TOXIC DIALOGUES: HERBICIDES, MICROBIAL VOICES, AND THE ECOSYSTEM’S RESPONSE

Daniela Todevska[1], Natalija Atanasova-Pancevska[2],*
[1] Goce Delcev University, Stip, Faculty of Agriculture, Department for Plant Production, Stip, Republic of North Macedonia
[*]corresponding author e-mail: daniela.dimovska@ufd.edu.mk, ddimovska1@gmail.com
[2]Ss. Cyril and Methodius University in Skopje, Faculty of Natural Sciences and Mathematics – Skopje, Institute of Biology, Department of Microbiology and Microbial Biotechnology, Skopje, North Macedonia

ABSTRACT

Herbicides, long heralded as precise tools in agricultural management, leave behind echoes that reverberate through the most intimate layers of ecological networks. This study explores how herbicidal interventions—especially those involving compounds like glyphosate—silently alter microbial communities that anchor essential ecosystem functions. These non-target effects begin at the microscopic scale, where shifts in soil microbiome composition interrupt vital processes such as nutrient cycling, rhizosphere signaling, and plant–soil feedback mechanisms.

Framed through a microbiome-centric lens, we present a synthesis of recent studies alongside conceptual models illustrating how herbicide residues serve not only as chemical stressors, but as agents that restructure the metabolic dialogues among microbes and their hosts. Alterations in microbial diversity and function affect plant vitality, reduce resilience to biotic and abiotic stresses, and cascade upward to influence animal performance, herbivory dynamics, and pollination success. As herbicides disrupt these finely tuned interdependencies, we observe potential tipping points that may reshape ecosystem trajectories and even influence microbial and host evolution.

More than collateral damage, microbial responses to herbicidal exposure represent a silent rebellion—one with the power to mediate or magnify ecological instability. We advocate for integrative strategies that acknowledge microbiome health as a central criterion in agrochemical risk assessments. Understanding these subterranean symphonies is essential for mitigating the long-term consequences of anthropogenic disturbance and for crafting sustainable, microbe-conscious stewardship of ecosystems.

Keywords: microbiome, herbicides, soil microbial networks, environmental resilience, agrochemical impact, microbe-mediated risk

INTRODUCTION

Herbicides have revolutionized modern agriculture by enabling targeted and efficient weed control, contributing significantly to crop productivity and food security. Among these, glyphosate stands as one of the most extensively used broad-spectrum herbicides worldwide due to its effectiveness and non-selective inhibition of the 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) enzyme in the shikimate pathway (Duke and Powles, 2008).

Soil microbial communities, particularly those inhabiting the rhizosphere, play a pivotal role in maintaining ecosystem functions. These communities mediate nutrient cycling, organic matter decomposition, and intricate plant–microbe interactions that influence plant growth, health, and resistance to environmental stressors (Berg et al., 2020). Disturbances to microbial composition and diversity—whether through direct toxicity or altered plant exudation patterns—can ripple through the entire ecosystem. Emerging evidence suggests that herbicide residues can suppress mycorrhizal colonization, shift bacterial community structures, and increase plant susceptibility to soil-borne pathogens (Zaller et al., 2014; Newman et al., 2016; Johal and Huber, 2009).

Herbicides may induce long-term restructuring of microbial networks, with implications for microbial evolution, functional redundancy, and overall soil resilience (Timmis et al., 2019). Furthermore, chronic exposure to glyphosate and similar compounds may drive microbial adaptation or resistance, potentially reducing the soil’s capacity to buffer abiotic stressors such as drought or nutrient depletion (Schlatter et al., 2017).

This paper synthesizes recent findings on the impact of herbicides—especially glyphosate—on soil microbial communities. It aims to elucidate the biochemical, ecological, and evolutionary consequences of microbial disruption, and to advocate for frameworks that prioritize microbial integrity as a cornerstone of sustainable agriculture.

