Soil Remediation Strategy

Subjects: Soil Science | Green & Sustainable Science & Technology

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Although soil is a valuable and non-renewable ecological system, it has always been subject to widespread degradation due to anthropic activities. The most severe risks are point source and diffuse soil pollution. The remediation of contaminated soils and sites is, therefore, a significant step in the protection of the environment and living organisms, and must be included in the broader multidisciplinary scenario of strategic green transition.

soil contamination green remediation climate change resilient remediation

1. Introduction

Protection, prevention, and remediation of soil are key goals in new environmental policies and strategies (European Green Deal and Agenda 2030), which aim at the comprehensive and sustainable transformation of major production, consumption, and trade systems [1][2][3]. Although soil is a valuable and non-renewable ecological system, it has always been subject to widespread degradation due to anthropic activities. The most severe risks are point source and diffuse soil pollution. Process industry, transport, urban sprawl, agriculture, and illegal dumping or landfill without adequate resource recovery [4] are currently among the main sources of pollutants [5][6]. The direct release or indirect deposition of organic and inorganic pollutants (including heavy metals, mineral oils, and polycyclic aromatic hydrocarbons) into the soil occurs from these activities, which has hazardous effects on the environment and human health [7]. Although the specific effects on soil and the risks to organisms are known for some pollutants, many uncertainties remain about their long-term impacts and their interactions with biodiversity and climate change.

The remediation of contaminated soils and sites is, therefore, a significant step in the protection of the environment and living organisms, and must be included in the broader multidisciplinary scenario of strategic green transition.

Various methods are currently applied to treating contaminated soils and water [8][9][10][11]. However, many of the traditional technologies (physical, chemical, and thermal) are currently considered outdated, as their only remediation objective is to remove contamination without any consideration of the side effects.

In addition, these techniques have proven to be extremely expensive in both energetic and economic terms and also highly invasive, thus, further impacting the already compromised environmental situation [12][13]. The environmental regulations of industrialized countries have also been modified in recent years, evolving towards assessing remediation through accurate risk analyses. Environmental Protection Agency (EPA) proposed the concept of “Green Remediation” (GR) to address the problem of soil contamination, in which remediation technologies are applied to the sustainable recovery of contaminated sites [14][15][16][17]. This new strategy involves innovative solutions and approaches that meet both the criteria of sustainable development and remediation. However, to address the new environmental challenges such as climate change, food security, and natural disasters, and to limit the damage they cause, further green remediation approaches are necessary for contaminated soils.

Extreme events such as heatwaves, floods, droughts, water shortages, forest fires, typhoons and tornadoes are occurring with increasing frequency and intensity, so effective countermeasures must be put in place to reduce their impact on soil remediation.

A sustainable and resilient remediation approach can be a solution to this problem. This integrated approach aims to optimise remediation outcomes, maximise the social and economic benefits, and reduce the environmental damage caused by remediation.

2. Green Remediation

The technical and scientific tools for exploring innovative solutions in soil remediation are constantly developing, in line with new international environmental policies and the challenges faced [14][16]. The evolution of remediation approaches is illustrated in **Figure 1**.

