

Toxic Trails: Land Degradation Induced By Pollutants

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Abstract

Land degradation, driven by various pollutants, poses a significant threat to global ecosystems, agriculture, and human well-being. This review article explores the mechanisms through which pollutants, including heavy metals, pesticides, industrial chemicals, and urban waste, contribute to soil erosion, salinization, acidification, and loss of soil biodiversity. The article presents detailed case studies from regions such as China, India, Nigeria, the United States, Europe, Sub-Saharan Africa, and Australia, highlighting the diverse impacts of land degradation across different environmental and socio-economic contexts. Agroforestry, crop rotation, conservation tillage, and organic farming are examples of sustainable land management techniques that are included in the critical discussion of mitigation and remediation solutions. Pollution control measures, including regulatory frameworks, waste management, and best management practices in agriculture, are emphasized as essential steps in preventing further degradation. The article also reviews various remediation technologies, such as phytoremediation, bioremediation, soil washing, thermal desorption, and chemical stabilization, which are used to restore contaminated soils. Finally, the role of international and national policies, including the United Nations Convention to Combat Desertification (UNCCD), is examined in promoting sustainable land use and achieving land degradation neutrality. The paper emphasizes the significance of integrated strategies that incorporate community involvement, policy-making, and scientific research to successfully address the problems associated with pollution-related land degradation.

Keywords: Degradation, erosion, desertification, deforestation, fertility, urbanization, restoration, biodiversity, climate, sustainability.

INTRODUCTION

Land Degradation Overview: Land degradation refers to the decline in land's productivity and ecological health, which affects about 33% of the global land area. This phenomenon involves the deterioration of soil quality, vegetation cover, and overall land utility, often exacerbated by human activities and climatic factors. The impact of land degradation extends to biodiversity loss, reduced agricultural yields, and increased vulnerability to natural disasters (ResearchGate) (Frontiers).\

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Importance and Impact: The economic implications are significant, with annual global costs estimated at around EUR 420 billion. The phenomenon affects roughly 3.2 billion people worldwide, disrupting livelihoods and contributing to poverty and food insecurity (ResearchGate).

Types of Pollutants Causing Land Degradation

Heavy Metals: Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are pervasive pollutants. They enter the soil through industrial processes, mining, waste disposal, and agricultural inputs like fertilizers and pesticides. Heavy metals can bind to soil particles, disrupting

soil chemistry and biological activity. Because of their bioaccumulation potential and persistence in the environment, they pose serious dangers to people, animals, and plants (SpringerLink).

Insecticides, herbicides, and fungicides are among the many pesticides used in agriculture to safeguard crops. However, they can have detrimental effects on non-target organisms, including beneficial soil microorganisms, insects, and plants. Pesticides can degrade slowly, leading to long-term soil contamination and ecosystem disruption (Frontiers).

Industrial Chemicals and Urban Waste: The disposal of industrial chemicals and urban waste, including organic pollutants like PCBs and heavy metals, leads to soil contamination. These substances can enter the soil through atmospheric deposition, wastewater irrigation, and direct dumping, affecting soil properties and ecosystem health (SpringerLink).

MECHANISMS OF LAND DEGRADATION DUE TO POLLUTANTS

Land degradation is a complex process resulting from various physical, chemical, and biological factors. When pollutants are involved, these mechanisms can be significantly exacerbated. Below provides a thorough examination of the main ways that pollution causes land degradation.

Erosion of Soil

Definition and Methodology: The term "soil erosion" describes how wind, water, or human activity can remove the topsoil layer, which is rich in nutrients and organic matter. This process decreases the ground's capacity to support vegetation and results in the loss of fertile soil, making it a significant form of land degradation.

Pollutant Contribution: Pollutants can exacerbate soil erosion in several ways. For instance, industrial chemicals and heavy metals can alter soil structure, reducing its cohesiveness and making it more susceptible to erosion. Beneficial soil organisms that aid in binding soil particles together can be killed by pesticides.

