

Commentary

Soil microbiome resilience under anthropogenic stressors

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Soil is the foundation of terrestrial ecosystems and its microbiome represents one of the most diverse and functionally significant communities on Earth. The soil microbiome plays an indispensable role in nutrient cycling, carbon sequestration, organic matter decomposition, soil fertility maintenance and plant health regulation. However, anthropogenic stressors such as agricultural intensification, pollution, climate change and urbanization increasingly threaten soil microbial diversity and functionality. While many disturbances lead to microbial dysbiosis, the soil microbiome demonstrates remarkable resilience, maintaining or recovering ecosystem functions through mechanisms like functional redundancy, horizontal gene transfer, microbial interactions and symbioses. This article explores the nature of soil microbiome resilience under anthropogenic pressures, highlighting both its adaptive capacity and its vulnerabilities. Understanding these dynamics is essential for sustaining soil health, global food production and climate regulation in the Anthropocene.

Keywords: Soil microbiome, Resilience, Anthropogenic stressors, Agriculture, Pollution, Climate change, Urbanization, Functional redundancy, Bioremediation, Ecosystem stability.

Introduction

Soil is far more than an inert substrate supporting plant growth; it is a living, breathing ecosystem that underpins terrestrial life. Central to this ecosystem is the soil microbiome, an immensely diverse and dynamic community of bacteria, archaea, fungi, protozoa and viruses. A single gram of healthy soil may harbor billions of microbial cells and thousands of distinct species, representing a staggering level of biodiversity. These microorganisms mediate critical ecological functions including decomposition of organic matter, nutrient mineralization, nitrogen fixation, carbon sequestration and the suppression of soil-borne pathogens. Beyond their ecological contributions, soil microorganisms also provide genetic and biochemical resources that are invaluable for biotechnology, medicine and agriculture (Seleiman MF, et al. 2021).

Despite its importance, the soil microbiome is increasingly under pressure from anthropogenic activities. Human-driven environmental changes—ranging from agricultural intensification and industrial pollution to climate change and urban expansion—alter soil physicochemical properties and impose novel stressors on microbial communities. These disturbances often reduce microbial diversity, disrupt ecological interactions and impair soil functions. Yet, unlike many aboveground ecosystems, the soil microbiome frequently demonstrates resilience: the capacity to resist stress, recover after disturbance and maintain ecosystem functionality (Veresoglou SD, et al. 2022). Resilience is mediated by factors such as microbial adaptability, ecological redundancy, gene exchange and cooperative interactions. However, resilience has thresholds; excessive or prolonged disturbances can push microbial communities into degraded states that are difficult to reverse.

Description

Agriculture represents one of the most significant human interventions in soil ecosystems. The widespread use of chemical fertilizers, pesticides, herbicides and monoculture farming systems has profound consequences for soil microbial communities. Excessive inputs of nitrogen and phosphorus alter nutrient availability, often reducing microbial diversity and favoring fast-growing taxa specialized in high-nutrient conditions. This phenomenon, known as community homogenization, reduces the functional diversity of soils, making them more vulnerable to subsequent stress. Pesticides and herbicides, while designed to target pests and weeds, exert collateral effects on non-target microorganisms, suppressing enzymatic activities, impairing organic matter decomposition and disrupting nitrogen fixation (Chen Y, et al. 2022). Intensive tillage further exacerbates microbial stress by breaking soil aggregates, exposing organic matter to rapid decomposition and disturbing fungal hyphae, particularly arbuscular mycorrhizal fungi that are critical for plant nutrition.

Industrial activities, mining, urban waste disposal and intensive agriculture contribute to the accumulation of pollutants in soils, particularly heavy metals, hydrocarbons, plastics and pharmaceuticals. Heavy metals such as cadmium, lead and mercury are persistent and non-biodegradable, exerting chronic toxicity on soil microorganisms by binding to enzymes, disrupting cell membranes and damaging DNA. These stressors often reduce microbial biomass and diversity, impairing processes like organic matter decomposition and nitrogen cycling. However, certain microorganisms evolve resistance mechanisms including efflux pumps, intracellular sequestration and enzymatic detoxification. Such adaptations allow not only survival but also active participation in bioremediation, where resistant microbes immobilize or transform contaminants, facilitating ecosystem recovery. Similarly, organic pollutants such as petroleum hydrocarbons create selective environments favoring hydrocarbon-degrading bacteria like *Pseudomonas* and *Rhodococcus*. Pharmaceutical residues, particularly antibiotics, exert additional pressures by selecting for resistant strains. Soil microbiomes become hotspots for antibiotic resistance genes (ARGs), which are exchanged among taxa via horizontal gene transfer (Nessner Kavamura V, et al. 2013). This phenomenon, while supporting microbial resilience under antibiotic stress, poses major risks for human and animal health, as ARGs may transfer to pathogenic bacteria. Thus, resilience in polluted soils is often a double-edged sword: it enables microbial persistence but may exacerbate global antimicrobial resistance.

Climate change introduces multifaceted stressors to soil ecosystems, including rising temperatures, altered precipitation regimes, increased drought frequency and extreme weather events. Warming accelerates microbial metabolism, leading to faster organic matter decomposition and greater release of greenhouse gases such as CO₂, methane and nitrous oxide. This creates a positive feedback loop that intensifies climate change. Drought is particularly detrimental, reducing soil moisture, impairing nutrient diffusion and inducing microbial dormancy or mortality. Bacterial populations often decline under drought, while fungi, with their filamentous structures and osmotic tolerance, become relatively dominant (Bouskill NJ, et al. 2013). This shift alters soil functionality, particularly in terms of carbon and nitrogen cycling. Conversely, flooding induces anoxic conditions that favor anaerobic microbes such as denitrifiers and methanogens, increasing emissions of potent greenhouse gases.

Conclusion

The soil microbiome represents a cornerstone of terrestrial ecosystem stability and global sustainability, yet it faces unprecedented challenges from anthropogenic stressors. Agricultural intensification, pollution, climate change and urbanization disrupt microbial communities, reducing biodiversity and impairing essential ecological functions. Nonetheless, the soil microbiome demonstrates remarkable resilience through mechanisms such as functional redundancy, horizontal gene transfer, microbial cooperation and plant-microbe symbioses. These adaptive processes allow soils to maintain or recover functionality even under significant stress. However, resilience is not limitless; prolonged or extreme disturbances can surpass microbial adaptive capacity, leading to irreversible degradation. Recognizing the dual reality of microbial resilience and vulnerability is critical for designing effective land management and restoration strategies. Sustainable agricultural practices, pollution control, climate adaptation measures and ecological restoration interventions are essential to safeguard soil microbiomes.

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Conflict of Interest

The authors declare no conflict of interest.

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