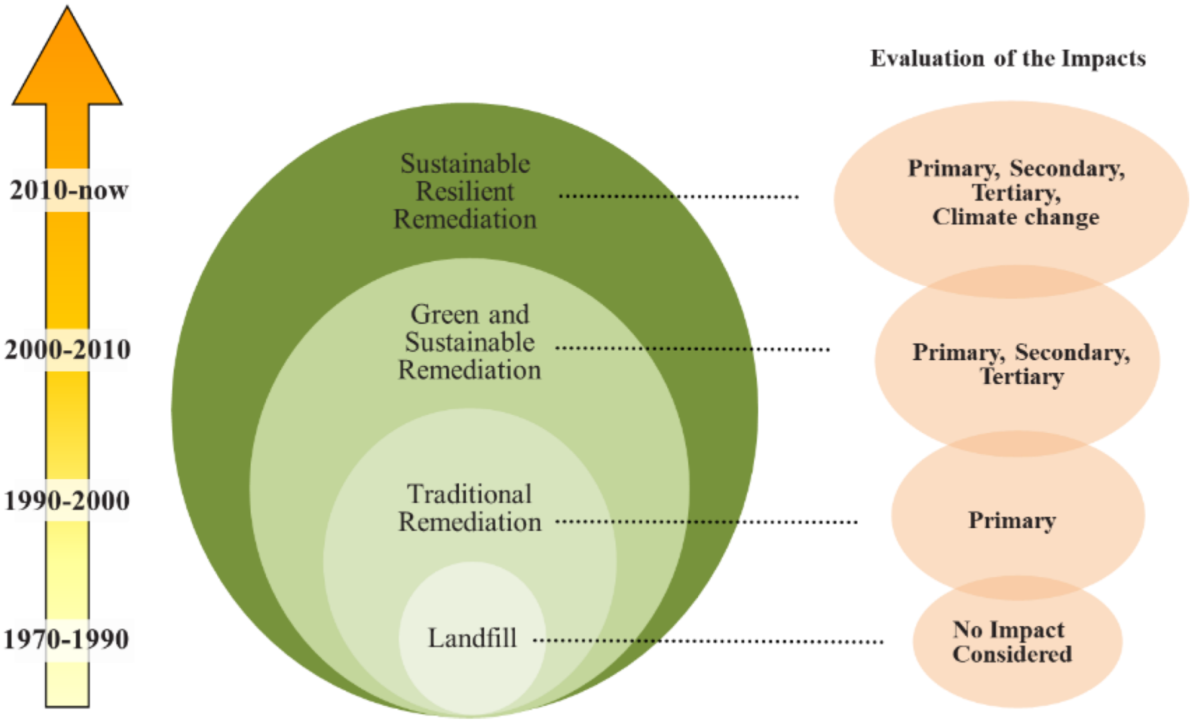

Figure 1. The evolution of remediation approaches to environmental impacts from the second half of the 20th century to the present. Primary impacts denote those associated with the situation of contaminated sites and site contaminants. Secondary impacts are those derived from remediation activity, such as the use of energy and

materials, as well as after remediation monitoring. Tertiary impacts are those associated with site redevelopment and final destinations.

In the past, contaminated soil was considered to be hazardous waste and landfilling was the most common method of disposal, due to low implementation costs. This approach was due to mistakenly equating contaminated soil with waste and, thus, waste treatment technologies were applied to soil remediation. Traditional techniques were exclusively aimed at removing contaminants and the effects of soil contamination (primary impacts) through highly invasive physical, chemical, thermal, and inertization treatments. These techniques did not consider the impact of the remediation process, such as waste generation, energy consumption, social acceptance, or the potential opportunities for economic growth and environmental sustainability. The landfill solution is, unfortunately, still used in countries with poor environmental cultures and limited economic resources [18][19]. The cleaning up of contaminated sites has, however, progressed in recent years, due to the increased attention given to environmental issues by international institutions and organisations [10][20][21]. Currently, the protection of soil functions is considered essential in the remediation process.

In the early 2000s, new remediation strategies were required as alternatives to the technologies of the time and the concept of “Green Remediation” emerged [14]. In addition to having the ultimate goal of cleaning up the soil, this new approach is addressed to reduce the environmental impacts of the contamination itself and the remediation techniques employed (secondary impacts). Interest in GR is increasing in all industrialized countries, as it includes new technologies that address the problem of remediation and also consider the socio-economic effects. This new vision of remediation, founded on Natural Based Solutions (NBS), also leads to a greater consideration of soil quality and a reduction in the use of limited environmental renewable resources.

In recent years, there has also been an increase in the publication of technical standards to ensure the efficient application of GR [22][23]. Thus, the management of a contaminated site involves the identification of best management practices (BMPs) in addition to the best available technology. BMPs improve the environmental footprint of remediation activities by considering environmental, social and economic elements [24].

In the GR approach, the prioritised remediation technologies are less-invasive and energy-passive. Suitable BMPs should be chosen to ensure that the approach is site-specific while maintaining the remediation targets.

Technology screening is, therefore, based on the assessment of environmental and socio-economic sustainability. The chosen technology must be sufficiently sustainable to overcome the negative side effects within a life cycle, through the use of BMPs that minimize secondary emissions and the production of waste. The social impacts on local communities can be addressed through the involvement of stakeholders.

The main principles of the BMPs applied to remediation [14] are summarized in **Table 1**.

