Nature-based Solutions to Restoration of Contaminated Soils and Enhance Biodiversity and Human Health

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Abstract: The soil environment and its biodiversity are the basis of human health, but currently, soil degradation on a large scale is causing soil pollution and threatening human development. In this context, the use of conventional soil remediation techniques will lead to waste of resources and secondary contamination of soil, in contrast to nature-based solutions that use natural processes to restore the original contaminated soil resources and improve sustainability, which is an appropriate and sustainable approach to address the problems associated with soil contamination. In this paper, we compiled the nature-based remediation measures for contaminated soils and proposed ecologically oriented measures based on plants, soil microorganisms, biochar and soil animals, and engineering-oriented measures based on artificial wetlands, non-intensive agricultural management and green natural nanomaterials, and focused on their mechanism of action and synergistic relationship, focusing on the effects of the two together on the soil remediation process and results. The focus is on the added benefits of nature-based solutions in the process and outcome of soil restoration to enhance biodiversity and human health.

1. Introduction

As a dynamic habitat for living organisms, soils support the functioning of ecosystems while maintaining human health and environmental quality. At present, due to human activities, land desertification, salinization, and other phenomena, have seriously damaged the characteristics and functions of soils and promoted the accumulation and spread of pollutants within soils, threatening the health and well-being of humans and other creatures. Conventional soil remediation technologies are generally based on a single chemical and engineering process, which is socially, economically, and environmentally costly.

In this context, Nature-based Solutions (NbS) provide new ideas to address soil contamination. In 2009, the World Conservation Union (IUCN) introduced NbS into the United Nations Framework Convention on Climate Change and is defined as nature-based interventions for the conservation, sustainable use, and restoration of nature or ecosystems that aim to enhance resilience through natural processes to mitigate, adapt to and withstand complex sustainability challenges. The aim is to provide for human well-being and biodiversity [1].

The soil restoration strategy of NbS can achieve more comprehensive and extensible social, environmental, and economic benefits through dynamic natural processes (Fig. 1)[2]. Among them, the social benefits of NbS have changed the situation that the traditional soil restoration method separates the living environment of the rich and the poor, reconnected with man and nature, and promoted social justice and social equality; second, in the environmental benefits of life cycle assessment (LCA) NbS, it is shown that the soil restoration measures of NbS have a low environmental footprint, in addition, NbS strategy pays more attention to the overall benefits, which can effectively promote urban renewal and improve the resilience of urban systems, providing long-term economic benefits. On the whole, the restoration strategy of NbS has protected the natural characteristics of soil, is better than the traditional restoration technology, has low cost, is easy to operate and popularize, and rarely causes secondary pollution. Restoration can enhance soil-related characteristics to maintain or restore local ecosystem services, and also effectively promote human health and biodiversity.

Fig. 1. Benefits brought by NbS's soil restoration strategy
2. NbS restoration strategy for contaminated soil

2.1. Eco-led NbS restoration strategy

The main body of NBS functioning under ecological domination

Bioremediation of NbS relies on soil-dependent organisms that act through natural physiological processes to reduce the mobility of contaminants in the soil and degrade them. It can be divided into phytoremediation, microbial remediation, biochar remediation, and animal remediation.

Phytoremediation is a plant-based green technology for soil purification, which uses plants' metabolic mechanisms to detect, absorb, degrade, remove, or control pollutants in soil [3](Table 1). Some of the pollutants adsorbed by plants are transferred to above-ground plant tissues through the root system, volatilized by transpiration, or degraded and weakened by plant metabolism, while the rest are temporarily stored in harvestable parts of plants through enrichment. The pollutants that do not enter the plant will be fixed in the plant roots through the transformation of plant secretions into their form, and decompose using plant growth process, or be absorbed or removed through their transpiration. Phytoremediation NbS emphasizes the use of near-natural approaches to enhance soil community richness, accelerate the recovery of biological habitats and enhance soil nutrient cycling processes.

