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The Ghost in the water: Micro-pollutants and Macro- Impacts of Herbicides on Aquatic health

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Abstract

Herbicides have transformed agricultural weed control, greatly reducing human labor costs and increasing crop yields. However, there are significant ecological concerns associated with their widespread usage, especially for aquatic environments. With a focus on both direct and indirect paths of pollution and injury, this chapter examines the complex effects of herbicides on freshwater habitats. Through runoff, leaching, spray dispersion, and air deposition, herbicides enter aquatic systems and poison non-targeted creatures. Food webs and ecosystem processes are upset when aquatic flora, especially primary producers like algae and macrophytes, experience physiological stress, stunted development, and disturbed photosynthesis. Exposure to herbicides causes behavioral, developmental, and reproductive abnormalities in a variety of fauna, including fish, amphibians, and macroinvertebrates. Because of their complicated life cycles and porous skin, amphibians are particularly vulnerable. Certain chemicals, such as glyphosate and atrazine, have been linked to developmental abnormalities and endocrine disruption. Aquatic food webs and human nutrition depend on fish populations, which are harmed by habitat degradation, bioaccumulation, and physiological harm. When taken as a whole, these results demonstrate the widespread and enduring ecological effects of pesticide contamination in aquatic habitats. In order to reduce herbicide hazards and protect aquatic biodiversity, the chapter emphasizes the critical necessity for integrated management techniques and regulatory control.

Introduction

Managing invasive plants has been a constant challenge since the dawn of agriculture by prehistoric beings. Due to this worry, people have developed various solutions, from using crude tools to applying lethal chemicals known as "herbicides." Herbicides reduce labor-intensive manual weeding and elevate the production and quality of cultivation. Herbicides have detrimental effects on the environment and human health, despite their effectiveness in eradicating weeds and undesirable plants. Because of their susceptibility to volatilization, leaching, and runoff, numerous herbicides may build up in soils, waterways, and tissue. These chemicals also have the potential to damage unexpected life forms (Mohd Ghazi *et al.*, 2023). The term "Ghost in the water" signifies the unseen detrimental effects of herbicides in water bodies. Herbicides can alter food chains, change patterns of energy flow and nutrient cycling, decrease variability in species and community frameworks, alter the health and endurance of ecosystems, and lower the sustainability of the environment once they are in aquatic ecosystems (Perez *et al.*, 2011).

Herbicides frequently cause phytotoxicity to aquatic species that are not their intended target, like algae and macrophytes. These negative impacts on primary producers can ripple up the food chain, changing the composition of communities. All compounds with herbicidal mode of impact must undergo legal screening on primary producers that are not their target because herbicides explicitly target critical functions in primary producers (Vonk & Kraak, 2020). Herbicides, which are intended to suppress undesirable plant development, can have a major impact on the growth, reproduction, and even survival of both specific and non-target species of plants. Herbicides can upset plant biological systems, perhaps changing plant populations and affecting other creatures that rely on them, even if they are made to kill certain weeds (Boutin *et al.*, 2014).

Although herbicides are good at keeping undesired plants under control, they may also have a direct negative impact on aquatic invertebrates via several processes, such as decreased oxygen levels, changed water chemistry, and direct toxicity. Both invertebrate populations and the aquatic ecology may be negatively impacted by these consequences (Hasenbein *et al.*, 2017).

Herbicides have the potential to affect fish directly or indirectly. Indirectly, it affects fish by eliminating plants that are necessary for their natural environment or as sources of nutrition. Additionally, the oxygen may be dropped to levels that are not sufficient for fish to survive due to the biological oxygen requirement from the decomposing plants. Direct impacts on fish include alterations in behavior, reproductive potential, and physiological system abnormalities. Some herbicides can have long-lasting impacts on fish, although most are not acutely harmful because of their unique plant-targeting mechanisms. These impacts may affect fish survival and population dynamics and might vary from stress and behavioral changes to developmental and reproductive disturbances (Solomon *et al.*, 2013).

This chapter aims to give a broad overview of the state of knowledge regarding herbicides' direct and indirect impacts on the aquatic environment.