Table 1. Main core elements of BMPs for green remediation strategies.

Minimization/Reduction	Maximization/Increase	Conservation/Protection of
Energy use Greenhouse gas emissions Air pollutants emission Water use Waste production Soil and habitat disturbance	Use of renewable energy Energy efficiency Waste reuse Materials management	Material resources Water quality Ecosystem services Soil quality Productive use of the contaminated site

These principles can be applied to all stages of remediation, from preliminary site investigation to site closure, and thus inform the process of selecting the most appropriate techniques.

3. Green and Sustainable Remediation

An integrated evaluation of the environmental, social, economic, and technological sectors for each phase of the remediation project is required to achieve these goals. This is the core principle of the innovative “Green and Sustainable Remediation” (GSR) movement [16], in which the decision-making process to identify the best solution involves policymakers, professional organizations, and all stakeholders. Thus, technology screening is based on the assessment of environmental and socio-economic sustainability. The sustainability of the chosen technology must involve overcoming the negative side effects within a life cycle through BMPs that minimize secondary emissions and waste production. Finally, the social impacts on local communities are addressed through the involvement of stakeholders.

The remediation of contaminated sites is only possible by applying this method, as soil quality and functionality is preserved and long-term environmental sustainability ensured.

The GSR complements the GR, as it retains all of the green principles but considers the environmental impact throughout the life of the project, rather than only in the remediation implementation phase [16]. Thus, the evaluation of the environmental footprint includes the tertiary impact of remediation, i.e., the impact associated with post-remediation effects of the site, such as redevelopment actions [25][26].

The practical implementation of the GSR strategy has been facilitated by new environmental policies designed to provide mitigation and adaptation solutions to environmental challenges (such as climate change, food security and safety). These synergistic actions, which consider both nature and society provide a sustainable and efficient alternative to traditional approaches [27]. They also represent a valuable long-term economic opportunity, with several benefits for the environment, economy, and society [28][29]. However, NBS such as phytoremediation or bioremediation in contaminated sites do not always support long-term environmental sustainability [30]. The implementation of a remediation project, even if based on natural green solutions, cannot be considered the best sustainable solution without any post-remediation activities being comprehensively evaluated.

Selecting sustainable remediation should not imply a deviation from the core goal of any remediation action, i.e., to achieve the desired level of environmental protection through the appropriate technologies. This level of protection can vary greatly, depending on the specific conditions of the site and the type of contamination. Therefore, sustainable remediation projects also require a detailed assessment of specific site characteristics and risk to ensure the regulatory requirements are met [22]. Only with such a site-specific assessment is it possible to determine the properties (e.g., solubility, mobility, volatility…) and behavior (leaching, persistence, transformation…) of the contaminants at that specific site [31].

In addition, the environmental benefit, life cycle impact, energy savings, resource recovery, waste reuse and socio-economic effects of a sustainable remediation project should be considered. The technique selected should ensure environmental and human safety and long and short-term sustainability. Thus, the sustainability of the remediation approach should be evaluated qualitatively and quantitatively using appropriate tools.

Many technologies can be considered sustainable, but this can only be confirmed over the long term through a detailed investigation of the current and future social, environmental and economic impacts of the remediation project.

Life cycle assessment (LCA) [32] is one of the most integrated quantitative methods to quantify the environmental impacts associated with the remediation technique, i.e., the secondary impacts of contamination [33]. For example, LCA allows quantifying material and energy consumption and emissions from the site characterization phase to the final treatment of any waste produced by the remediation process. When combined with qualitative models (such as a health risk assessment), this tool can assist in the decision-making in selecting and planning green remediation strategies for specific contaminated sites and targets [30][34]. With a view to sustainability, the recovery of energy and materials is an essential aspect in evaluating technologies [35][36]. Resilience and sustainability should be integrated into the remedial project life cycle.

Thus, in the design of a remediation intervention, it is necessary to identify objectives that comply with sustainability and resilience, including considerations of local climate changes impacts and the final use of the site.

Any LCA that considers resilience in a remediation project must aim to predict the frequency of severe climatic events and their potential effects not only on the area to be remediated, but also on the economy and on the local community. Technologies must also be evaluated in terms of protection of human health and the environment.