Table 1 Phytoremediation pathway for NbS restoration of contaminated soil

<table>
<thead>
<tr>
<th>Function</th>
<th>Action process</th>
<th>Contaminant accumulation</th>
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<tbody>
<tr>
<td>Adsorption</td>
<td>Degradation and weakening of pollutant toxicity through plant metabolism</td>
<td>Atmosphere in plant tissue</td>
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<tr>
<td>Extraction</td>
<td>Removal of pollutants from the soil by accumulating harvestable plant biomass</td>
<td>Root/stem/m/leaf</td>
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<tr>
<td>Degradation/Conversion</td>
<td>Use of plants or related microorganisms to absorb, store, degrade or transform organic pollutants</td>
<td>Within plant tissue</td>
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<tr>
<td>Inter-root degradation</td>
<td>Degradation of organic pollutants by plant roots and inter-rooted microorganisms</td>
<td>Root</td>
</tr>
<tr>
<td>Filtration</td>
<td>Absorption, concentration, degradation, precipitation, or transformation of pollutants by plant roots and associated microorganisms</td>
<td>Above-ground parts/roots</td>
</tr>
<tr>
<td>Stabilization</td>
<td>Reducing the bioavailability of pollutants through the biomass in and around the root system</td>
<td>Soil near roots/roots</td>
</tr>
<tr>
<td>Plant Volatilization</td>
<td>Removal of pollutants from the growing substrate by plants and their transformation or dispersion into the atmosphere</td>
<td>Release into the atmosphere</td>
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Soil microorganism’s population size and structure are related to soil vegetation, soil type, food web nutrient levels, and environmental factors. Soil microorganisms metabolize or degrade soil contaminants, regulate plant growth, and promote soil structure formation by coupling underground to above-ground ecological processes. The restoration of contaminated soil in NbS uses the life metabolism of soil microorganisms to change the chemical forms of pollutants in soil, thus reducing their mobility and bioavailability in soil environment. Create a rich and complete food web to purify the site environment and alleviate soil erosion.

Biochar is a powder or particle produced by pyrolytic carbonization of plant or biomass waste. Biochar's strong recalcitrance, high porosity, and adsorption capacity allow it to act as a biofilter in NbS soil restoration by effectively inhibiting and adsorbing contaminants in the soil, thereby reducing the mobility and transforming power of contaminants and enhancing soil quality, water retention, and soil aggregate formation. The input of biochar will also increase the organic matter content of the soil. For example, the addition of hardwood biochar to contaminated soils, will restore the soil polluted by cadmium and arsenic by increasing the content of soluble arsenic in the soil or inhibiting the Restoration of arsenic.

Soil animals have high mobility and reproductive capacity, can metabolize organic matter, and are an important link in the process of transferring pollutants from the soil to the food chain. Their survival activities in the soil and the emission of intestinal microorganisms can break down, reduce or eliminate contaminants in the soil, thus affecting the composition and distribution of soil materials. For example, Pheretima lumbricus, as a soil animal, Restoration of soil is mainly through its own activities to improve soil permeability and biological effectiveness of heavy metals. Pheretima lumbricus can be the focus of current research on soil Restoration by animals in NbS.

Ecological joint restoration measures of NbS

The process of restoration of contaminated sites by NbS emphasizes the coexistence and interactions between multiple organisms [4], which can effectively reduce the stress of pollutants on soil organisms and achieve the purpose of overall restoration.

Microbial communities usually live in the inter-root zone of plants and can provide nutrients to plants through a variety of mechanisms, and the extracellular secretions of microorganisms also enhance plant growth resistance and increase the availability of pollutants to plants. Similarly, plant roots can modify the structure and ecological functions of soil microorganisms by influencing the nutrients in the inter-root microenvironment, such as regulating soil acidity. When microorganisms and plants are combined in Restoration, the plants play the inter-rooting effect to ensure the number of microorganisms around the roots and build a "transition layer" of microorganisms between pollutants
and the roots, mainly by releasing iron hydroxide complexes to fix or absorb metals in the soil [5], and improving the soil environment and promoting plant growth.

The combined microbial-animal restoration mechanism is divided into two aspects: animal foraging activities and digestion and excretion. Firstly, the activity of soil animals in the soil improves the microbial community structure to enhance the degradation effect [6]. Secondly, by feeding on microorganisms, soil animals combine the dominant strains with the rich flora in the gut and excrete back into the soil, thus reducing the residual amount of soil contaminants, enhancing the viability and degradation of the dominant strains [7], and providing nutrients for microorganisms.

The plant-animal association provides plants with soluble salts and humus through the physiological processes of soil animals and soil animal manure, and enhances the original soil nutrient structure. For example, the combined restoration of Zn-contaminated soil with earthworm manure and mustard can increase the heavy metal transport capacity of mustard while improving its yield.

When plants are affected by diseases, biochar acts as a regulator to reduce contaminants in the plant's periphery [8]. For example, cyanobacteria are soil-borne diseases caused by cyanobacteria, and biochar can suppress the occurrence of cyanobacteria by absorbing contaminants in the soil and increasing the diversity of microorganisms in the plant's root zone [9]. In addition, the presence of biochar can provide energy and influence soil properties, improve the diversity and activity of soil microorganisms, and provide suitable habitats for them.

2.2. Engineering-led NbS restoration strategies

Single bioremediation is vulnerable to the complex environment. NbS unifies engineering and ecological restoration strategies, mainly including, the construction of Constructed Wetlands (CW), conservation tillage, and green natural nano-remediation restoration techniques.

