Science World Journal Vol. 20(No 1) 2025
www.scienceworldjournal.org
ISSN: 1597-6343 (Online), ISSN: 2756-391X (Print)
Published by Faculty of Science, Kaduna State University
https://dx.doi.org/10.4314/swj.v20i1.23

Full Length Research Article

LEGACY OF EXTRACTION: UNRAVELING HEAVY METAL CONTAMINATION IN WATER AND SOIL AT ABANDONED MINE SITES

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ABSTRACT

The global proliferation of abandoned mine sites (AMS) constitutes a significant and enduring environmental predicament. These sites represent a legacy of past extractive industries, frequently leaving behind contaminated water and soil, thereby posing substantial risks to human health and ecological integrity. These contaminants which are usually heavy metals including arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), zinc (Zn), and mercury (Hg) persist in the environment for extended periods. This review article synthesizes current studies on heavy metal contamination associated with AMS, focusing on the sources, pathways, extent and impacts of this contamination, along with assessment methodologies, and remediation strategies.

Keywords: Mining, Heavy Metals, Contamination, Extraction, Environment

INTRODUCTION

The environmental effects of mining, especially from abandoned mine sites, have been receiving increasing attention due to their long-lasting impacts on ecosystems, human health, and the surrounding communities. The sheer scale of this issue is vast, with countless abandoned mines worldwide contributing to long-term environmental degradation. The consequences extend beyond immediate vicinity, impacting downstream ecosystems and potentially affecting human populations through contaminated water sources and food chains (Younji*et al.*, 2022). The long-term persistence of heavy metals in the environment, coupled with the potential for remobilization due to weathering and climatic changes, underscores the urgency of addressing this global challenge. Improper management of these sites can lead to heavy metal contamination of agricultural soil, groundwater, and surface water, creating a long-term source of contamination (Younji*et al.*, 2022). The potential for heavy metal pollution to spread through streams and runoff, contaminating soil and water in surrounding areas, necessitates regular monitoring to minimize impacts on water resources, flora, and fauna (Shamsoddini*et al.*, 2014). The economic costs associated with remediation efforts, coupled with the long-term health implications, further emphasize the need for comprehensive strategies to manage AMS (Hosik*et al.*, 2009).

SOURCES AND PATHWAYS OF HEAVY METAL CONTAMINATION

Mine Tailings and Waste Rock

Mine tailings and waste rock represent the primary sources of heavy metal contamination emanating from abandoned mine sites (Seo-Jin *et al.*, 2014;Hachimi*et al.*, 2014)Xun*et al.*, 2017. These materials frequently exhibit elevated concentrations of various heavy metals, including arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), and zinc (Zn) (Hosik*et al.*, 2009;Seo-Jin *et al.*, 2014). The inherent variability in the composition of these materials, depending on the ore type and mining processes, contributes to the complexity of assessing and managing heavy metal contamination (Hosik*et al.*, 2009). Weathering processes, coupled with leaching and runoff, play a pivotal role in mobilizing these metals into the surrounding water bodies and soils (Xun*et al.*, 2017). The rate of leaching is significantly influenced by a range of environmental factors, including pH, redox potential, and the frequency and intensity of rainfall events (Younji*et al.*, 2022). The physical and chemical properties of tailings and waste rock, such as particle size distribution, surface area, and mineral composition, also influence the rate and extent of heavy metal release (Xun*et al.*, 2017). The long-term stability of these materials is a critical concern, as continued weathering can lead to the sustained release of heavy metals over decades or even centuries (Younji*et al.*, 2022). Moreover, the spatial distribution of tailings and waste rock around the mine site influences the extent and pattern of heavy metal contamination in the surrounding environment (Madzin*et al.*, 2017).