Furthermore, acid rain, resulting from atmospheric deposition of sulfur and nitrogen oxides, can lead to soil acidification, weakening soil particles and making them more prone to erosion (MDPI) (SpringerLink).

Impact: The loss of fertile land decreased agricultural production, sedimentation in water bodies, and a rise in the frequency of natural disasters like floods and landslides can all result from soil erosion.

It also contributes to the loss of biodiversity by destroying habitats and reducing soil microbial diversity.

Soil Salinization

Definition and Methodology: The buildup of soluble salts in the soil, which can happen naturally or because of human activity, is known as soil salinization. It is a significant cause of land degradation, especially in areas that are semi-arid or desert. *Pollutant Contribution:* The use of poor-quality irrigation water, which often contains high levels of salts, is a primary contributor to soil salinization. Additionally, industrial effluents can introduce various salts and toxic elements into the soil. These salts have the potential to build up on the soil's surface in areas with significant rates of evaporation, which can result in salinization. By raising the salt content of the soil, overuse of chemical fertilizers can also exacerbate this issue (MDPI).

Impact: Salinization reduces soil fertility by affecting soil structure and water infiltration. Agricultural yields can be negatively impacted by high salt concentrations, which can stunt plant development or even cause plant death. Additionally, it may cause groundwater to become contaminated and unfit for irrigation and drinking.

The Process of Acidification

Definition and Process: The process by which the pH of the soil falls and becomes more acidic is known as "soil acidification." Although this process can happen spontaneously, human activity frequently speeds it up.

Pollutant Contribution: One of the main causes of soil acidification is acid rain, which is produced when sulfur dioxide (SO₂) and nitrogen oxides (NO_x) from industrial emissions are deposited in the atmosphere. These substances have the ability to combine with atmospheric water vapor to produce nitric and sulfuric acids, which descend to the earth as acid rain.

Additionally, the overuse of nitrogen-based fertilizers can lead to the leaching of base cations such as calcium and magnesium, further lowering soil pH ([ResearchGate](#)).

Impact: Plants may not be able to absorb vital nutrients as a result of acidification. Additionally, it releases harmful metals like aluminum, which can damage soil organisms and plant roots.

Acidic soils can reduce agricultural productivity and affect the health of terrestrial and aquatic ecosystems by altering the chemical composition of the soil and water.

Loss of Soil Biodiversity

Definition and Methodology: The diversity of living things in the soil, such as bacteria, fungus, insects, and other microbes, is referred to as soil biodiversity. These organisms are essential to the breakdown of organic matter, cycling of nutrients, and preservation of soil structure.

Pollutant Contribution: Pollutants such as heavy metals, pesticides, and industrial chemicals can be toxic to soil organisms. These substances can alter the microbial community structure, reduce the abundance of beneficial organisms, and increase the prevalence of harmful species. For instance, pesticides can kill not only target pests but also beneficial insects and microorganisms, disrupting soil ecosystems ([Frontiers](#)) ([SpringerLink](#)).

Impact: The loss of soil biodiversity can lead to a breakdown in ecosystem functions, such as nutrient cycling and organic matter decomposition. This can result in decreased soil fertility, increased disease prevalence, and reduced resilience of ecosystems to environmental changes.

Contamination and Soil Structure Degradation

Definition and Procedure: The term "soil contamination" describes the occurrence of dangerous compounds at concentrations that endanger both the environment and human health.

Soil structure degradation involves the breakdown of soil aggregates and the loss of soil porosity.

Pollutant Contribution: Contaminants such as heavy metals, industrial chemicals, and organic pollutants can accumulate in the soil, leading to toxicity. These substances can disrupt soil structure by binding with soil particles, altering their cohesion and porosity. For example, the introduction of heavy metals can replace essential nutrients in the soil matrix, weakening soil aggregates and making the soil more prone to compaction and erosion ([MDPI](#)) ([SpringerLink](#)).