CW by using wetland vegetation that is tolerant and able to absorb pollutants, the type of substrate used (e.g. limestone), and the chemical and microbial processes involved, the wastewater generated by stormwater runoff is treated to avoid contamination and harm to the soil. For example, a French artificial wetland consisting of four shallow ponds can effectively eliminate 75-90% of leachate pollutants through sedimentation and microbial reactions. In addition, CW reuses the collected rainwater for landscape irrigation to improve species richness and landscape amenities, which also enhances social, economic, and ecological benefits.

Conventional intensive farming practices neglect and disturb soil biodiversity, resulting in nutrient loss and declining organic matter content, directly affecting plant and crop productivity and quality. In this context, scientists have provided ecological agricultural management practices and measures for NbS, using non-intensive management that enhances soil biodiversity (e.g., increased protection of cover crops, etc.). The best measures to balance soil fertility and stabilize microorganisms.

The currently developed green natural nanomaterials of NbS have shown good performance in the degradation and adsorption of soil contaminants. It can completely degrade some contaminants without removing dirt or siphoning groundwater [10]. They are also low-cost, safe, and eco-friendly. In addition, green synthetic restoration nanotechnology can be combined with the phytoremediation of NbS by using the antioxidant properties of polyphenols and caffeine molecules present in plant extracts as reducing or capping agents in restoration activities.

3. Incidental value of NbS restoration soil

3.1. Contaminated soil restoration strategies for NbS enhance biodiversity

Soil biodiversity threatened by habitat degradation, pollution, urbanization, and other phenomena that can lead to biodiversity loss and simplification, which in turn directly or indirectly affects plant diversity, nutrient cycling, and human health. Traditional restoration of contaminated soils rarely considers biodiversity, which is closely related to soil ecological functions. However, the coupling of ecological and engineering measures with NbS can replace or assist anthropogenic interventions for ecological restoration of contaminated soils, improving the richness of the soil biological community, and enhancing nutrient cycling processes in the soil. In the process of restoration, the relevant measures are gradually formed into a system and matured, which maintains its elastic and stable development (Fig.2).
soil biomes that have not been eroded by contaminants. In contrast, NbS absorbs and degrades pollutants through ecological means to properly promote microbial communities’ aggregation and vitality, thus creating a rich and complete food web to purify the site environment and relieve soil erosivity. A complete food web that converts various nutrients into plant-needed nutrimental, and inhibits soil diseases, thus increasing the richness of the biological community and maintaining the functional efficiency of the ecosystem.

3.2. Restoration of NbS soil promotes human health

The soil restoration strategy of NbS can promote the development of biodiversity while restoring the function of soil, thus reducing the risk of diseases in the soil after restoration, alleviating climate change, increasing water and food supply, and promoting human health and well-being.

People can be infected with parasitic diseases such as ascariasis and hookworm disease through direct contact with or consumption of contaminated soil products. In contrast, soil biodiversity mitigates and reduces the effects of soil pathogens and parasites, increases the diversity and density of pest suppression and pathogen-associated organisms, and decreases bacterial pathogens as microbial diversity increases. Therefore, the microbial activity of the soil is directly proportional to soil disease suppression. Compared with the large-scale disinfection of traditional soil restoration technology, NbS maximizes the retention of beneficial organisms in soil, and promotes competition and predation between soil microorganisms and pathogens, thereby reducing or suppressing disease incidence. For example, phages can "specifically hunt" pathogenic bacteria, reducing their competitive ability to survive, while restructuring the inter-rhizosphere soil flora and restoring community diversity.

Studies suggest that exposure to soil-borne allergic microorganisms (e.g., endotoxins) or beneficial microbiota may be effective in reducing the prevalence of chronic inflammatory diseases and may help build immune resilience or improve immune regulation. The soil restoration strategy of NbS not only enhances the immune resilience or improve immune regulation. The microbiota may be effective in reducing the prevalence of chronic inflammatory diseases and may help build immune resilience or improve immune regulation. The soil restoration strategy of NbS maximizes the retention of beneficial organisms in soil, and promotes competition and predation between soil microorganisms and pathogens, thereby reducing or suppressing disease incidence. For example, phages can "specifically hunt" pathogenic bacteria, reducing their competitive ability to survive, while restructuring the inter-rhizosphere soil flora and restoring community diversity.

4. Conclusions

NbS brought with it new challenges and opportunities for soil restoration technologies from the scientific, policy, and practical perspectives, respectively, to mitigate and restore contaminated sites in an integrated manner that minimizes restoration costs and maximizes net environmental benefits. This paper acknowledges the synergy and benefits of the various components of the NbS soil Restoration strategy by presenting the ecological and engineering tools included in the restoration and treatment of contaminated soils with NbS, which can be used to mitigate and restore contaminated lands to fully utilize natural laws to enhance soil biodiversity and human well-being.

References