Acid Mine Drainage (AMD)

Acid mine drainage (AMD) is a significant contributor to heavy metal contamination in both water and soil environments associated with abandoned mines (Xun*et al.*, 2017;Yiwen*et al.*, 2023). The oxidation of sulfide minerals, primarily pyrite (FeS_2), is the fundamental process underlying AMD generation (Jin *et al.*, 2011; Yiwen*et al.*, 2023). This oxidation reaction produces sulfuric acid and releases ferrous iron (Fe^{2+}), which subsequently oxidizes to ferric iron (Fe^{3+}) (Yiwen*et al.*, 2023). Ferric iron is highly reactive and can dissolve many other heavy metals from the mine waste, leading to the formation of acidic, metal-rich solutions (Yiwen*et al.*, 2023). AMD can contaminate surface water and groundwater resources, impacting downstream ecosystems and potentially posing risks to human health through drinking water contamination (Xun*et al.*, 2017; Yiwen*et al.*, 2023). The transport of AMD through surface runoff and groundwater flow patterns is influenced by geological factors, such as the presence of fractures and aquifers, and hydrological characteristics, such as rainfall intensity and infiltration rates (Xun*et al.*, 2017). Furthermore, the severity of AMD is often amplified by climatic conditions, with increased rainfall and temperature potentially leading to higher rates of metal leaching (Younji*et al.*, 2022). The long-term consequences of AMD include soil acidification, vegetation dieback, and the impairment of aquatic ecosystems (Lenka*et al.*, 2017). The neutralization of AMD, often through costly and complex remediation strategies, remains a significant challenge (Xun*et al.*, 2017).

Atmospheric Deposition

Atmospheric deposition represents another pathway for the dissemination of heavy metals in the vicinity of abandoned mine sites (Hachimi*et al.*, 2014; Musa *et al.*, 2019). Particulate matter and gaseous emissions generated during mining and smelting operations can transport heavy metals over considerable distances, resulting in their deposition on surrounding land surfaces (Hachimi*et al.*, 2014; Musa *et al.*, 2019). The composition and quantity of these emissions are dependent on various factors, including the type of ore being processed, the technology employed, and the efficiency of emission control measures. The deposition of heavy metals on soil and vegetation can lead to contamination of agricultural products and potential exposure to humans through food consumption (Musa *et al.*, 2019). Wind erosion of exposed mine wastes, particularly tailings and waste rock, can further contribute to the widespread dispersal of heavy metals over broader areas, potentially impacting a larger region than would be expected from simple leaching and runoff processes (Hachimi*et al.*, 2014). The long-range transport of heavy metals via atmospheric deposition necessitates consideration of regional-scale patterns and the potential for cumulative impacts from multiple sources (Hachimi*et al.*, 2014). The impact of climatic factors, such as wind speed and precipitation, on the atmospheric transport and deposition of heavy metals further complicates the assessment of contamination risks (Hachimi*et al.*, 2014).

ASSESSMENT METHODOLOGIES FOR HEAVY METAL CONTAMINATION

Sampling Strategies and Analytical Techniques

Effective assessment of heavy metal contamination in the context of abandoned mine sites necessitates the implementation of rigorous sampling strategies and the utilization of appropriate analytical techniques (Shamsoddini*et al.*, 2014). The selection of sampling locations is crucial to capture the spatial variability of contamination, which can be significant due to factors such as topography, hydrological flow patterns, and the distribution of mine wastes (Hachimi*et al.*, 2014). A stratified random sampling approach is often employed to ensure representative coverage of the study area, with sampling density adjusted based on the heterogeneity of the site (Hosik*et al.*, 2009). The depth of soil sampling should also be considered, as the vertical distribution of heavy metals can vary significantly (Fang *et al.*, 2018). In addition to soil samples, water samples (surface water and groundwater) should be collected to assess the extent of contamination in aquatic environments (Hosik*et al.*, 2009).

Analytical techniques such as Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Atomic Absorption Spectrometry (AAS) are widely used to determine heavy metal concentrations in soil and water samples (Musa *et al.*, 2019). ICP-MS offers higher sensitivity and the ability to analyze a wider range of elements compared to AAS (Musa *et al.*, 2019). However, both methods require careful sample preparation and quality control to ensure accurate and reliable results. The choice of sampling strategy and analytical method should be guided by the specific research objectives, the available resources, and the characteristics of the AMS (Shamsoddini*et al.*, 2014; Sung-Min *et al.*, 2017). The use of portable X-ray fluorescence (PXRF) instruments offers a rapid and cost-effective method for initial assessment of heavy metal contamination, although calibration with more accurate methods such as ICP-AES is often necessary (Sung-Min *et al.*, 2017).