HERBICIDES AND THEIR LEGACY

Herbicides have revolutionized modern agriculture by enabling efficient weed control, reducing labor costs, and increasing crop yields. Since the introduction of synthetic herbicides like 2,4-D in the 1940s, over 270 active ingredients have been commercialized, shaping global farming practices and food systems (Mesnage et al, 2021; U.S. EPA, 2004). Herbicides have played a central role in modern agricultural intensification, with compounds like glyphosate, atrazine, and 2,4-D becoming dominant tools in weed control (Duke and Powles, 2008). Glyphosate, in particular, has been praised for its broad-spectrum action and post-emergent use. However, its primary target—the shikimate pathway, absent in animals but present in most plants and microbes—raises significant concerns about non-target effects on microbial communities (van Bruggen et al., 2018).

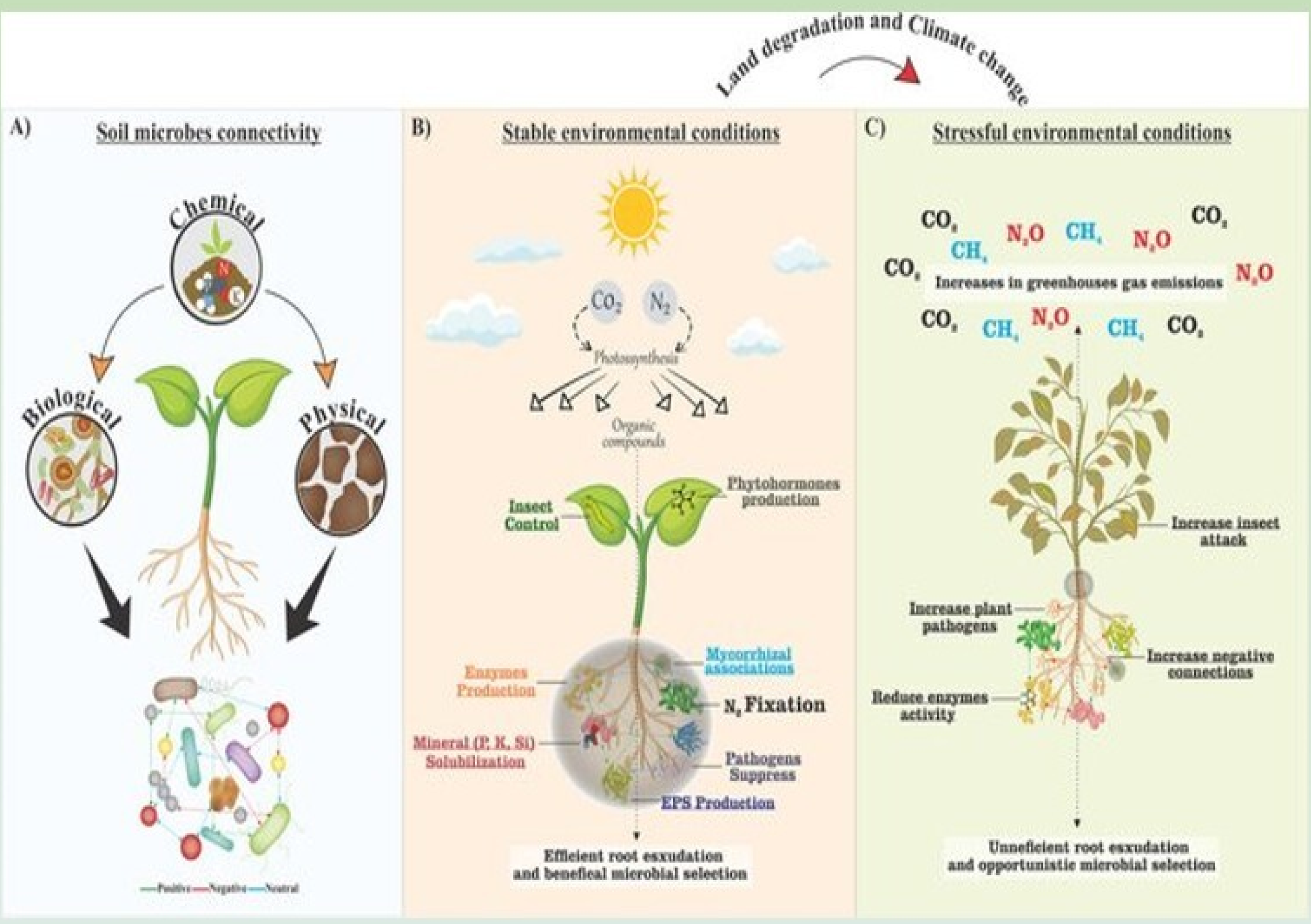

Figure 1. The intricate connections between soil biodiversity and plants. a These interactions are influenced, including chemical, physical, and biological variability. b In a stable ecosystem with no or low human disturbances, plants can effectively recruit their microbial communities, primarily facilitated through rhizosphere exudation and selection processes. This plant-soil biodiversity interactions catalyze multiple ecosystem processes such as enhanced enzyme activity, solubilization, nitrogen fixation, and disease suppressiveness. However, land degradation