Environmental Science and Ecotechnology 27 (2025) 100601

Contents lists available at ScienceDirect

Environmental Science and Ecotechnology

journal homepage: www.journals.elsevier.com/environmental-science-and-ecotechnology/

Review

Restoring landscapes and communities: Insights from critical, urban, and plant ecology

Alexandria N. Igwe [a], Karlisa A. Callwood [b,c], Delia S. Shelton [c,d,*]

[a] Department of Biological Sciences, Virginia Tech, 24060, USA
[b] Perry Institute for Marine Science, Waitsfield, VT, 05673, USA
[c] Abess Center for Ecosystem Science & Policy, University of Miami, 33146, USA
[d] Biology Department, University of Miami, 33146, USA

A R T I C L E I N F O

Article history:
Received 20 December 2024
Received in revised form
5 July 2025
Accepted 11 July 2025

Keywords:
Political ecology
Critical ecology
Redlining
Green technology
Phytoremediation

A B S T R A C T

Humans shape the world through policies, practices, and behavior that create environmental heterogeneity. Political and critical ecology offer frameworks for understanding how societies have historically and currently used power, policies, and practices to shape environmental landscapes and conditions, ultimately influencing the ecology and evolution of biodiversity. We suggest that integrating political and critical ecology can enhance our understanding of anthropogenic influences, such as luxury effects and legacy effects, including redlining—a form of structural racism implemented in the United States. Here, we review the consequences of legacy and luxury effects on urban ecosystems, with a focus on their impact on the fauna and flora. We propose that legacy and luxury effects can have independent and interdependent influences on ecological diversity, abundance, biological invasions, and pollution exposure. Although these effects can persist, environmental remediation may provide a pathway to restorative justice. We also discuss *Plantago*, herbaceous plants with the potential to mitigate the impacts of cadmium, a notorious environmental contaminant whose disposition parallels redlining patterns. Phytoremediation can contribute to biofuels, biofoundries, and the green economy, offering solutions to restore affected communities. By applying political and critical ecology lenses, we can identify socio-ecological mechanisms that affect humans and the environment. These insights can inform the development of green infrastructure to help remediate adverse effects. Ideally, these approaches provide pathways to address historical injustices, enhance equity, and restore ecological landscapes.

1. Introduction

Structural racism, how societies perpetuate discrimination through mutually reinforcing systems of inequity [1], refers to deeply entrenched and systemic inequalities that have historically disadvantaged communities of color across multiple domains, including housing, education, healthcare, and the environment. Structural racism operates primarily through policies, practices, and norms that contribute to the perpetuation of inequities and often lead to disparities in wealth, access to resources, and overall well-being.

One of the most pervasive manifestations of structural racism is redlining, a discriminatory practice originating in the 1930s. Redlining was a form of institutionalized racism that systemically denied minoritized communities' access to mortgage loans and investment opportunities in the United States (US). The Home Owners' Loan Corporation (HOLC), established during the Great Depression, created maps that ranked neighborhoods from A through D based on their racial composition and economic status. Neighborhoods designated with an “A” were considered “Best” and outlined green on maps; those designated with a “D” were considered “Hazardous” and outlined in red, signifying high-risk areas where banks would not approve loans or investments. These so-called redlined areas were largely occupied by non-white populations, predominantly African Americans. These policies prevented these residents from building home equity and

* Corresponding author. Abess Center for Ecosystem Science & Policy, University of Miami, 33146, USA
E-mail address: dshelton@miami.edu (D.S. Shelton).

https://doi.org/10.1016/j.ese.2025.100601
2666-4984/

accessing financial resources available to their white counterparts, leading to generational economic disadvantages for people of color [2,3].

Although redlining was declared illegal in 1968, its impacts persist today [4]. The practice entrenched residential segregation and laid the foundation for modern structural racism, where housing, economic opportunity, and environmental quality continue to reflect racial inequities. Redlined areas, largely populated by nonwhite communities, were often selected for industrial development and hazardous land uses [2]. Decades of disinvestment coupled with discriminatory urban planning have resulted in reductions in green spaces [3,5–9], higher localized temperatures/urban heat islands [10,11], and persistent environmental degradation (environmental degradation can include pollution, contamination, resource depletion, ecosystem destruction, loss of ecosystem functions, extinction of flora and fauna, erosion, etc.) [12–20] in historically redlined neighborhoods. This practice has led to disproportionately high levels of environmental pollutants and increased exposure to air, water, and soil contaminants [21–24]. The environmental consequences of redlining are profound and long-lasting, particularly in terms of their impact on public health outcomes. Exposure of residents to harmful pollutants exacerbates health conditions such as cardiovascular disease, asthma, respiratory issues, cancer, and pre-term birth [25–30], and generally results in poorer physical and mental health [25–27].