Conduits of Ecological Risk: How Herbicides Invade Water Bodies

Agricultural conduct is among the primary causes of herbicide pollution in aquatic environments; however, there are other diffuse and point sources as well. Herbicides can enter adjacent reservoirs through a variety of hydrological and atmospheric channels after being administered to terrestrial ecosystems, contaminating surface and groundwater widely and occasionally permanently (Carter, 2000). The most common routes of herbicides disposal in water bodies are:

1) **Agricultural practices:** The foremost source is drainage from agriculture. Excess herbicides that aren't taken up by crops or soils may be carried from fields into waterways during rainfall or irrigation events. Several variables, including soil type, herbicide composition, rainfall intensity, and application time, affect how much runoff occurs. Erosion is another way through which herbicides

attached to soil particles might get into aquatic systems.

2) **Leaching/Percolation:** Another significant route is leaching, especially for herbicides with limited soil absorption capacity and elevated affinity for water. These substances have the ability to pollute groundwater beneath the soil cover. Because groundwater pollution is persistent, has little natural attenuation, and takes an extended period to recover, it is especially worrying.

3) **Chemical drift/Spray drifts:** When applying herbicides, spray drift happens, particularly when aerial equipment is being used. Wind has the ability to carry tiny droplets and lodge them straight into nearby bodies of water. The danger of contamination from drift can be greatly increased by inappropriate spraying methods.

4) **Chemical deposition from the atmosphere:** An indirect but significant pathway is atmospheric deposition, which involves the dispersion of herbicides from the treated areas and their further airborne transportation. Even at far-flung distances from their initial application locations, these compounds can subsequently be deposited into water bodies by precipitation or particle settling.

Effects of herbicides on aquatic flora

[1] Non-Target Effects and Environmental Variables Influencing Aquatic Plant Sensitivity: Herbicides affect the ecosystem's flora, which is not their intended target. Through disruptions to food web, nutrient cycling, and the health of water, utilization may also have indirect effects on the larger environment. All species of aquatic plants are susceptible to herbicides in water, whereas developing and floating ones can be exposed in the air, and rooted plants and benthic algae can be exposed in sediment. Herbicide dosage, interaction time, chemical characteristics (such as solubility and permanence), and the sensitiveness of certain plant species are some of the variables that affect the impact's magnitude. Acute exposure to large dosages can have an ecological impact, but so can long-lasting exposure to minute quantities. Phytoplankton and free-living submerged plants in water are most vulnerable to soluble herbicides in water (Vonk & Kraak, 2020). Photosystem II inhibitors, including atrazine and bentazone, are among the several herbicides that interfere with photosynthetic processes. These substances impede the movement of electrons within chloroplasts, which results in decreased growth, hampered photosynthesis, and, in extreme situations, plant mortality. Additionally, physiological functions, including pigment production, respiration, and nutrient absorption, can be interfered with by sub-lethal doses (Zhu *et al.,* 2009).

[2] Functional Roles of Macrophytes and Consequences of Herbicide Interference: Herbicide exposure is especially dangerous for aquatic macrophytes, whose survival is essential to freshwater ecosystems. In addition to stabilizing sediments and producing oxygen, these plants provide crucial habitat for a variety of fish and invertebrate species. Herbicide exposure may cause more resistant macrophyte species to multiply while sensitive macrophyte species may decrease, altering the makeup of communities and upsetting the ecosystem's general structure and functionality (Chander *et al.,* 2020). Contact herbicides have the potential to harm cell membranes or prevent certain enzymes that are essential for development and growth. Macrophytes may be directly or indirectly impacted by herbicides. Disruption of photosynthetic reactions, decreased development rates, injury to cells, and even plant death are examples of direct consequences. For instance, systemic herbicides like glyphosate can cause physiological stress by interfering with amino acid synthesis and being absorbed and transported throughout the plant. The 5-enolpyruvyl-shikimate-3-phosphate synthase (EPSPS) enzyme is inhibited by glyphosate-based herbicides, which damage the shikimate pathway and frequently kill plants (Freitas-Silva *et al.,* 2022). Atrazine is often found in aquatic habitats and has been shown to influence aquatic plant and animal reproduction, which in turn affects the general framework of the ecosystem.