and ongoing climate changes disrupt these interactions, leading to an increased negative correlation among taxa. c As a result, plants become more vulnerable to harmful and opportunistic agents like insects and pathogens (from Pedrinho et al., 2024).

Despite their utility, herbicides pose significant risks, as s**oil degradation** (long-term use alters microbial communities, reduces biodiversity, and impairs nutrient cycling), w**ater contamination** (runoff and leaching introduce herbicide residues into aquatic ecosystems, affecting non-target organisms like amphibians, fish, and invertebrates) and r**esistance development** (overuse has led to herbicide-resistant weed populations, complicating management and increasing chemical dependency (Mesnage and Antoniou, 2017).

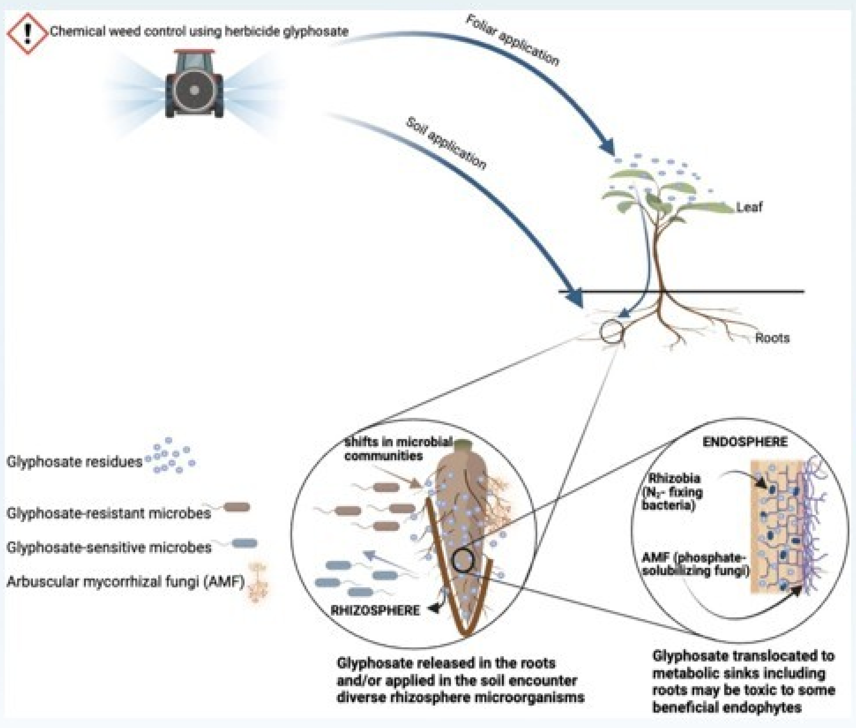

Figure 2. Possible interference of glyphosate with microbial communities in the rhizosphere and endosphere (from Sibalekile et al., 2025).

CONCLUSION

Herbicides, while instrumental in modern agriculture, pose complex ecological challenges that extend far beyond weed control. Their influence on soil microbial consortia—especially in the rhizosphere—triggers cascading effects that alter nutrient cycles, suppress beneficial taxa, and potentially promote antibiotic resistance. These microbial disruptions reshape plant–soil interactions, reduce ecosystem resilience, and compromise vital services such as pollination, pest regulation, and carbon sequestration.