After identifying the specific climatic impacts to which a site may be exposed, it is essential to assess the vulnerability of the site to each potential impacts and the appropriate corrective actions during all the phases of remediation should be identified, from site characterization to long-term monitoring.

A remediation project must be adaptive so it can incorporate frequent updates and new forecasting information about climate change.

The future effectiveness of current remedies can then be considered. For resilience assessment, climate models of the site should be inserted in the LCA consideration and procedures [37][38][39]. Socio-economic factors that involve stakeholder participation should also be considered in concepts of resilience [40][41][42].

4. Sustainable Resilient Remediation

Awareness of the necessity of sustainable actions has recently increased in the scientific community, government, and industry organisations. However, many of the realized environmental strategies on climate change have not been completely successful [30] thus a comprehensive green transformation is yet to be implemented. Change must be cultural and behavioural to effectively counteract the now compelling evidence for global climate change.

Thus, the age of climate crisis has arrived, with increasingly frequent and extreme weather and climatic events. In Europe, there is an increasing occurrence of river and coastal floods, heatwaves, droughts, hydrogeological instability, wildfires, windstorms, typhoons, and tornadoes [43][44]. This inevitably has implications for soil remediation, and so any planning should consider the potential climate events in the site-specific context.

This adaptation to climate change must also be considered in sustainable green remediation strategies. This leads to an extension of the concept to one of sustainable resilient remediation (SRR). This SRR solution is an optimised GSR that is resilient to climate threat. To ensure the long-term effectiveness of remediation interventions and to protect the environment and human health, the impacts of climate change must be considered in any projects. The protection of environmental quality over time can also support the considerable financial investment required for the remediation of contaminated sites.

The climates of all global regions have experienced rapid change, including that of the Mediterranean, which is typically characterized by cold and rainy winters and hot and dry summers, during which water availability is often limited.

The Mediterranean area has been observed to be warming rapidly in recent years and the average annual temperature has increased by 1.4 °C from pre-industrial levels [44][45]. This trend suggests that summer rainfall in the Mediterranean area could drastically decrease in the future. This will aggravate the lack of water, and periods of drought will become more frequent and with longer duration while rainy periods will become both rarer and more violent.

The sea level of the Mediterranean has also risen by 60 mm in recent years. This will continue to increase due to the rising average temperatures leading to glacier melting at the North Pole [43][44].

This increase in extreme meteoric events and the reduction in precipitation has led to soil degradation processes becoming increasingly evident. Appropriate tools for the management and planning of remediation interventions based on future climate scenarios are, therefore, required. The impacts of climate change on soil can significantly influence the effects of remediation and compromise the long-term protection and effectiveness of applied green technologies.

Many contaminated sites exist throughout the world, with an estimated 2.8 million of contaminated sites where polluting activities have taken place in Europe [46].

Many of these sites are located in areas highly threatened by extreme weather events, which can undermine the effectiveness of the site remediation project. Contaminated industrial areas close to the sea may, for example, be at risk. As industries developed, many processing plants were built on the seashore to facilitate the discharge of residues into the sea, with the belief that the dilution effect would reduce the risk posed by the released materials.

5. Effects of Global Change on Contaminant Behaviour

Location is not the only issue affecting contaminated sites. The changing of climatic variables (e.g., temperature, winds, precipitation, currents, and snow cover) can also influence the behavior of contaminants (bioavailability, toxicity, transport, transfer, deposition and fate) and the organisms that may potentially inhabit them (i.e., their migration and distribution) [47].

Table 2 summarises the main effects of changing climatic variables on the environmental behavior of organic and inorganic soil contaminants. However, the effect of each variable can lead to secondary knock-on effects that increase the environmental risk and are difficult to predict.

Table 2. Main impacts of major environmental/climatic events on organic and inorganic soil contaminants. For each alteration of the climatic variables, the possible processes that organic or inorganic contaminants might be subjected to, are marked with a dot.