Addressing the environmental and health disparities in redlined communities requires a holistic approach that integrates the interconnected social, ecological, and economic factors shaping urban systems. A socio-ecological systems (SES) perspective emphasizes that solutions must target the root causes of environmental injustice and focus on the embedded structural inequalities [28]. Rather than treating the symptoms of environmental degradation, intended actions and policies must address the systemic forces that have shaped these conditions over time. While SES approaches offer a valuable lens through which to understand the complexities existing between social, ecological, and economic systems, they often do not fully acknowledge the contributions of power and equity in these relationships. This highlights the importance of incorporating other frameworks that can place particular emphasis on these additional factors.

1.1. Looking forward through integrating political and critical ecology

Political ecology (PE) focuses on how power relations shape environmental conditions and access to resources, examining how social inequalities become embedded in the environment and contribute to systems of environmental injustice. PE asserts that environmental conditions are inextricably linked to human existence and social systems, making it impossible to separate nature from society [29,30]. This is especially true in this age of the Anthropocene, where driving forces (i.e., socio-cultural and -economic factors), human activity, and pressures (i.e., stressors from human activity on the environment) now play a dominant role in shaping ecosystems and natural processes [31–35]; yet, traditional environmental management practices often ignore this interconnectedness of social and ecological systems by treating humans as separate from nature. Political ecology challenges this divide by recognizing that human actions influence and are influenced by ecological processes, and power dynamics mediate these interactions.

One of the key contributions of PE is its ability to examine why some groups have greater access to environmental goods, such as clean air and water, while others bear the brunt of environmental "bads," including pollution and toxic waste [36]. This uneven distribution of resources and harms is often a result of both systemic racism and institutionalized power structures. These patterns of inequity are not just ecological issues but are also social, as decisions made by those in power determine which communities have greater access to vital resources and which are left to contend with environmental degradation. By examining power relations in human-environmental interactions, political ecology helps explain how environmental injustices are produced and maintained, providing a framework to understand community vulnerability to environmental risks and to assess how systems of oppression intertwine with environmental conditions (Fig. 1). This type of framework can be applied to the environmental issues surfacing from the implementation of redlining, as well as to the implementation of potential solutions to address and/or mitigate, such as green infrastructure.

Critical ecology also emphasizes the need to consider ecological issues within the broader context of social justice and history [37,38]. It challenges traditional conservation and environmental management practices, which often fail to account for the root causes of environmental degradation—namely, the historical practices and structures that have led to the exploitation of marginalized groups and environmental harm [38,39]. Whereas political ecology examines the unequal power relations at play and how these power dynamics lead to marginalization and degradation, critical ecology examines how past and present actions and decisions contribute to environmental change and the resulting impacts and inequities evident in many communities.

Together, political and critical ecology provide essential tools for understanding and addressing environmental inequities. By centering issues of power, equity, and historical legacies, these fields of study advocate for solutions that not only address environmental harms but also dismantle the underlying factors that create and sustain them. They highlight the importance of examining the social and political elements that shape human-environment interactions and emphasize the need to confront the structural causes of environmental injustice. These approaches are particularly relevant in the context of urban environments, where the historical legacies of practices like redlining have created lasting environmental and health consequences.

The legacy of redlining exemplifies how structural racism intersects with environmental injustice, creating an enduring cycle of marginalization and health disparities for communities in these redlined areas. It also underscores the importance of considering both the ecological and social dimensions of efforts aimed at addressing environmental issues to enhance public health. Though redlining has left long-lasting social, economic, and environmental damage on impacted communities, we propose that there are paths towards repair. One path forward is to acknowledge how socioeconomic factors related to wealth and development can influence and shape the ecology of urban landscapes. By examining development and social policies through the lens of legacy and luxury effects, spatial heterogeneity, including the emergence of ecological "bads" in certain communities, can be explained. Another path forward includes environmental remediation, specifically phytoremediation, i.e., using plants to remove or sequester contaminants in soil, water, and air. With this technology, cadmium and other harmful pollutants can be neutralized while also revitalizing communities through improved environmental health and economic opportunities. In the forthcoming sections of this paper, we (1) present the hypotheses of legacy and luxury effects, providing examples of how they have shaped the ecology and evolution of biodiversity in cities and (2) utilize *Plantago* species as a case study to examine cadmium tolerance, thereby exploring the mechanisms of phytoremediation. This study will also consider the potential role of this plant-based