Conventional herbicide risk assessments often overlook these microbiome-mediated effects, focusing narrowly on chemical residues and plant toxicity endpoints. Integrating microbiome-centric metrics into regulatory frameworks—such as microbial diversity indices, functional group profiling, and gene transfer monitoring—offers a path toward more holistic ecological stewardship.

A microbiologically informed approach to weed management can help sustain soil health, foster agroecosystem stability, and safeguard public and environmental well-being. The microbial voice, long silent in regulatory discourse, must now become a guiding force in rethinking agricultural sustainability.

THE RHİZOSPHERE MİCROBİOME: KEYSTONE OF SOİL HEALTH

The rhizosphere microbiome—microorganisms that inhabit the narrow zone surrounding plant roots—plays a foundational role in nutrient cycling, stress response, and plant immunity (Berg et al., 2020).

The specific functions of soil microbes can be divided into seven major groups (Berendsen et al., 2012; Cheng et al., 2022; Kumar et al., 2022):

Decomposition: Microbes—bacteria and fungi—break down organic matter such as crop residues, insect carcasses, animal manure, and other organic materials in the soil. .

Nutrient cycling: Microbes are involved in the circulation of essential nutrients in the soil. They can “unlock” nutrients that are locked up in forms inaccessible to the plant and therefore promote the availability of nutrients for plant absorption.

Soil structure and aggregation: Certain bacteria and fungi produce sticky substances such as polysaccharides that bind soil particles together, forming aggregates. Soil aggregates improve soil structure, porosity, and water-holding capacity, allowing for better root penetration and aeration.

Disease suppression: Certain beneficial bacteria and fungi called biocontrol agents can suppress soil-borne pathogens and pests.

Phytohormone Production: Some soil microbes can produce plant hormones in the soil, many of which are called "plant growth regulators" or PGRs. Hormones such as auxin, cytokinin, and gibberellin are known to support plant growth, yield, and stress tolerance when applied as foliar products.

Symbiotic relationships: Many plants form beneficial symbiotic relationships with soil microbes.

Salinity regulation: Some microbes have adapted to survive in saline environments and possess mechanisms to tolerate high salt concentrations.

These microbial consortia are sensitive to external chemical inputs and serve as early indicators of soil disturbance (Kurenbach et al., 2021; Yang et al., 2023; El-Helow et al., 2024). Herbicides can alter:

- Microbial richness and evenness
- Community composition (e.g., shifts from *Proteobacteria* to *Actinobacteria*)
- Enzyme activity, such as dehydrogenase and phosphatase
- Plant–microbe communication, such as root exudate signaling

ADAPTIVE RESPONSES AND MICROBIAL RESISTANCE

Repeated herbicide exposure can drive **microbial adaptation**, including **degradation capability evolution** (e.g., *Pseudomonas* acquiring glyphosate degradation genes), **shift toward resistant or resilient taxa or horizontal gene transfer** of resistance traits. While such adaptations may improve degradation efficiency, they may also alter **microbial network interactions**, affecting ecological balance (Rousidou et al., 2013). Microbial shifts may feed back into **plant susceptibility**, nutrient cycles, and carbon dynamics, especially under climate stress.

HERBICIDE EFFECTS ON ECOSYSTEM-LEVEL PROCESSES

While the rhizosphere is a well-studied hotspot of microbial activity, recent research reveals that microbial alterations extend far beyond root zones, influencing **macroecological processes** such as nutrient cycling, carbon sequestration, biodiversity patterns, and ecosystem resilience. These changes are not confined to local soil patches—they ripple across landscapes and biomes, shaping ecological trajectories at multiple scales (Wang and Zou, 2024; Mohanram and Kumar, 2019). Beyond the rhizosphere, microbial alterations influence **macroecological processes, such as carbon sequestration** via changes in microbial respiration, **nitrogen and phosphorus cycling and soil aggregation and erosion resistance.** Several studies report that herbicide-induced microbial imbalance can decrease **soil organic matter**, reduce **greenhouse gas buffering capacity**, and lower **crop resilience to drought and pests** (Ghimire et al., 2020). These indirect impacts challenge the long-held belief in herbicide neutrality toward ecosystem services