Pollution Indices and Risk Assessment

A range of pollution indices and risk assessment tools are employed to evaluate the extent and potential impacts of heavy metal contamination at abandoned mine sites (Hosik*et al.*, 2009; Jesmin*et al.*, 2020). The Integrated Pollution Index (IPI) provides a comprehensive assessment by integrating multiple parameters related to water, soil, and sediment quality (Hosik*et al.*, 2009;Jesmin*et al.*, 2020). The IPI offers a standardized approach for comparing pollution levels across different sites, which is useful for prioritizing remediation efforts (Hosik*et al.*, 2009). However, the weighting of different parameters in the IPI can be subjective, potentially affecting the overall ranking of sites (Jesmin*et al.*, 2020). Other indices such as the geoaccumulation index (I_{geo}) provide a measure of the degree of contamination relative to background levels (Xun*et al.*, 2017; Stephen &Mbamalu, 2020). The I_{geo} is particularly useful for identifying areas with significant anthropogenic influence (Stephen &Mbamalu, 2020). The enrichment factor (EF) is often used to assess the relative contribution of anthropogenic sources to heavy metal contamination (Julin*et al.*, 2024). The potential ecological risk index (RI) integrates the toxicity and concentration of heavy metals to assess the potential ecological risks (Julin*et al.*, 2024). Risk assessment methodologies further consider both the concentration of heavy metals and their potential toxicity to humans and ecosystems (Park *et al.*, 2020;Bouwdo*et al.*, 2024). Risk assessments often involve calculating hazard quotients (HQ) and hazard indices (HI) to estimate the potential for non-carcinogenic effects, and carcinogenic risks to evaluate the probability of cancer development (Park *et al.*, 2020;Bouwdo*et al.*, 2024). The selection of appropriate indices and risk assessment methods depends on the research objectives, the available data, and the specific characteristics of the site.

Spatial Mapping and Geostatistical Analysis

Geostatistical techniques, in conjunction with Geographic Information Systems (GIS), serve as invaluable tools for visualizing and analyzing the spatial distribution of heavy metal contamination at abandoned mine sites (Fang *et al.*, 2018). These techniques allow for the identification of hot spots, areas of high contamination, and spatial patterns that can inform remediation efforts and risk management strategies (Sung-Min *et al.*, 2017; Fang *et al.*, 2018). Spatial mapping assists in understanding the factors influencing heavy metal transport and dispersal from AMS, such as topography, hydrological flow patterns, and wind erosion (Fang *et al.*, 2018).

Geostatistical methods, such as kriging, are used to interpolate data from point samples to create continuous surface maps of heavy metal concentrations (Fang *et al.*, 2018). These maps can reveal subtle spatial variations in contamination that may not be apparent from point data alone (Fang *et al.*, 2018). The integration of spatial data with other environmental variables, such as soil properties, land use, and proximity to mine wastes, can enhance the understanding of the factors controlling the distribution of heavy metals (Fang *et al.*, 2018). Hot spot analysis, using techniques such as the Getis-OrdGi* statistic, can identify statistically significant clusters of high contamination, helping to prioritize areas for remediation (Sung-Min *et al.*, 2017). The visualization capabilities of GIS allow for the integration of various data layers, such as heavy metal maps, geological maps, and hydrological data, to provide a comprehensive understanding of the contamination patterns (Sung-Min *et al.*, 2017).

HEAVY METAL SPECIATION AND BIOAVAILABILITY

Fractionation and Mobility

The speciation of heavy metals in soil and water significantly influences their bioavailability and potential for uptake by organisms (Julin*et al.*, 2024). Heavy metals exist in various forms, including free ions, complexed ions, adsorbed species, and organically bound species (Semenkov*et al.*, 2024). The relative proportions of these different forms, termed speciation, determine the mobility and bioavailability of the metals (Julin*et al.*, 2024). Sequential extraction procedures are commonly used to operationally fractionate heavy metals into different geochemical phases, such as exchangeable, carbonate-bound, organically bound, and residual fractions (Julin*et al.*, 2024). The exchangeable fraction represents the most bioavailable fraction, readily available for uptake by plants and organisms (Julin*et al.*, 2024). The carbonate-bound and organically bound fractions are less readily available, while the residual fraction is generally considered immobile (Semenkov*et al.*, 2024). Understanding the speciation of heavy metals is crucial for assessing their potential ecological and human health risks. Metals in the labile fractions pose a higher risk than those in less bioavailable forms (Julin*et al.*, 2024). The mobility of heavy metals is influenced by various factors, including pH, redox potential, organic matter content, and the presence of competing ions. Changes in environmental conditions, such as fluctuations in pH or redox potential, can alter the speciation of heavy metals and affect their mobility and bioavailability (Semenkov*et al.*, 2024).