Impact: Through direct contact or the food chain, contaminated soils can present serious health concerns to both humans and animals. Soil structure degradation can lead to reduced water infiltration, increased surface runoff, and decreased root penetration, further exacerbating erosion and reducing land productivity.

CASE STUDIES

India: India faces significant land degradation challenges, with around 96.4 million hectares affected by various degradation processes. Factors such as intensive farming, deforestation, and the overuse of chemical inputs contribute to soil erosion, salinization, and nutrient depletion. These issues have profound socio-economic impacts, including reduced agricultural productivity and increased rural-to-urban migration (MDPI).

Nigeria: In Nigeria, industrial activities in urban areas like Lagos have led to high concentrations of heavy metals in roadside soils. These pollutants pose risks to human health and disrupt local agriculture, impacting food security and economic stability (SpringerLink).

China: In China, rapid industrialization and urbanization have led to widespread heavy metal contamination in agricultural soils. Studies have shown that soils in industrial regions, particularly around mining areas and metal smelting plants, are heavily contaminated with metals like cadmium, lead, and arsenic. Due to the possibility of these metals being absorbed by crops and entering the food chain, this contamination poses serious hazards to human health and food safety.. Efforts to remediate these soils have included phytoremediation and soil washing, though challenges remain due to the large scale of contamination and the persistence of heavy metals in the environment (MDPI).

United States: One of the most productive agricultural areas in the world, the Central Valley of California, has had serious problems with pesticide pollution. The intensive use of pesticides in this region has led to contamination of both soil and groundwater. Studies have documented the presence of various pesticide residues in soils, which can persist for long periods and potentially harm non-target organisms, including beneficial insects and soil microorganisms. The contamination has raised concerns about the long-term sustainability of agricultural practices in the region and the health of farmworkers and local communities (Frontiers).

Europe: In Scandinavia, soil acidification has been a significant environmental issue, largely driven by acid rain resulting from industrial emissions of sulfur dioxide (SO₂) and nitrogen oxides (NO_x). The acidification of soils in this region has led to the leaching of essential nutrients and the mobilization of toxic metals like aluminum, which can harm plant roots and aquatic ecosystems. Efforts to mitigate soil acidification include reducing emissions through cleaner technologies and regulations, as well as applying lime to neutralize soil acidity (ResearchGate).

Sub-Saharan Africa: The Sahel region of Sub-Saharan Africa is characterized by fragile ecosystems that are highly susceptible to land degradation. Severe soil erosion and desertification are the results of overgrazing, deforestation, and unsustainable farming practices. Crop yields and soil fertility have decreased as a result of these issues being made worse by the overuse of chemical fertilizers and the extension of agricultural area.

Various initiatives, such as the Great Green Wall project, aim to restore degraded lands and improve the resilience of local communities through reforestation and sustainable land management practices (MDPI).

Australia: The Murray-Darling Basin in Australia is a key agricultural region but has been severely affected by soil salinity. The extensive use of irrigation, combined with the region's naturally saline soils, has led to the accumulation of salts in the soil profile. This salinization has reduced soil productivity and affected water quality in the basin. Efforts to address the issue include improved water management practices, the use of salt-tolerant crops, and the implementation of salinity control measures (ResearchGate).

METHODS OF MITIGATION AND REMEDIATION

Pollution-related land degradation must be mitigated and remedied using a multifaceted strategy that considers both the sources of the pollution and the affected areas.

Effective strategies encompass sustainable land management practices, pollution control, and the application of remediation technologies. Below, we delve into these strategies in detail:

Sustainable Land Management (SLM)

To meet growing food demands while maintaining ecosystem services and livelihoods, sustainable land management (SLM) incorporates biodiversity, water, land, and environmental management methods. Important elements consist of:

Crop Diversification and Rotation

Crop rotation is the process of planting several crops in the same spot for successive growing seasons. This technique helps in maintaining soil fertility, reducing soil erosion, and breaking the cycles of pests and diseases. Diversifying crops can improve soil health by varying root structures and nutrient requirements, which in turn reduces the need for chemical fertilizers and pesticides (MDPI).