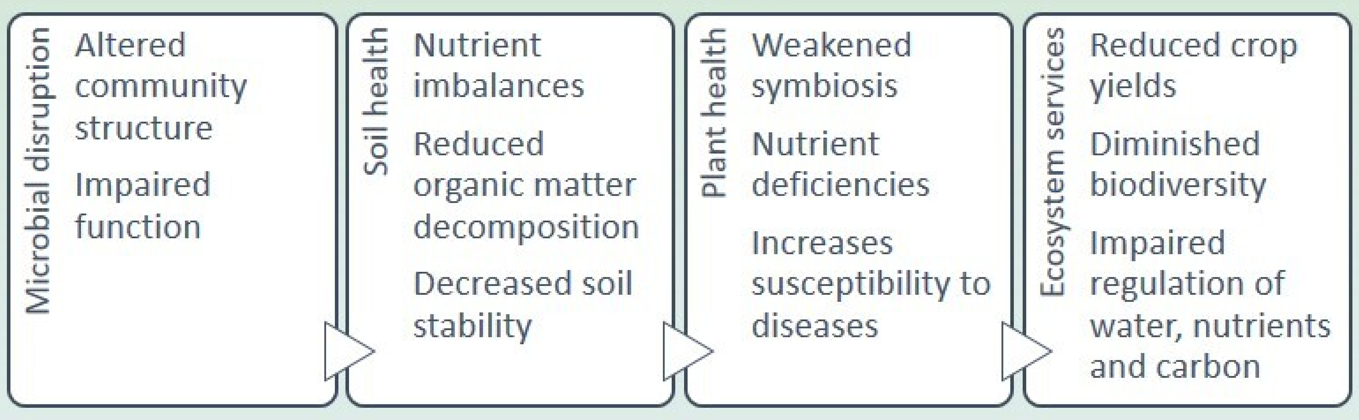

Figure 3. Ecosystem model showing cascading impacts of microbial disruption—soil health, plant health, insect interactions, and ecosystem services.

Assessment Domain	Current Gaps
Soil Health	Focused mainly on chemical residues and physical structure
Non-target Effects	Limited consideration of microbial collateral damage
Temporal Dynamics	Assessed via static endpoints (e.g., residue half-life)
Bioindicator Integration	Rarely utilizes microbial indicators
Interaction Effects	Ignores chemical synergy or antagonism with microbial networks
Resistance Development	Focused on weed resistance only
Ecosystem Services Impact	Underrepresents microbial contributions to services
Standardized Protocols	Lacks harmonized microbial toxicity assays

Table 1. Gaps in Herbicide Risk Assessment.

REFERENCES

Berendsen, R.L., Pieterse, C.M. and Bakker, P.A. 2012. The rhizosphere microbiome and plant health. *Trends in plant science*, *17*(8), pp.478-486 https://doi.org/10.1016/j.tplants.2012.04.001.

Berg, G., Rybakova, D., Fischer, D., Cernava, T., Vergès, M.C.C., Charles, T., Chen, X., Cocolin, L., Eversole, K., Corral, G.H. and Kazou, M. 2020. Microbiome definition re-visited: old concepts and new challenges. *Microbiome*, *8*(1), p.103. https://doi.org/10.1186/s40168-020-00875-0.

Cheng, Y., Chen, Y., Zhang, Q., Xu, X., & Hu, F. 2022. Keystone microbiome in the rhizosphere soil reveals the effect of long-term conservation tillage. *Plant and Soil*. https://doi.org/10.1007/s11104-022-05297-5.

Duke, S.O. and Powles, S.B. 2008. Glyphosate: a once-in-a-century herbicide. *Pest Management Science: formerly Pesticide Science*, *64*(4), pp.319-325.. https://doi.org/10.1002/ps.1518.

El-Helow, E. R., Omar, H. A., El-Shora, H. M., et al. 2024. Microbial degradation of pesticides in agricultural environments. *WSEAS Transactions on Systems and Applications*, *21*, Article a165115-1269. https://wseas.com/journals/msa/2024/a165115-1269.pdf.