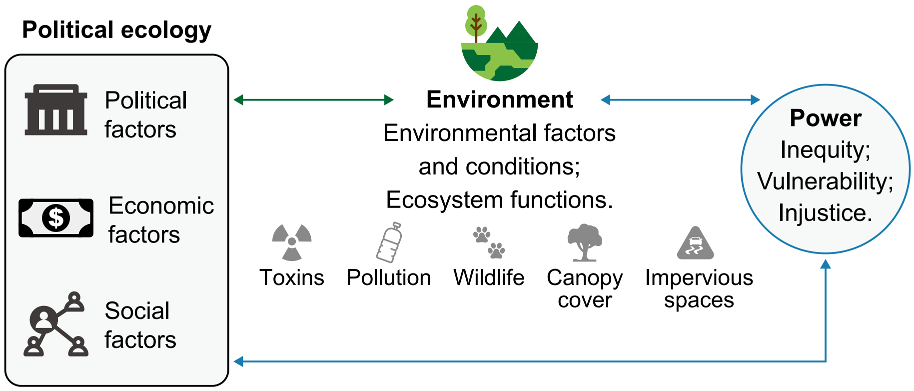

Fig. 1. Political ecology framework. Political ecology examines the dynamics between power relations and human-environmental interactions, explaining how environmental inequities and injustices, as well as community vulnerabilities to environmental risks, are produced and maintained. Some of the environmental factors and conditions that we explore throughout this manuscript are depicted in gray, including toxins, pollution, wildlife, canopy cover, and impervious spaces.

environmental remediation approach in addressing both the degradation of the land and the historical implications of redlining. With growing interest in the bioeconomy, phytoremediation presents an innovative path forward—one that addresses environmental contamination while also supporting sustainable development and community well-being.

2. Legacy and luxury effects shape landscapes

Anthropogenic factors have been recognized as key determinants of environmental landscapes. These anthropogenic factors have largely been in the realm of climate and pollution [34,35,40]; however, other explanatory variables, such as policy and socio-economic status, have also gained attention in explaining ecological heterogeneity. Increasingly, there is recognition that socioeconomic factors related to wealth and development contribute to shaping the ecology of urban environments. Development and social policies have contributed to the creation of heterogeneous urban landscapes by influencing the distribution and abundance of impervious surfaces, pollution, heat islands, and green spaces. These factors, in turn, affect water, soil, and air quality, with wide-ranging consequences for both human and environmental health. To explain the spatial heterogeneity in urban landscapes, several hypotheses have been proposed, including the legacy [15] and luxury [41] effects. Here, we will present these two hypotheses and provide examples of how they have shaped the ecology and evolution of biodiversity in cities.

2.1. Legacy effects: redlining effects

Legacy effects are suggested to arise from environmental changes induced by historical human activities, particularly in urban ecology [15]. Legacy effects are frequently used to explain patterns in natural communities and have been proposed to account for relationships between development, biodiversity, and health. Here, we will focus on the legacy effects of redlining in urban environments in the US (see the “Introduction” section) and briefly discuss other studied legacy effects worldwide and in rural communities.

A prominent example of a legacy effect is redlining (see the “Introduction” section). Although redlining was instituted in the 1930s and later repealed, persistent impacts of this structural racism continue to shape urban landscapes. Legacy effects attributed to redlining have been documented in nearly all classes of vertebrates, with a notable paucity of aquatic organisms (Fig. 2) [15,42]. The focus on terrestrial systems extends to plant biodiversity and abundance. Multiple studies consistently find higher biodiversity and abundance in HOLC grade A zones compared to lower levels in HOLC grade D zones, although some studies report only regional or negligible effects [13,43]. Differences in biodiversity and abundance between HOLC zones are often linked to variations in impervious surfaces and green space [8], and, more recently, to biases in crowd-sourced repositories (e.g., eBird) [44]. HOLC grade A zones typically feature more green spaces, which can support a greater diversity and abundance of wildlife than HOLC grade D zones [13]. In a comparative study of 37 cities, HOLC grade D zones were found to have 21 % less canopy cover than HOLC grade A zones [45]. This disparity in tree cover contributes to the observed 2.6 °C higher temperatures in HOLC grade D zones compared to HOLC grade A zones [10]. The elevated temperatures in HOLC grade D zones may impact species that exhibit temperature-dependent sex determination, as well as other temperature-sensitive physiological processes [46,47]. Recent studies on the effects of urban heat islands on ectotherms, such as amphibians and reptiles, suggest that while some species suffer from increased mortality, altered morphology, and impaired development, others exhibit greater resilience. This resilience stems from maternal nest site selection decisions, plasticity, and transgenerational inheritance of thermal tolerance, which enable adaptation to urban heat [48–50]. Although these studies explore the effects of urban heat islands on the behavior and physiology of ectotherms, direct investigations into the physiological impacts of redlining on organisms and their capacity to cope with these conditions are still needed.