Influence of Soil Properties

Soil properties play a critical role in influencing the mobility and bioavailability of heavy metals in the vicinity of abandoned mine sites (Kazemi*et al.*, 2021; Younji*et al.*, 2022). Soil pH is a key factor determining the solubility and mobility of heavy metals. Acidic conditions (low pH) generally enhance the solubility and mobility of many heavy metals, making them more readily available for uptake by plants and organisms (Younji*et al.*, 2022). Conversely, alkaline conditions (high pH) can reduce the solubility and mobility of many heavy metals (Younji*et al.*, 2022). Organic matter content in soil also plays a significant role in heavy metal binding and bioavailability. High organic matter content can bind heavy metals, reducing their mobility and bioavailability through complexation and adsorption processes (Younji*et al.*, 2022). The cation exchange capacity (CEC) of soil, a measure of its ability to retain positively charged ions, also influences heavy metal availability. Soils with high CEC tend to retain more heavy metals, reducing their mobility and bioavailability (Kazemi*et al.*, 2021). The texture and structure of the soil also influence heavy metal mobility and bioavailability. Clayey soils, with their high surface area and adsorption capacity, tend to retain more heavy metals than sandy soils. The presence of other ions in the soil solution can also compete with heavy metals for binding sites, affecting their bioavailability (Kazemi*et al.*, 2021). Understanding these complex interactions between soil properties and heavy metal behavior is crucial for predicting the long-term fate and transport of heavy metals in contaminated soils (Kazemi*et al.*, 2021).

REMEDIATION STRATEGIES FOR HEAVY METAL CONTAMINATION

Physical and Chemical Remediation

A variety of physical and chemical remediation techniques have been employed to address heavy metal contamination at abandoned mine sites (Jin *et al.*, 2011;(Kazemi*et al.*, 2021. These methods aim to either remove heavy metals from the contaminated media or to immobilize them, reducing their bioavailability and mobility. Excavation and disposal of contaminated soil or sediment is a common approach, particularly for highly contaminated areas. This method physically removes the heavy metals from the site, but it is often expensive and may require finding suitable disposal locations (Jin *et al.*, 2011).

Soil washing involves leaching heavy metals from soil using chemical solutions, which are then separated from the soil. This method is effective for removing some heavy metals but may require further treatment of the leachate to prevent secondary contamination (Jin *et al.*, 2011). Stabilization/solidification involves the addition of binding agents to the contaminated soil or sediment to immobilize heavy metals, reducing their mobility and bioavailability (Jin *et al.*, 2011). This method is relatively cost-effective but may not completely remove heavy metals (Jin *et al.*, 2011). Other chemical methods, such as chemical extraction using chelating agents, can be used to remove specific heavy metals from soil, but they can be expensive and may have environmental implications (Kazemi*et al.*, 2021). The selection of an appropriate physical or chemical remediation method depends on various factors, including the extent of contamination, the type of heavy metals involved, the cost, and site-specific conditions (Jin *et al.*, 2011). The effectiveness of these methods can be enhanced by considering the speciation of heavy metals and tailoring the remediation strategy accordingly (Jin *et al.*, 2011).