Impacts of herbicides on aquatic fauna

Despite their intended use against foreign weeds, herbicides can have unexpected effects on aquatic life because of their durability and prevalence in freshwater environments. Fish, amphibians, macroinvertebrates, and zooplankton are among the aquatic creatures prone to herbicides by direct contact with polluted waters, consumption of polluted food, or uptake through gill membranes. Numerous aquatic creatures may experience diminished growth and reproduction, behavioral and physiological abnormalities, and even death as a result of herbicide exposure.

Based on the species and phase of development, herbicides have a wide range of adverse impacts on aquatic life. Herbicide poisoning can cause numerous kinds of physiological and developmental problems in fish and amphibians, including hormone imbalances, decreased capacity for reproduction, impaired development, and increased death rates. As endocrine inhibitors, several herbicides interfere with the control of reproductive hormones and change the course of normal reproductive growth. Even modest, non-lethal concentrations have the potential to have long-term effects on the population, making early life stages—especially larvae and juveniles—particularly sensitive.

With their critical roles in nutrient cycling and as a major source of nutrition for upper-trophic levels, aquatic macroinvertebrates are essential to the composition and operation of freshwater ecosystems. Even at low doses, herbicides can have a detrimental effect on the eating habits, mobility, respiration, and general survival of multiple macroinvertebrate species. A decrease in the variety or richness of macroinvertebrates is commonly employed as a bioindicator of declining water quality, which usually indicates widespread ecological damage (Rumschlag *et al.*, 2020). In this section, we will study the harmful effects of herbicides on various aquatic species.

[1] Hebicides effects on macroinvertebrates: In aquatic environments, herbicides can have a detrimental effect on macroinvertebrate populations, reducing their variety, distribution, and even leading to malformations. According to a study assessing the cumulative impact of herbicides and insecticides on aquatic ecosystems, streams with higher herbicide concentrations had lower overall biomass shares of Trichoptera and Ephemeroptera relative to streams with lower herbicide concentrations. This demonstrates how the cumulative impacts of food-mediated herbicides on the biomass of vulnerable insect species upset food networks at the ecological level (Liebmann *et al.*, 2024). When bentazone concentrations were applied to plankton and benthic ecosystems, the most impacted group concerning community structure was plankton. With indirect impacts leading to the displacement of big filter feeders by tiny filter feeders, zooplankton was the subsequent most impacted group. This indicates that the herbicide had significant bottom-up impacts, changing the community pattern of primary producers, which subsequently had an indirect impact on important zooplankton species (Grillo-Avila *et al.*, 2025). Hence, from these studies, we conclude that herbicides have harmful effects on aquatic macroinvertebrate fauna.

[2] Impacts on amphibians: Herbicides can enter the bodies of amphibians via their skin, gills, or by consuming tainted food or water. Excessive levels might result in serious destruction of tissues or instant death. Behavior, development, and physiology can all be impacted by even minute doses. For instance, Skin damage and respiratory problems, decreased body mass and delayed growth, altered swimming and foraging behavior can be observed. Glyphosate and atrazine, two often researched herbicides, have demonstrated notable sublethal toxicity in a variety of frog species. Herbicides containing glyphosate, such as Roundup, have the potential to kill a lot of amphibian larvae. According to one study, Roundup killed 96–100% of the larval amphibians after three weeks of exposure (Relyea, 2005). Glyphosate's disruption of normal development and growth represents one of its prominent effects. In both larval and juvenile amphibians, exposure to even trace amounts can slow down development rates, postponing metamorphosis and lowering body size, which may have an impact on subsequent survival and reproduction. Additionally linked to teratogenic effects, glyphosate can result in developmental defects in early life, including limb malformations and craniofacial anomalies. Glyphosate can cause major physiological system disruptions in addition to physical abnormalities. According to certain research, it disrupts metabolic and reproductive systems, resulting in changed hormone levels, decreased fertility, and aberrant gonad development (Paetow *et al.*, 2023).

Being a well-known endocrine disruptor, atrazine, one of the most commonly used herbicides worldwide, may have an impact on the hormonal systems that control amphibian developmental processes and reproduction. The feminization of male frogs is among the most concerning consequences of atrazine exposure. Studies have revealed that it can result in intersex, a condition in which males produce both testes and ovaries, and in certain instances, it can lead to total chemical castration. This happens when testosterone levels are drastically lowered, which hinders the development of characteristics and behaviors unique to males that are necessary for effective reproduction. Alongside these reproductive disturbances, atrazine can also affect juveniles' normal gonadal development, which further skews sex ratios and lowers reproductive fitness in wild populations (Hayes *et al.*, 2006). Hence, from these studies, one can find harmful effects of herbicides on developmental and reproductive pathways in amphibians.