Other areas of fastidious study include the relationship between redlining and pollution. There has been an emphasis on chemical and air pollution, as redlining often stratifies with abandoned hazardous waste sites, including brownfields and Superfund sites, such as incinerators, landfills, mines, and manufacturing facilities. For example, in Detroit, historically, HOLC grade D zones were located near 1.7 times more hazardous waste sites and twice the number of risk management plan sites than HOLC grade A zones [19]. A broader study of 8871 HOLC-grade neighborhoods further highlighted the legacy effects of redlining on disparities in pollution and green spaces. HOLC grade D neighborhoods were found to have significantly higher levels of environmental hazards, including 32 % more diesel particulate matter and 65 % higher traffic volumes, compared to their HOLC grade A counterparts [19]. These pollutants can have adverse effects on olfactory, auditory, and other organ systems, further exacerbating health inequities in historically marginalized communities.

Fig. 2. Structural racism in the form of redlining has led to disparities in wildlife and plant diversity and abundance, as well as pollution. Neighborhoods graded A by the Home Owners' Loan Corporation (HOLC) exhibit greater diversity and abundance of wildlife and plants, as well as increased tree canopy coverage. Conversely, neighborhoods graded D by HOLC demonstrate lower levels of wildlife diversity and abundance, reduced canopy cover, a higher presence of impervious surfaces, and greater instances of pollution. We also illustrate a physical barrier in the form of train tracks, symbolizing various obstructions (such as water bodies, bridges, and highways) that frequently hinder and limit movement between zones graded by the HOLC. Figure designed using graphic elements from Freepik.

Other forms of pollution, such as noise and light, also stratify with redlining and may shape the ecology of cities. Disparities in noise pollution from industrial and transportation networks, which often reverberate over long distances, are increasing and are projected to continue growing with ongoing urban migration [51]. Structural investments aligned with HOLC grades may explain inequalities in noise pollution distribution and its consequent effects on wildlife behavior. Noise pollution that exceeds 50 dB is well-documented for its harmful effects on both human health and the well-being of wildlife and lower noise levels may also pose harm [52–56]. In a study assessing excessive noise levels (>17.4 dB A) across 263 redlined counties in the US, researchers found that HOLC grade A zones had significantly lower maximum noise levels compared to HOLC grade C and D zones [57]. The average decibels in HOLC grade D zones were 92 % higher than in HOLC grade A zones. The elevated noise pollution in HOLC grade D zones is thought to have profound consequences for wildlife, including disruptions to foraging, communication, movement, and predator-prey interactions [42,58–60]. These effects can cascade, influencing survival rates, community structure, and even genetic diversity [16,61,62].

2.2. Luxury effects

The luxury effect suggests a positive relationship between socioeconomic status and urban biodiversity. Unlike legacy effects, which link urban biodiversity to historical human activities, luxury effects focus on the influence of current human factors. Socioeconomic status can be measured using variables such as education, income, and employment, which are often analyzed alongside biodiversity, environmental, or health variables to assess the luxury effect. Studies examining the luxury effect predominantly focus on terrestrial flora and fauna, with only a few addressing aquatic organisms such as fish and arthropods [41]. Evidence supporting the luxury effect is robust for terrestrial organisms, although the strength of the effect varies depending on factors such as income inequality, species invasiveness, and local climate. For instance, luxury effects for lizards are more pronounced in drier cities [63].

The luxury effect can have complicated impacts on ecosystems. While wealthier neighborhoods typically have more green spaces and plant diversity than poorer neighborhoods, this biodiversity often includes a higher proportion of non-native plants and animals [64]. Counties with higher per capita income also tend to have a greater abundance of exotic plant species [65]. Another ecological phenomenon at play is that hotspots of native plant diversity are more vulnerable to plant invasions [66]. Thus, HOLC grade A neighborhoods might have more invasive plants due to the “rich get richer” phenomenon observed in plant invasions in the US [66]. While more research is needed, one hypothesis is that richer households or counties that have experienced more intense development can purchase more exotic plants, creating habitats that facilitate the propagation of invasive species. These invasives can displace native wildlife and threaten local biointegrity, potentially undermining ecosystem health.

