photo 1. Salt-affected soil surface and profile depth (Foto by Çullu, Harran Plain, Türkiye)

As salinity increases, plant productivity declines, resulting in lower carbon inputs to the soil. Consequently, the accumulation of soil organic carbon becomes limited. Several studies have reported significant reductions in soil carbon stocks in highly saline environments due to decreased biomass production and reduced organic matter inputs (Singh, 2016).



Photo 2. Aggregates breakdown, dispersion and crust formation (Foto by Çullu, Harran Plain, Türkiye)

Stable soil aggregates play a critical role in protecting organic carbon from microbial degradation. High concentrations of exchangeable sodium cause dispersion of clay particles and destruction of soil aggregates (Photo 2). Therefore, aggregate breakdown under saline conditions can accelerate carbon losses from the soil system.

High salt accumulation in soils, particularly under conditions where sodium (Na^+) is the dominant exchangeable cation, adversely affects both soil physical and chemical properties. Excessive sodium promotes the dispersion of clay particles, leading to the breakdown of soil aggregates, deterioration of soil structure, surface sealing, and crust formation. These changes reduce water infiltration, hydraulic conductivity, soil aeration, and root penetration, thereby restricting plant growth and productivity.

Furthermore, salinity and sodicity-induced degradation decrease vegetation cover and biomass production, resulting in lower organic matter inputs to the soil and a consequent decline in soil organic carbon (SOC) stocks. As a result, salt-affected soils often exhibit reduced carbon sequestration capacity and may contribute to increased carbon losses to the atmosphere, with important implications for soil health, ecosystem functioning, and climate change mitigation (Rengasamy, 2006; Qadir et al., 2014; Wong et al., 2010; Choudhary et al., 2022).

Effects of Salinity on Soil Microbial Biomass

Soil microorganisms, including bacteria, fungi, actinomycetes, and archaea, are fundamental components of soil ecosystems and play a critical role in maintaining soil fertility and ecosystem functioning. These microbial communities are involved in organic matter decomposition, nutrient cycling, humus formation, and carbon stabilization. Microbial biomass represents the living fraction of soil organic matter and serves as a sensitive indicator of soil health and biological activity.

Soil salinity is one of the major environmental stresses affecting microbial communities. Elevated concentrations of soluble salts increase the osmotic potential of the soil solution, making water less available to microorganisms. Under saline conditions, microbial cells experience osmotic stress, cellular dehydration, ionic toxicity, and increased energy demands for osmotic regulation. As a result, microbial growth, reproduction, and metabolic activity are often significantly reduced (Photo 3).

Numerous studies have demonstrated that increasing soil salinity leads to a decline in microbial biomass carbon (MBC) and alters the composition and diversity of soil microbial communities (Wichern et al., 2006; Rath and Rousk, 2015). Salt-sensitive microbial populations generally decrease, while only a limited number of halotolerant and halophilic microorganisms can survive and remain active. Consequently, total microbial abundance and biological activity tend to decline as salinity levels increase.

The reduction in microbial biomass has important implications for soil functioning. Lower microbial activity decreases organic matter decomposition rates and disrupts nutrient cycling processes, ultimately reducing soil productivity. Furthermore, diminished microbial biomass weakens the biological mechanisms responsible for carbon sequestration and long-term soil carbon stabilization. Therefore, salinity-induced reductions in microbial biomass

contribute not only to soil degradation but also to declines in soil organic carbon storage and ecosystem resilience.



Photo 3. Salt-affected soil surface with weak plant cover (Photo by Çullu, Harran Plain, Türkiye)

Effects of Salinity on Soil Enzymatic Activity

Soil enzymes are biochemical catalysts involved in nutrient cycling and organic matter transformation. Reduced enzyme activity slows organic matter transformation and impairs the formation of stable soil carbon pools. Studies have reported reductions ranging from 20% to 80% in enzymatic activities under severe salinity conditions (Rietz and Haynes, 2003).

Carbon Use Efficiency (CUE) is defined as the proportion of assimilated carbon converted into microbial biomass rather than released as carbon dioxide through respiration.

The simplified equation is:

$$CUE = \frac{Microbial\ Growth}{Microbial\ Growth + Respiration}$$

High CUE values indicate: Efficient carbon utilization, greater microbial biomass production, increased soil carbon storage.

Low CUE values indicate: Greater carbon losses through respiration, lower microbial growth, reduced carbon sequestration.

Under saline conditions, microorganisms allocate substantial amounts of energy to survival mechanisms such as:Osmoregulation, Ion transport, Cellular repair.

As a result: Growth decreases, Respiration costs increase, Carbon Use Efficiency declines.

Lower CUE means that a larger fraction of carbon is released to the atmosphere as CO_2 rather than being incorporated into microbial biomass or stable soil organic matter (Manzoni et al., 2012). Consequently, salinity reduces the efficiency of soil carbon storage mechanisms.

Soil Salinity, Nitrogen Fertilization and Greenhouse Gas Emissions

Soil salinity affects greenhouse gas emissions by altering microbial activity, carbon cycling, and nutrient transformations. Carbon dioxide (CO_2) emissions originate mainly from microbial respiration, root respiration, and organic matter decomposition. Although high salinity can suppress microbial activity and soil respiration, it also reduces plant growth and organic matter inputs, leading to long-term declines in soil carbon stocks (Rengasamy, 2006; Choudhary et al., 2022). Methane (CH_4) emissions are generally lower in saline soils because sulfate-reducing bacteria often outcompete methanogenic microorganisms under saline conditions (Poffenbarger et al., 2011).