Biological Remediation

Biological remediation offers environmentally friendly and potentially cost-effective alternatives for managing heavy metal contamination at abandoned mine sites (Kim *et al.*, 2008). These methods utilize biological agents, such as plants or microorganisms, to remove, transform, or immobilize heavy metals (Rohit*et al.*, 2021). Phytoremediation involves the use of plants to extract, stabilize, or volatilize heavy metals from contaminated soil or water (Kazemi*et al.*, 2021). Phytoextraction involves the uptake of heavy metals by plants, which are then harvested and disposed of, effectively removing the metals from the contaminated site (Kazemi*et al.*, 2021). Phytostabilization involves the immobilization of heavy metals in the soil by plants, reducing their mobility and bioavailability (Rohit*et al.*, 2021). Rhizofiltration involves the uptake of heavy metals by plant roots from contaminated water (Kazemi*et al.*, 2021). Bioaugmentation involves the introduction of microorganisms, such as bacteria or fungi, to enhance the biodegradation or biotransformation of heavy metals (Rohit*et al.*, 2021). Microorganisms can transform heavy metals into less toxic forms or can immobilize them through precipitation or adsorption processes (Rohit e al., 2021). The effectiveness of biological remediation methods depends on several factors, including the choice of plant species or microorganisms, the type and concentration of heavy metals, soil properties, and climatic conditions (Kazemi*et al.*, 2021). The use of indigenous microorganisms, adapted to the specific site conditions, can enhance the effectiveness and sustainability of bioaugmentation strategies (Kazemi*et al.*, 2021)).

Integrated Remediation Approaches

Integrated remediation approaches, which combine multiple remediation techniques, often provide the most effective and sustainable solutions for managing complex heavy metal contamination at abandoned mine sites (Madzin*et al.*, 2024; Rohit*et al.*, 2021). These approaches take advantage of the strengths of different methods to overcome their individual limitations(Briffa *et al.*, 2020). For example, an integrated approach might involve the use of physical methods, such as capping to prevent further spread of contamination, combined with biological methods, such as phytoremediation to remove or stabilize heavy metals in the soil(Zhao *et al.*, 2022). The selection of an integrated remediation strategy requires careful consideration of site-specific factors, including the extent and nature of contamination, the presence of other environmental concerns, cost-effectiveness, and the long-term sustainability of the chosen approach (Madzin*et al.*, 2024).

Integrated approaches often involve a phased implementation, starting with preliminary assessments to characterize the site and identify the most appropriate remediation methods. Subsequent phases involve the implementation of selected remediation techniques, followed by monitoring to evaluate their effectiveness. Adaptive management strategies may be necessary to adjust the remediation plan based on the observed results (Madzin*et al.*, 2024). The development of integrated remediation strategies requires collaboration between various stakeholders, including scientists, engineers, regulators, and local communities (Rohit*et al.*, 2021). A holistic approach is essential to ensure that the chosen remediation strategy is both effective and environmentally sustainable(Abdolmaleki *et al.*, 2024).

HUMAN HEALTH AND ECOLOGICAL RISKS

Human Health Impacts

Heavy metal contamination from abandoned mine sites poses significant risks to human health through various exposure pathways (Heeseung*et al.*, 2015; Jung-Yeon*et al.*, 2023). Ingestion of contaminated water or food is a primary route of exposure, particularly in communities that rely on local water sources or consume locally grown produce (Jesmin*et al.*, 2020). Inhalation of heavy metal-contaminated dust can also lead to significant exposure, especially for individuals living near or working in contaminated areas(Treviño*et al.*, 2019). Dermal contact with contaminated soil can contribute to heavy metal uptake (Jung-Yeon*et al.*, 2023). Exposure to heavy metals such as lead, cadmium, and arsenic can result in a range of adverse health effects, depending on the specific metal, the level of exposure, and the duration of exposure (Jung-Yeon*et al.*, 2023). These effects can include kidney damage, neurological disorders and developmental problems in children, reproductive issues, cardiovascular disease, and cancer (Xu *et al.*, 2021). Children are particularly vulnerable to the adverse health effects of heavy metal exposure due to their higher ingestion rates, developing organ systems, and increased susceptibility to neurotoxic effects (Bouwdo*et al.*, 2024). The long-term health consequences of heavy metal exposure from abandoned mine sites can be severe and can impose substantial burdens on individuals and healthcare systems (Jesmin*et al.*, 2020). The assessment of human health risks associated with heavy metal contamination requires considering the various exposure pathways, the bioavailability of heavy metals, and the sensitivity of different population groups (Park *et al.*, 2020).