There is a paucity of studies that have assessed the luxury effect in aquatic organisms. In the United Kingdom (UK), pollutant-tolerant aquatic macrophytes were observed more frequently in areas with higher median home prices compared to areas with lower median home prices [67]. When assessing lakes, rivers, and streams for macroinvertebrates and fish and relating their diversity to house values and impervious surface areas, it was found that these factors had differing effects on macroinvertebrate and fish diversity [68]. House values paralleled increases in fish diversity, whereas impervious surface area did not affect fish diversity. For macroinvertebrates, diversity increased with higher house values and decreased with a greater amount of impervious surfaces [68]. These findings suggest that various urban factors influence the strength of the luxury effect for aquatic plants, invertebrates, and fish.

2.3. Interrelated effects

While the legacy and luxury effects can be assessed independently, they are often interconnected, with their co-occurrence influencing observed relationships with biodiversity and abundance. The strength of the legacy effect may be shaped by present-day income stratification, with legacy effects being more pronounced in areas where strong luxury effects are present. For instance, in redlined zones that have undergone gentrification, the removal of income disparities between zones may result in diminished legacy effects. Similarly, climatic effects might disrupt the expression of legacy effects. Climatic events can also disrupt the expression of legacy effects. In New Orleans, soil lead levels were stratified with HOLC-grade zones prior to Hurricane Katrina. However, the 2005 hurricane caused widespread destruction, including the loss of over 100,000 homes, massive flooding, sediment redistribution, and significant demographic shifts. These changes altered the city's ecological landscape and potentially erased prior legacy effects. Post-Katrina, the distribution of lead in the soil became more uniform and levels decreased. After Katrina, the lead distribution in the soil became more uniform, and levels decreased [69]. The hurricane also had immediate and long-term impacts on urban biodiversity. Bird abundance plummeted immediately following the storm, and the most populous species had not returned to pre-Katrina levels three years later [70]. A decade after the hurricane, rodent assemblages reflected contemporary urbanization patterns, with the greatest abundance and richness observed in areas characterized by high vacancy rates and unmanaged vegetation, such as the Lower 9th Ward. These areas historically housed a higher percentage of minoritized and lower-income individuals before the hurricane [71]. Minoritized and lower-income communities remain disproportionately vulnerable to climate threats. Future research should explore the persistence of redlining effects in the context of climate change and their implications for urban biodiversity and environmental justice.

The presence and expression of the luxury effect may depend on the types of physical barriers used to separate communities of different socioeconomic statuses. For instance, in Johannesburg, water bodies have been used to demarcate communities by economic status [72]. Interestingly, communities with lower socioeconomic status in these areas were found to have greater bird diversity than their more affluent counterparts. This phenomenon may be attributed to water bodies acting as buffers, protecting poorer communities from environmental degradation and thereby mitigating the typical patterns of the luxury effect on bird biodiversity [72]. In the US, the presence of the luxury effect varies, with some communities documenting it while others do not. This variability may be influenced by the types of physical barriers, such as highways and train tracks, used to segregate communities. Physical barriers, such as impervious surfaces, can increase residents' exposure to pollutants and reduce suitable habitats for wildlife, thereby exacerbating disparities in wildlife abundance and biodiversity [73,74]. Exploring the role of physical barriers in shaping the luxury effect presents a valuable opportunity to understand and address socio-economic disparities in wildlife diversity. Identifying strategies to minimize these disparities by mitigating the ecological impacts of such barriers could significantly improve urban biodiversity equity.

2.4. Legacy and luxury effects around the world and in rural communities

Legacy and Luxury effects have been documented in the US and UK, and to a lesser extent, around the world, including in Australia, Canada, Ecuador, Japan, South Africa, and in rural communities [68,75–80]. Certain biases and political practices such as "Ag-gag" laws that criminalize the reporting of conditions inside industrial farms, lack of access to procedural justice because legal services, courts, and political decision-makers are located in cities or are under restricted access, systematic denial of justice for disenfranchised communities, privileged access to resources (e.g., tax breaks, subsidies) in exchange for shaping the pollution narrative and coercion has led to environmental injustices in these communities being understudied and under-reported [75–79]. We encourage the reader to explore recent reviews on the legacy effects of apartheid in South Africa [81,82], tribal environmental injustices in the US [83,84] and rural communities around the world [75–77,79,85], as well as climate apartheid globally [86].