		Bioavailability Change	Toxicity Change	Volatilization	Mobilization/Transport	Deposition on Soil	Transfer in Food Chain	Atmospheric Deposition
Climatic Variables		Inorganic Contaminant						
Temperature	Heatwave	•		• (Hg, As)	•	• (Hg, As)	•	•
	Freezing	•		• (Hg, As)	•	• (Hg, As)	•	•
Precipitation	Drought	•	•	•	•	•	•	•
	Rainfall	•	•	•	•	•	•	•
Wind	Erosion			•	•	•		•
	Wind Storm			•	•	•		•

		Bioavailability Change	**Toxicity Change**	**Volatilization**	**Mobilization/Transport**	**Deposition on Soil**	**Transfer in Food Chain**	**Atmospheric Deposition**
Flooding	Hypoxia	•	•	•	•	•	•	•
	Transport	•	•	•	•	•	•	•
Fire		•	•		•		•	•
Secondary Effects								
pH alteration		•	•	•	•		•	
Salinity		•			•		•	
Climatic Variables					Organic Contaminant			
Temperature	Heatwave	•	•	•	•		•	•
	Freezing	•	•	•	•		•	•
Precipitation	Drought	•	•	•	•	•	•	•
	Rainfall	•	•	•	•	•	•	•
Wind	Erosion	•	•	•	•	•	•	•
	Wind Storm	•	•	•	•	•	•	•
Flooding	Hypoxia	•	•	•	•	•	•	•
	Transport	•	•	•	•	•	•	•
Fire		•	•	•	•	•	•	•
Secondary Effects								
pH alteration		•	•	•	•	•	•	•
Salinity			•			•	•	•

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Soil erosion induced by climate change can also cause the migration and transport of metals, as the direct loss of surface soil can lead to both landslides and the loss of significative quantities of soil organic matter. The fractions of metals strongly bonded to humic materials can thus be transported and lost at a distance from the original site [48][49].

Organic matter affects both the retention and bioavailability of heavy metals, so its decomposition, due to temperature increase, may release more contaminants into the soil solution, resulting in increased uptake by plants [50]. Although this increase can be viewed as an advantage in remediation techniques such as phytoextraction, it can cause the dangerous and uncontrolled process of contaminant biomagnification in living beings.

The increased frequency and intensity of forest fires is also a consequence of climate change. Soil properties are significantly altered by the heatwave accompanying a fire, in terms of both immediate effects and delayed modifications resulting from the changes in the soil's physical, chemical, and biological composition [51]. Apart from the dramatic impact on the biological activity of the soil, a fire greatly affects organic matter content. Organic matter is the most important erosion-preventing agent of the soil, due to its ability to form stable aggregates. In general, the higher the temperature, the greater the change in organic matter. At around 600/700 °C, practically all organic matter in the soil will be destroyed. This has immediate consequences on particle size distribution, aggregation, permeability, porosity, and plasticity, which are all parameters associated with soil erodibility.

The destruction of organic matter by fire can also dramatically affect the behavior of metals in the soil. Their altered mobility can lead to significant quantities of heavy metals leaching into groundwater [52], which can be a major source of environmental contamination. This should also be considered for green technologies that leave traces of metals in the soil during the remediation process.

In addition persistent organic pollutants (POPs) are significantly influenced by environmental changes, and particularly by increased rainfall and temperature. An increase in rainfall can result in a greater runoff of pesticides and POPs, and potential deposition in uncontaminated environments, while decreased rainfall may increase their persistence in soil [53]. Rising temperatures are generally combined with higher solar intensity and can also severely affect organic compounds such as polycyclic aromatic hydrocarbons (PAHs). Low molecular-weight PAHs are observed to volatilise more rapidly with increased temperatures and light intensity. However, the subsequent partial photo-degradation of these PAHs at the highest solar intensities can result in the formation of intermediates that are more toxic than the original compounds [54].

Contaminated sites can, thus, be considered under threat from climate change, which may reduce the efficiency of the technologies used. The efficiency of technologies can be improved through appropriate adaptive measures that can be used during the remediation process (**Figure 2**).