Tillage for Conservation

A agricultural technique called conservation tillage reduces soil disturbance. It covers methods such as reduced-till and no-till farming, which leave crop leftovers on the soil's surface to prevent erosion and retain soil moisture. This practice helps maintain soil organic matter, enhances water infiltration, and reduces the carbon footprint of farming (SpringerLink).

Agroforestry

Trees and bushes are incorporated into agricultural areas through agroforestry. This practice provides multiple benefits, including improving soil structure, enhancing biodiversity, sequestering carbon, and protecting crops from wind and water erosion. Trees also contribute to nutrient cycling and soil fertility through leaf litter and root systems (SpringerLink).

Organic Farming

Organic farming eliminates synthetic chemical inputs like pesticides and fertilizers, instead relying on organic matter, compost, and biological pest control. By boosting microbial activity, strengthening soil structure, and adding more organic matter, this method improves soil health. Organic farming also reduces the risk of chemical runoff and pollution (MDPI).

Prevention and Control of Pollution

By boosting microbial activity, strengthening soil structure, and adding more organic matter, this method improves soil health.

Regulatory Frameworks and Policies

Effective legislation and policies are crucial for controlling pollution. Regulations can set limits on the release of pollutants, mandate the use of cleaner technologies, and enforce penalties for non-compliance. For example, laws regulating the discharge of industrial effluents and emissions can significantly reduce soil and water contamination (Frontiers).

Waste Management and Recycling

Proper waste management practices, including the safe disposal and recycling of hazardous materials, are essential for preventing soil contamination. Industries can implement waste minimization strategies, such as reusing by-products and treating waste before disposal, to reduce the environmental impact (SpringerLink).

Best Management Practices (BMPs) in Agriculture

BMPs include the efficient use of fertilizers and pesticides, proper irrigation techniques, and soil conservation measures. Integrated Pest Management (IPM) combines biological, cultural, and chemical practices to control pests in a way that minimizes environmental impact. Proper timing and precise application of agrochemicals can also reduce runoff and leaching into the soil (Frontiers).

Remediation Technologies

Remediation technologies are used to clean up polluted soils and restore them to a healthy state. The

kind and degree of contamination, the characteristics of the soil, and financial factors all influence the technological selection. Important corrective methods consist of:

Using phytoremediation

Utilizing plants, phytoremediation removes, gathers, and purges contaminants from the soil. Hyperaccumulators are certain types of plants that have the ability to absorb heavy metals from the soil and store them in their tissues. This technique can be utilized to clean up big contaminated land tracts and is both economical and environmentally beneficial.

However, it requires time and the proper selection of plant species for specific pollutants (SpringerLink).

Bioremediation

Bioremediation involves the use of microorganisms to degrade or neutralize pollutants in the soil. Organic contaminants can be broken down by microbes into innocuous compounds. Techniques such as bioaugmentation (adding specific microbes) and biostimulation (adding nutrients to stimulate indigenous microbes) are used to enhance the biodegradation process. When it comes to organic pollutants such as petroleum hydrocarbons (MDPI), this approach works very well.

Soil Washing

Soil washing involves the physical separation of contaminants from the soil using a washing solution. It is possible to eliminate heavy metals and other inorganic contaminants with this method. The process typically involves the excavation of contaminated soil, which is then mixed with water and chemical additives to separate pollutants from soil particles. The cleaned soil is returned to the site, while the contaminated wash water is treated (SpringerLink).

Thermal Desorption

In thermal desorption, contaminants are volatilized by heating contaminated soil, after which they are collected and processed. When it comes to organic pollutants, such as volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs), this technique works very well. Thermal desorption can be applied in situ or ex situ, depending on the contamination scenario and site characteristics (Frontiers).