3. Redlining legacy addressed by environmental remediation

The practice of redlining and its impact have been described, but what can be done to remedy the negative social, economic, and environmental influence of the practice? Broadly, environmental remediation is the process by which contamination that could be harmful to human health is lessened or removed from the environment [87]. The contaminants can be organic and susceptible to degradation. Alternatively, contaminants can be inorganic, which means they can only be stabilized, sequestered, or removed [88]. While over 20 remediation techniques are used onsite (*in situ*) or offsite (*ex situ*) to address environmental contamination [89], the focus of this section will be phytoremediation. We encourage the reader to explore other remediation techniques via a recent review that details the physical, chemical, and biological methods of soil, water, and air remediation [90]. Phytoremediation is a specific type of environmental remediation process that uses plants, their metabolic pathways, and physiological properties to sequester, stabilize, or degrade contaminants [91] in soil and water (Fig. 3). In addition to its usefulness as an environmental remediation tool, phytoremediation can be useful for stimulating community well-being and addressing some of the negative impacts of redlining [92,93].

Phytoremediation can be subdivided based on its mode of action as phytoextraction, phytostabilization, phytovolatilization, phytostimulation, or phytodegradation [91] and these modes of action can happen alone or simultaneously (Fig. 3). The type of phytoremediation that is necessary for soil clean up depends on the soil type, contaminant type, climate, and level and location of contamination. Some reviews discuss phytoremediation [94–96], but here, the focus will be on describing cadmium tolerance in *Plantago* as a representative of the mechanisms and potentials of plant-based remediation techniques. Furthermore, we aim to contextualize plant-based remediation technology in the growing bioeconomy.

Cadmium is an inorganic contaminant with no known biological function and is toxic at low levels [97,98]. Unfortunately, it is also one of the most mobile metal contaminants due to its ability to leach into groundwater and remain in solution, whereas other metals would precipitate out [99]. Cadmium exposure can occur by mining cadmium-containing ores or through smoke inhalation, as the tobacco plant readily uptakes cadmium. Smokers have been shown to have higher levels of cadmium than non-smokers [100–102]. Generally, people are exposed to cadmium through the foods they eat, such as cereals, bread, leafy vegetables, potatoes, legumes, nuts, and stem or root vegetables [103,104]. Community gardens in previously redlined areas often have higher occurrences of heavy metals which increases contaminant exposure to the people who rely on the garden for food [105]. In addition to cadmium exposure through behavior, environmental exposure to cadmium is prevalent in communities near Superfund sites [106]. Superfund sites are locations contaminated by hazardous substances that pose potential threats to public health and the environment [107]. These sites are more common in areas that were previously redlined [19], and the impacts of that practice are still visible in the demographics of populations near Superfund sites. About 22 % of the US population lives within three miles of a Superfund site (~73 million people); 49.4 % are from minoritized groups, and 15.1 % are households below the poverty line [108]. As of 2007, 1014 of the 1669 Superfund sites that are proposed for inclusion on the National Priorities List contain cadmium [109]. Unfortunately, even low levels of cadmium can cause vision impairment, renal failure, or cancer of the lung, endometrium, bladder, and breast, and heart disease, and adversely affect social behavior [110–113]. The consequences of redlining can further be seen through environmental and health disparities [13,114]. With a growing global population and increased urbanization, foraging, and cadmium exposure, in urban areas is also expected to increase [115]. Dissecting the mechanisms of metal tolerance in plants like *Plantago* provides a way to improve plant-based technologies and