Nitrous oxide (N_2O) emissions are strongly influenced by nitrogen fertilization in salt-affected soils. Salinity reduces plant nitrogen uptake efficiency, leaving more nitrogen available for microbial nitrification and denitrification processes. Consequently, excessive nitrogen fertilization can increase N_2O emissions, particularly under moderately saline and poorly aerated conditions (Butterbach-Bahl et al., 2013). Given the high global warming potential of N_2O, inefficient nitrogen management can substantially increase the environmental impact of saline agricultural systems (IPCC, 2021).

The relationship between salinity and climate change is bidirectional. Climate change promotes salinization through increased drought, evaporation, and saltwater intrusion, while salinity reduces vegetation productivity, microbial biomass, and soil organic carbon stocks, thereby weakening the soil's capacity to act as a carbon sink (Qadir et al., 2014; Wichern et al., 2006). Therefore, improving salinity management and optimizing nitrogen fertilizer use are essential for enhancing carbon sequestration and mitigating greenhouse gas emissions in salt-affected soils.

Management Strategies for Enhancing Carbon Stocks in Saline Soils

Improving carbon storage in saline soils requires integrated management practices that address both salinity reduction and soil quality enhancement. Physical approaches such as

improving drainage systems, leaching excess salts, and controlling groundwater levels help reduce salt accumulation and create favorable conditions for plant growth. Biological strategies, including the cultivation of salt-tolerant plants, cover crops, and agroforestry systems, increase biomass production and organic carbon inputs to the soil. In addition, organic amendments such as farmyard manure, compost, crop residues, and biochar contribute to soil organic carbon accumulation and improve soil structure. Among these amendments, biochar has received considerable attention due to its ability to increase soil carbon stocks, enhance microbial habitats, improve aggregate stability, and reduce greenhouse gas emissions. Collectively, these management practices can enhance soil carbon sequestration, improve soil health, and increase the resilience of saline soils to environmental stresses.

Conclusions

Soil salinity is a major environmental challenge affecting soil carbon stocks, microbial biomass, enzymatic activity, and greenhouse gas emissions. Increased salinity reduces vegetation productivity, limits carbon inputs, alters microbial communities, decreases Carbon Use Efficiency, and lowers the capacity of soils to store carbon.

Because soils represent the largest terrestrial carbon reservoir, salinity-induced reductions in soil carbon stocks have important implications for climate change mitigation. Sustainable management and reclamation of salt-affected soils can improve carbon sequestration, restore ecosystem functioning, and contribute to long-term environmental sustainability.

References

Choudhary, O. P., Ghuman, B. S., Bijay-Singh, Thuy, N. T., & Buresh, R. J. (2022). Soil salinity, sodicity, and their impacts on soil carbon dynamics and ecosystem sustainability. *Land Degradation & Development*, 33, 2501–2518. https://doi.org/10.1002/ldr.4370

FAO. (2021). *Global Map of Salt-Affected Soils (GSASmap) Version 1.0*. Food and Agriculture Organization of the United Nations, Rome.

Huang, Y., Song, X., Wang, Y.-P., Canadell, J. G., Luo, Y., Ciais, P., Chen, A., Hong, S., Wang, Y., Tao, F., Li, W., Xu, Y., Mirzaeitalarposhti, R., Elbasiouny, H., Savin, I., Shchepashchenko, D., Viscarra Rossel, R. A., Goll, D. S., Chang, J., Zhang, G.-L. (2024). Size, distribution, and vulnerability of the global soil inorganic carbon. *Science, 384*(6692), 233–239. https://doi.org/10.1126/science.adi7918

IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677), 1623–1627. https://doi.org/10.1126/science.1097396

Lin, Z., Dai, Y., Mishra, U., Wang, G., Shangguan, W., Zhang, W., & Qin, Z. (2024). Global and regional soil organic carbon estimates: Magnitudes and uncertainties. *Pedosphere, 34*(4), 685–698. https://doi.org/10.1016/j.pedsph.2023.06.005

Qadir, Quillérou, E., Nangia, V., Murtaza, G., Singh, M., Thomas, R. J., Drechsel, P., & Noble, A. D. (2014). Economics of salt-induced land degradation and restoration. *Natural Resources Forum*, 38(4), 282–295. https://doi.org/10.1111/1477-8947.12054

Rath, K. M., & Rousk, J. (2015). Salt effects on the soil microbial decomposer community and their role in organic carbon cycling: A review. *Soil Biology and Biochemistry*, 81, 108–123. https://doi.org/10.1016/j.soilbio.2014.11.001

Rengasamy, P. (2006). World salinization with emphasis on Australia. *Journal of Experimental Botany*, 57(5), 1017–1023. https://doi.org/10.1093/jxb/erj108 *(Not: Listenin sonundaki mükerrer/kopya olan kayıt temizlenmiştir)*

Rengasamy, P. (2010). Soil processes affecting crop production in salt-affected soils. *Functional Plant Biology*, 37(7), 613–620. https://doi.org/10.1071/FP09249

Rietz, D. N., & Haynes, R. J. (2003). Effects of irrigation-induced salinity and sodicity on soil microbial activity. *Soil Biology and Biochemistry*, 35(6), 845–854. https://doi.org/10.1016/S0038-0717(03)00125-1

Singh, K. (2016). Microbial and enzyme activities of saline and sodic soils. *Land Degradation & Development*, 27(3), 706–718. https://doi.org/10.1002/ldr.2385

Wichern, J., Wichern, F., & Joergensen, R. G. (2006). Impact of salinity on soil microbial communities and decomposition processes. *Geoderma*, 137(1–2), 100–108. https://doi.org/10.1016/j.geoderma.2006.08.001

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