Johal, G. S., & Huber, D. M. 2009. Glyphosate effects on diseases of plants. *European Journal of Agronomy*, *31*(3), 144–152. https://doi.org/10.1016/j.eja.2009.02.004.

Kumar, A., Singh, M., & Kumari, S. 2022. Rhizospheric microorganisms: The gateway to a sustainable plant health. *Frontiers in Sustainable Food Systems*, *6*, Article 925802. https://doi.org/10.3389/fsufs.2022.925802.

Kurenbach, B., Marjoshi, D., Amábile-Cuevas, C. F., Ferguson, G. C., Godsoe, W., Gibson, P., & Heinemann, J. A. 2021. Herbicide selection promotes antibiotic resistance in soil microbiomes. *Molecular Biology and Evolution*, *38*(6), 2337–2350. https://doi.org/10.1093/molbev/msab057.

U.S. Environmental Protection Agency. 2004. *Herbicides*. https://www.epa.gov/caddis/herbicides

Mesnage, R., Székács, A., & Zaller, J. G. 2021. Herbicides: Brief history, agricultural use, and potential alternatives for weed control. In *Herbicides* (pp. 1-20). Elsevier. . https://doi.org/10.1016/B978-0-12-823674-1.00002-X.

Newman, M. M., Hoilett, N., Lorenz, N., Dick, R. P., Liles, M. R., Ramsier, C., & Kloepper, J. W. 2016. Glyphosate effects on soil rhizosphere-associated bacterial communities. *Science of the Total Environment*, *543*, 155-160. https://doi.org/10.1016/j.scitotenv.2015.11.008.

Roesch, L. F. W., Camargo, F. A. O., & Oliveira, M. R. R. 2023. Rhizosphere microbiome: Plant–microbial interactions for resource acquisition. *Journal of Agricultural and Biological Sciences*, *133*(5), 2864–2878. https://doi.org/10.1093/jambio/jmad005.

Sibalekile, A., Araya, T., Castillo Hernandez, J., & Kotzé, E. 2025. Glyphosate-microbial interactions: metagenomic insights and future directions. *Frontiers in Microbiology*, *16*, 1570235. doi: 10.3389/fmicb.2025.1570235. PMID: 40485833; PMCID: PMC12142625.

Zhao, Y., Wang, Y., Lu, J., Zhu, B., & Li, A. D. 2025. Exploring the Ecological Impacts of Herbicides on Antibiotic Resistance Genes and Microbial Communities. *Life*, *15*(4), 547.

Yang, Y., Wang, Z., et al. 2023. Exploring the ecological impacts of herbicides on antibiotic resistance genes and microbial communities. *Life*, *13*(4), 547. https://doi.org/10.3390/life13040547.

Zaller, J. G., Heigl, F., Ruess, L., & Grabmaier, A. 2014. Glyphosate herbicide affects belowground interactions between earthworms and symbiotic mycorrhizal fungi in a model ecosystem. *Scientific reports*, *4*(1), 5634.

Zhao, Y., Wang, Y., Lu, J., Zhu, B., & Li, A. D. 2025. Exploring the Ecological Impacts of Herbicides on Antibiotic Resistance Genes and Microbial Communities. *Life*, *15*(4), 547. https://doi.org/10.3390/life15040547.

Van Bruggen, A. H., He, M. M., Shin, K., Mai, V., Jeong, K. C., Finckh, M. R., & Morris Jr, J. G. 2018. Environmental and health effects of the herbicide glyphosate. *Science of the total environment*, *616*, 255-268.

Wang, Y., & Zou, Q. 2024. Deciphering microbial adaptation in the rhizosphere: Insights into niche preference, functional profiles, and cross-kingdom Co-occurrences. *Microbial Ecology*, *87*(1), 74. https://doi.org/10.1007/s00248-024-02390-3.

Wend, K., Zorrilla, L., Freimoser, F. M., & Gallet, A. 2024. Microbial pesticides–challenges and future perspectives for testing and safety assessment with respect to human health. *Environmental Health*, *23*(1), 49. https://doi.org/10.1186/s12940-024-01090-2.