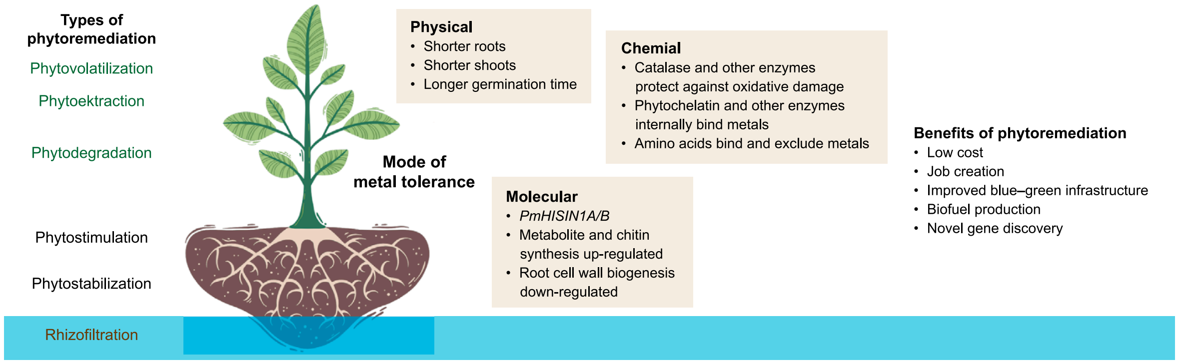

Fig. 3. Phytoremediation: types (colored by general location of action), modes of tolerance, and benefits. Phytoremediation uses plant-based technology to remove, sequester, or volatilize organic and inorganic pollutants in air, soil, and water. The most effective phytoremediators are tolerant to the contaminants that they are remediating. Plant tolerance and susceptibility to contaminants exist on a spectrum and can be measured physically, chemically, and molecularly. Utilizing this technology can mitigate the negative environmental impacts of redlining's legacy and provide social and economic benefits to communities that adopt it. Figure created using Canva.com.

offer a potential respite for the legacy effects of redlining and environmental contamination.

Plantago is a genus of mostly herbaceous plants belonging to the family Plantaginaceae. With over 250 species, these plants are globally distributed and have a variety of purposes, including medicinal [116]. Over 200 patents exist that feature this genus as a major component [117]. *Plantago* species are known to tolerate harsh environments [112–114], and co-cropping with this genus can help protect food crops, such as tomatoes, from contamination [118]. Dissecting the molecular, chemical, and physical mechanisms these plants use for cadmium tolerance can provide a roadmap for discerning similar mechanisms in other plants and contaminants.

Phytoremediation provides a cost-effective solution to cadmium contamination in urban environments. A trade-off for the low cost, however, is that this technology is time-intensive and requires regular monitoring to assess its success. Yet, the money saved and monitoring requirements can offer routes for socio-economic revitalization by planting dual-purpose plants (i.e., those that can be used for phytoremediation and biofuels), contribute to work-force development and professional development opportunities (i.e., United States Department of Agriculture International Phytoremediation Training Academy), and establish relationships with community for on-going scientific research [119].

3.1. Modes of cadmium tolerance in plantago

Cadmium tolerance and detoxification by *Plantago* is a process that occurs through the coordination of physical, chemical, and molecular plant mechanisms [120]. Physical changes in *Plantago* can be used as a biomonitoring tool to assess the extent of cadmium contamination [121]. If concentrations are high enough, the amount of seeds that germinate decreases, the time to germination increases, and seedling growth is inhibited [122]. Additionally, shoot and root lengths decrease, making a small herbaceous plant even smaller in stature [123,124]. Still, the genera's ability to accumulate cadmium in its roots and leaves in a nearly 1:1 ratio makes it an excellent bioindicator that accurately reflects the soil conditions in which it grows [125,126].

Chemical changes in *Plantago* underscore the observable physical changes, but specialized protocols or equipment are required to measure them. For example, catalase and superoxide dismutase are enzymes that generally protect against abiotic stress caused by reactive oxygen species (ROS), such as hydrogen peroxide and hydroxyl radicals [127]. These ROS can cause damage to plant protein and deoxyribonucleic acid (DNA), which can result in plant death [128]. Most simply, these enzymes can be measured using a small tissue sample and a spectrophotometer that measures light absorbance at specific wavelengths [129]. In *Plantago*, catalase and superoxide dismutase activity decrease as leaf cadmium concentration increases [130]. These enzymes protect plants from abiotic stress at multiple stages of development, including seed germination and subsequent plant growth and development [131]. L-ascorbate peroxidase (APX) and L-gulonolactone oxidase (GULO) are similar enzymes that play a role in managing oxidative stress and abiotic stress tolerance by regulating dehydroascorbate and contributing to cadmium resistance [130]. While catalase, superoxide dismutase, APX, and GULO indirectly protect the plant from the effects of cadmium toxicity, direct detoxification of cadmium occurs through enzymes such as phytochelatin and metallothionein [132]. These enzymes can be measured using various types and combinations of liquid chromatography, mass spectrometry, and stable isotope probing techniques [133]. Phytochelatin 2 and metallothionein function as metal-chelating agents that bind metals like cadmium [134,135]. Phytins, organic acids, and amino acids can also serve as metal-binding agents, increasing metal tolerance [130,136]. For example, *Plantago* can exclude cadmium by secreting various amounts of amino acids. Specifically, the secretion of acetic acid decreases, while the secretion of fumaric acid increases [137]. Genetic and molecular changes within the plant control these chemical secretions. A genome assembly was performed on *Plantago*, a species with a broad distribution, and revealed 1048 genes unique to the genus, including several related to metabolite biosynthesis. These genes controlled the biosynthesis of polyphenols and amino acids, such as histidine. Histidine can serve as a metal chelator, similar to phytochelatin and metallothionein [138], thereby improving metal tolerance. This effect was observed when *P. major* and *Arabidopsis* were treated with nickel sulfate, and only *Arabidopsis* exhibited phenotypic changes associated with metal toxicity. Genetic investigation identified *PmHISN1A/B* as a source of metal tolerance in *P. major*, and then transgenically modified *Arabidopsis* with *PmHISN1A/B*, a component of the histidine pathway. The resulting *Arabidopsis* showed improved metal tolerance [138]. Plants use similar metal detoxification mechanisms and pathways to remediate water [139,140]. Overall, in all environments, metal tolerance in plants is a tightly coordinated process that involves physical, chemical, and molecular changes.