[3] Effects on fish: As important moderators within food webs, fish play an essential role in aquatic environments by regulating the populations of different creatures and preserving ecological equilibrium. Apart from their biological relevance, fish are also useful bioindicators of the health of the environment. Fish populations' existence and condition can indicate the presence of contaminants like herbicides and provide insight into the general health of aquatic ecosystems, since they are susceptible to fluctuations in water quality and chemical pollution. Fish have a vital part in human society in addition to their function in the environment. They assist both food security and economic lives by serving as a significant source of protein and vital nutrients for people worldwide. Herbicides can harm fish by directly harming them, lowering their food supplies, and upsetting their environment. Fish are essential to aquatic systems and human food chains. Additionally, herbicides can build up in fish tissues, resulting in chronic health issues (Solomon, 2013; Travers-Trolet *et al.*, 2025).

At high quantities, herbicides—even those deemed to be relatively low in toxicity—can be detrimental to fish, impairing their ability to survive, develop, and reproduce. By destroying plants that offer vital food and shelter, they can upset aquatic ecosystems, resulting in habitat loss and anomalies in the food chain. Herbicides can affect fish habits, development, and reproductive success even at sublethal concentrations. Over time, some substances may build up in fish tissues, which might endanger human consumers and result in long-term health problems. Herbicides have also been demonstrated to affect such survival-related behaviors as mating, predator prevention, and foraging. They may also occasionally result in histopathological harm to essential organs such as the kidneys, liver, and gills, which would further jeopardize the health and population stability of fish (Yang *et al.*, 2021; Lopes *et al.*, 2022; Ribeiro *et al.*, 2022).

Integrated Strategies for Controlling Herbicide Runoff

It takes a mix of sustainable methods, regulatory actions, and ecological rehabilitation to lessen the negative effects of herbicides on aquatic habitats. Adopting Best Management Practices (BMPs) in agriculture, such as integrated weed control, precision application, and appropriate scheduling to minimize runoff, is one of the key tactics. Creating riparian vegetation and buffer zones aids in filtering pollutants before they enter water bodies. Herbicides are broken down by plants and bacteria in phytoremediation and artificial wetlands, which also act as natural filters. Better herbicide solutions, including targeted or compostable chemicals, can lessen toxicity and longevity in the environment. Controlling herbicide contamination requires stricter laws that include concentration limits, environmental risk assessments, and periodic monitoring. Sustainable alternatives and appropriate use may be encouraged through public education. Finally, continuous monitoring and research are essential for comprehending long-term impacts and directing adaptive management initiatives. When combined, these strategies support the preservation of aquatic plants, animals, and the general health of the environment.

Research Gaps and Future Outlook

Comprehensive evaluations of newly developed herbicides and their prolonged, persistent effects under ecologically relevant settings should be the top priority of forthcoming studies on herbicide poisoning in aquatic flora and animals. Understanding the ecological dangers of herbicide combinations will be enhanced by looking into the cumulative impact, along with the molecular and biochemical processes that underlie toxicity. Furthermore, research ought to concentrate on how herbicides influence ecosystem services and processes, including food web stability and nutrient cycling. Creating safer pesticide substitutes and enhancing risk assessment models through the integration of ecological and hydrological data are urgent priorities. It is also crucial to take into account how climate change affects the toxicity and behavior of herbicides. Last but not least, standardizing testing procedures for various aquatic environments would improve data comparability and facilitate improved environmental management.

Conclusion

Despite being essential for agricultural output, herbicides continue to pose problems for aquatic ecosystem health. Ecosystem services, biodiversity, and ecological balance can all be negatively impacted by their toxicity to aquatic plants and animals. The intricacy of these effects, which are regulated by variables including exposure time, chemical combinations, and environmental circumstances, is highlighted by current research. We must improve our knowledge of the short- and long-term impacts of herbicides and use this information to environmental management and policy to protect aquatic life. Reducing damage and maintaining the sustainability of aquatic habitats will need ongoing innovation in safer pesticide formulations and enhanced risk assessment methodologies.

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