Chemical Stabilization and Solidification

Chemical stabilization involves adding reagents to contaminated soil to convert pollutants into less soluble or less toxic forms. Solidification involves mixing contaminated soil with binding agents to immobilize pollutants and prevent their migration. These methods are commonly used for heavy metals and radionuclides. While they do not remove pollutants from the soil, they reduce the risk of exposure and environmental impact (SpringerLink).

Global Initiatives and Policy Structures

UNCCD, the United Nations Convention to Combat Desertification

A significant international agreement aimed at resolving drought, land degradation, and desertification is the UNCCD. It strives for land degradation neutrality and supports sustainable land management techniques.

The convention encourages countries to develop national action plans, invest in land restoration projects, and collaborate on knowledge-sharing and capacity-building initiatives (Frontiers).

Global Environmental Agreements and Initiatives

Land degradation is one of the goals included in a number of international accords, including the Sustainable Development Goals (SDGs) and the Paris Agreement on climate change.

These agreements encourage countries to adopt sustainable land use practices, protect biodiversity, and enhance ecosystem resilience. Initiatives to stop land degradation and advance sustainable development are supported by international funding sources like the Global Environment Facility (GEF)

(SpringerLink).

Regional and National Programs

Regional and national programs play a crucial role in implementing and enforcing policies aimed at mitigating land degradation. For instance, financial incentives and rules are used by the European Union's Common Agricultural Policy (CAP) to promote sustainable agriculture.

National governments also implement land-use planning and conservation programs, often in collaboration with local communities and non-governmental organizations (Frontiers).

These mitigation and remediation strategies demonstrate the importance of a comprehensive approach to tackling land degradation. By integrating sustainable practices, pollution control, and advanced remediation technologies, it is possible to restore degraded lands and prevent further environmental damage.

Talk

Pollution-related land degradation is a complicated problem that requires a multidisciplinary strategy that combines community involvement, policymaking, and scientific study. The working mechanics by which pollutants impact land, as discussed in this review, highlight the intricate interplay between natural processes and human activities. The evidence from various regions demonstrates the global scope of this issue and underscores the need for tailored solutions that consider local environmental and socio-economic contexts.

Implications of Pollutant Types and Sources

The types and sources of pollutants significantly influence the severity and nature of land degradation. For instance, heavy metals, often derived from industrial activities and mining, pose long-term contamination risks due to their persistence in the environment. The case studies from China and Nigeria illustrate how heavy metals can accumulate in soils, leading to toxic conditions that adversely affect plant growth and food safety (MDPI) (SpringerLink). The challenge lies in the complex chemistry of these metals, which often require advanced and costly remediation technologies such as phytoremediation and soil washing.

Pesticides, primarily from agricultural sources, have both immediate and long-term impacts on soil health. The widespread use of these chemicals in regions like California's Central Valley highlights their dual role in protecting crops and contributing to soil and water contamination. The persistence of certain pesticide residues poses a significant risk to non-target species, including beneficial soil microorganisms, which are crucial for maintaining soil fertility and ecosystem balance (Frontiers). Addressing pesticide pollution requires a careful balance between effective pest management and environmental protection, possibly through integrated pest management (IPM) strategies.

Efficacy of Mitigation and Remediation Strategies

The efficacy of sustainable land management (SLM) practices is well-documented, yet their implementation often faces socio-economic and institutional barriers. Conservation tillage, agroforestry, and organic farming are effective in preserving soil health and enhancing biodiversity, but their adoption may be limited by factors such as land tenure issues, lack of access to knowledge and resources, and market incentives (MDPI) (SpringerLink). Moreover, while organic farming reduces chemical input, it may face challenges in terms of lower yields and higher labor costs, which can impact its economic viability.

Remediation technologies offer promising solutions for restoring contaminated soils. Nevertheless, a number of variables, such as the kind and level of contaminants, the properties of the soil, and budgetary constraints, influence the technology selection. Phytoremediation and bioremediation are

cost-effective and environmentally friendly options, particularly for organic pollutants. Yet, they are often slow and may not be effective for highly contaminated sites or for pollutants like heavy metals that plants and microbes cannot easily degrade or sequester (SpringerLink). In such cases, more intensive methods like soil washing or thermal desorption may be required, despite their higher costs and potential environmental side effects.