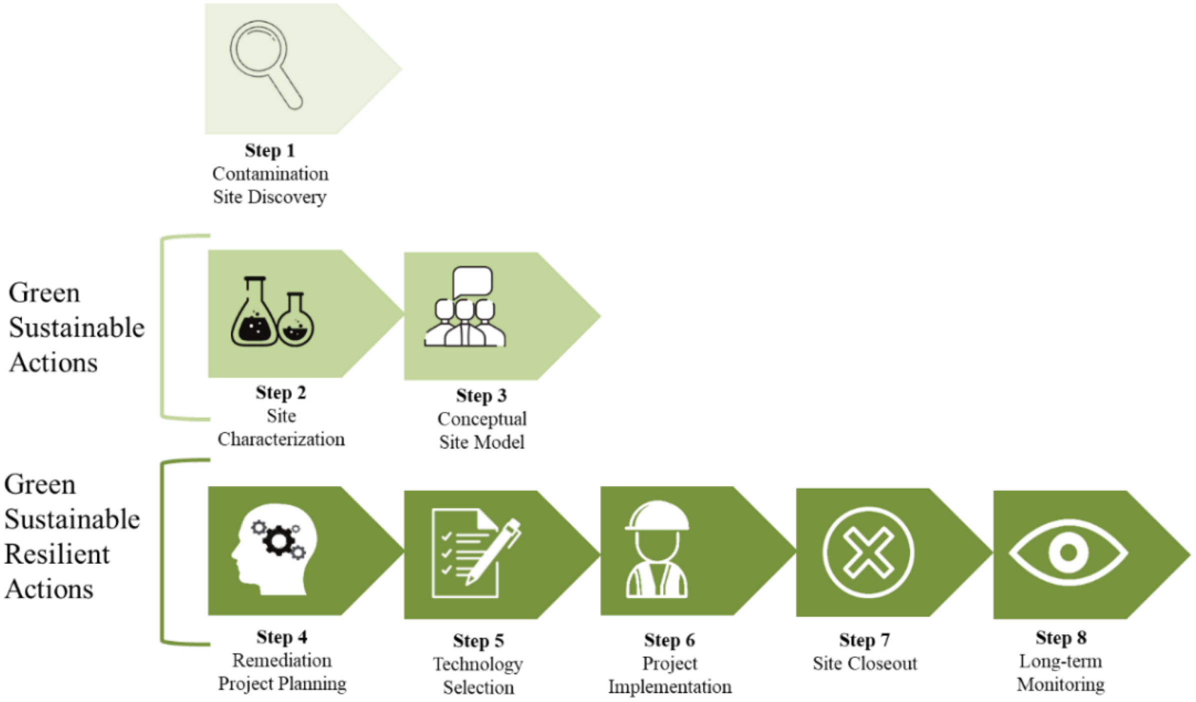

Figure 2. Framework of a contaminated soil remediation project. The steps are subdivided according to the principles of sustainability and resilience applied to the activities of each phase.

This implementation must be based on the assessment of the risks of a changing climate, to ensure appropriate adaptation strategies developed to increase the resilience of the remediation procedures. Thus, starting from the characterization phase (step 2) in addition to the traditional investigations on the nature of the contamination of soil, groundwater, etc.; it is also necessary to examine the vulnerability of the site to climate changes that could affect the effectiveness of the remediation and the risk assessment concerning potential receptors. When creating the conceptual model (step 3), the potential resilience to the impacts of local climate change can be evaluated, to ensure that the remediation process avoids any unexpected problems, such as a depletion of natural resources or an increase in unwanted emissions. These aspects should be considered in the executive remediation project (step 4), in which the concept of resilience should be integrated into remediation activities. The planning of the project, which is considered the basis of the clean-up intervention, must also involve all interested parties in the remediation and site development.

In terms of SRR, the selection of the most appropriate technology (step 5) is conducted to identify the remediation technologies of the site with the lower environmental impacts. These technologies should achieve the remediation targets, while opportunities for economic development should also be evaluated. The technologies chosen must be characterized by a high degree of adaptability in order to be able to respond to any impacts due to climate change that may occur in the geographical area of the contaminated site.

Unexpected environmental impacts can occur in the execution phase (step 6), so the technology must include appropriate resilience measures to address extreme weather events and, thus, reduce the potential negative impacts. The technology adaptability can also minimize the risks to the local community and the environment resulting from remediation.

The closure process (step 7) includes both a regulatory phase linked to achieving remediation targets and considerations of resilience, which can enable the redevelopment and reuse of a site based on the socio-environmental characteristics of the area. After remediation is completed, climatic parameters (e.g., expected rainfall, groundwater rises or falls, soil erosion, landslides) should continue to be evaluated in the long-term monitoring phase (step 8). In this way, it is possible to tackle any critical issues and the level of risk for a site can then be identified.

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