Ecological Impacts

Heavy metal contamination from abandoned mine sites can have profound and long-lasting impacts on the structure and function of ecosystems (Shamsoddini*et al.*, 2014;Mayon*et al.*, 2024). Heavy metals can accumulate in plants and animals through various pathways, including direct uptake from contaminated soil or water and through food chain transfer (Shamsoddini*et al.*, 2014). This bioaccumulation can lead to adverse effects on organism growth, reproduction, and survival (Shamsoddini*et al.*, 2014). Heavy metal contamination of water bodies can have devastating consequences for aquatic organisms, altering community structure and food web dynamics (Mayon*et al.*, 20204). The toxicity of heavy metals can lead to reduced biodiversity, impacting the overall health and resilience of ecosystems (Mozhgon*et al.*, 2015). Soil acidification, a common consequence of AMD, can further exacerbate ecological impacts by reducing soil fertility and affecting plant growth (Lenka*et al.*, 2017). The long-term consequences of heavy metal contamination can include habitat degradation, loss of biodiversity, and the disruption of ecological processes (Mozhgon*et al.*, 2015). The assessment of ecological risks associated with heavy metal contamination from abandoned mine sites necessitates considering the various exposure pathways, the bioavailability of heavy metals, and the sensitivity of different species and ecosystems (Mayon*et al.*, 2024). Long-term monitoring and ecological studies are essential to fully understand the impacts of heavy metal contamination on ecosystem health and to develop effective management strategies (Mozhgon*et al.*, 2015).

Conclusions

This review has underscored the significant environmental and human health risks associated with heavy metal contamination emanating from abandoned mine sites. Mine tailings, waste rock, and acid mine drainage (AMD) are primary sources of contamination, with multiple pathways facilitating the mobilization and transport of heavy metals into surrounding ecosystems. Various assessment methodologies are available for evaluating contamination levels and risks; however, the optimal approach depends heavily on the specific circumstances, resources, and objectives. A diverse array of remediation strategies exists, encompassing physical, chemical, and biological methods, with integrated approaches frequently proving most effective. Long-term monitoring and research are indispensable for effectively managing the legacy of extraction from abandoned mines. The varying levels of heavy metal contamination observed across different sites highlight the need for site-specific assessments and tailored remediation strategies. The complexity of heavy metal speciation and bioavailability necessitates a thorough understanding of the geochemical processes influencing metal mobility and uptake by organisms. The long-term health consequences for both human populations and ecosystems underscore the urgency of addressing this global environmental.

Future Directions

Despite considerable progress in understanding and managing heavy metal contamination at abandoned mine sites, several key knowledge gaps persist. These include:

Development of more effective and cost-efficient remediation technologies: Current remediation technologies can be expensive and may not be suitable for all site conditions. Further research is needed to develop innovative and cost-effective remediation technologies, including advanced bioremediation strategies (and improved methods for removing heavy metals from contaminated water

Refinement of risk assessment methodologies: Existing risk assessment methodologies often simplify the complexities of heavy metal speciation and bioavailability. Further research is needed to develop more sophisticated risk assessment models that account for these complexities and better predict potential ecological and human health risks.

Enhanced understanding of long-term effects: The long-term effects of heavy metal contamination on human and ecosystem health are not fully understood. Long-term monitoring studies are needed to assess the chronic health effects of heavy metal exposure and to evaluate the effectiveness of different remediation strategies over time.

Development of predictive models: Predictive models are needed to assess the long-term behavior of heavy metals in contaminated environments under changing climate conditions .These models should incorporate factors such as rainfall patterns, temperature changes, and soil properties to better predict the potential for future heavy metal release and transport.

Exploration of innovative monitoring techniques: Further research is needed to explore innovative monitoring techniques, such as remote sensing technologies, to improve the efficiency and cost-effectiveness of assessing heavy metal contamination at a large scale.

Strengthening policies and regulations: Stronger policies and regulations are needed to ensure responsible mine closure and remediation practices. These policies should include provisions for long-term monitoring, financial guarantees for remediation, and clear accountability mechanisms for mine operators.

Addressing these knowledge gaps is crucial for developing effective and sustainable management strategies for abandoned mine sites worldwide. Interdisciplinary research collaborations, incorporating geochemistry, hydrology, ecology, and public health expertise, are essential for creating comprehensive and holistic solutions to this global environmental challenge. The integration of advanced technologies, such as machine learning and remote sensing offers promising avenues for improving the efficiency and effectiveness of AMS management. The ultimate goal is to minimize the risks posed by heavy metal contamination from abandoned mines, protecting both human health and ecological integrity.

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