Policy and Governance Challenges

Policy frameworks play a critical role in mitigating land degradation. A forum for international collaboration and resource mobilization is provided by the United Nations Convention to Combat Desertification (UNCCD) and other international accords. However, there are many obstacles to the application of these frameworks, including a lack of political will, insufficient financing, and weak enforcement measures.

National policies must align with international commitments while being adaptable to local conditions and needs (Frontiers). For example, effective regulation of industrial emissions and waste management practices is crucial for preventing soil contamination, but it requires robust monitoring and enforcement infrastructure.

Research Needs and Future Directions

In the future, both mitigation and remediation technologies will require ongoing study and development. For the purpose of maintaining polluted sites, it is imperative that novel, economical, and environmentally friendly remediation techniques be developed. Advances in biotechnology, such as genetically modified plants and microbes tailored for specific contaminants, offer promising avenues for improving the efficiency of phytoremediation and bioremediation (SpringerLink). Additionally, there is a growing recognition of the importance of ecosystem-based approaches, which consider the broader ecological and social systems in which land degradation occurs.

Effective land management techniques also include community involvement and education as essential elements. Giving local communities the tools and information they need can help them embrace sustainable practices and make sure land restoration efforts are successful in the long run. Public awareness campaigns and stakeholder participation in decision-making processes can help build support for environmental policies and initiatives.

CONCLUSION

The degradation of land due to pollutants is a multifaceted environmental challenge that has far-reaching implications for ecosystems, agriculture, and human health. This comprehensive review has highlighted the critical mechanisms through which various pollutants, including heavy metals, pesticides, industrial chemicals, and urban waste, contribute to soil erosion, salinization, acidification, and loss of soil biodiversity. The impact of these processes is global, as evidenced by case studies from diverse regions such as China, India, Nigeria, the United States, Europe, Sub-Saharan Africa, and Australia. These examples illustrate the widespread nature of the problem and its severe consequences on soil fertility, agricultural productivity, water quality, and biodiversity.

Mitigating and remediating land degradation requires an integrated approach that combines sustainable land management practices, effective pollution control measures, and advanced remediation technologies. Crop rotation, conservation tillage, agroforestry, and organic farming are examples of sustainable land management techniques that provide workable answers for preserving soil health and improving agricultural sustainability.

Moreover, pollution control efforts, including stringent regulatory frameworks, efficient waste management, and the adoption of best management practices in agriculture, are essential to prevent further contamination of soils and water bodies.

Remediation technologies such as phytoremediation, bioremediation, soil washing, thermal desorption, and chemical stabilization provide practical methods for restoring contaminated lands. These techniques, while varied in application and effectiveness, share the common goal of reducing the presence and impact of pollutants, thus reclaiming soil for productive use. However, the choice of remediation strategy must be carefully considered based on the specific pollutants involved, the extent of contamination, and the local environmental and economic conditions.

International and national policy frameworks play a crucial role in addressing land degradation. Coordinated action and resource mobilization are made possible by initiatives such as the United Nations Convention to Combat Desertification (UNCCD) and other international environmental agreements. They also promote knowledge-sharing and capacity-building, which are vital for the successful implementation of land restoration projects. At the national level, governments must enforce environmental regulations, support sustainable land use practices, and engage local communities in conservation efforts.

In conclusion, addressing land degradation due to pollutants is not only an environmental necessity but also a socio-economic imperative. A comprehensive strategy that incorporates scientific research, policy-making, technology innovation, and community involvement is essential for the success of mitigation and cleanup activities.

. By fostering collaboration across these domains, it is possible to protect and restore our land resources, ensuring a sustainable future for all. The path forward requires continued commitment to sustainable practices, investment in clean technologies, and robust policy support to achieve the dual goals of environmental preservation and human development.

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