3.2. Other plants, heavy metals and contaminants

There are many plant, contaminant, and environmental combinations for which plant-based remediation technologies can be beneficial. Some examples of other plant, contaminant, and environment combinations that have been explored include lead and *Hydrangea macrophylla* [141], manganese and *Celosia argentea* [142], and copper and lead, as well as *Sedum alfredii* [143]. Recent reviews have broadly detailed specific pollutants and the plants and phytoremediation mechanisms used to remove them from the environment [95,144–146]. Here, we will highlight some of the physical, chemical, and molecular basis of tolerance to other heavy metals. For example, two *Hydrangea macrophylla* cultivars were used to explore the chemical mechanisms of lead tolerance in the plant. One cultivar was tolerant to lead, while the other was sensitive. The tolerant cultivar had higher amounts of antioxidant enzymes, including superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT), compared to the lead-sensitive cultivar after exposure to 137 ppm of lead [141]. Interestingly, the amounts of these antioxidant enzymes increased as the lead concentration increased, which is the opposite trend observed with *Plantago* and cadmium. In *Sedum alfredii*, catalytic activity increased in response to copper tolerance [143]. It is clear that antioxidant enzymes play a role in stress tolerance; however, the exact role is dependent on the specific plant and the type of stressor. Physically, *Celosia argentea* responds to manganese stress by reducing the contents of chlorophyll *a*, chlorophyll *b*, and carotenoids, which negatively impacts photosynthesis and results in leaves that no longer appear green. Molecularly, the heavy metal-associated isoprenylated plant protein, metal transporter Nramp (natural resistance-associated macrophage protein), and zinc transporter were all implicated for their role in supporting tolerance to manganese [142]. Future research can identify analogs to these proteins in other plants to assess the range of metal-binding capabilities.

3.3. Dual-use plants for phytoremediation and the bioeconomy

The remediation of cadmium using plant-based technology has the potential to reduce soil toxicity, contribute to urban greening, develop a skilled workforce, and integrate into the growing bioeconomy, especially in areas experiencing the negative impacts of redlining. While this review focused on *Plantago*, the study and use of other plants on cadmium-contaminated soil and water can offer additional benefits, such as biofuel production, cadmium mining, and the identification of genes related to cadmium-resistance [147,148]. Using plants in this way enables communities to address environmental health concerns and contribute to the emerging bioeconomy [149,150]. The bioeconomy can be described as the “sustainable production of goods and services through the use or transformation of biological resources” [151].

When evaluating plants suitable for remediation, biofuel production, or mining, it is essential to consider several factors. Foremost among these is a plant's capacity to tolerate and absorb or degrade the target contaminant, particularly cadmium in this instance. Due to genetic variation, some plants are naturally more tolerant to pollutants than others [152]. This natural variation provides a foundation through which the ecological process of selection can function. Selective breeding can be used to amplify stress-tolerant traits in plants and further develop plant cultivars that address the needs of people. For example, biofuel production often competes with food production on arable lands, but contaminated lands cannot be safely used for food production. Therefore, stress-tolerant, weedy plants are a viable option for soil remediation, biofuel production, and community-selective breeding programs [153,154]. Considering “the global biofuel industry market was valued at $123.2 billion in 2023 and is projected to grow at a compound annual growth rate of 7.6 % during the forecast period 2024–2034,” it is worthwhile to investigate plants that can be used for biomass production for biofuels while serving an environmentally prudent purpose [155]. Additionally, the potential dual-use of these plants is part of blue–green infrastructure, which “absorbs and filters pollutants,” and can relate to the following United Nations Sustainable Development Goals Affordable and Clean Energy, Sustainable Cities and Communities, and Life on Land.

In general, plants exhibit various mechanisms to tolerate contaminants. Genetic information codes for proteins that correlate to a specific part of the stabilization or degradation process. These genes can be determined through ecological methods that compare the genomes of plants that are resistant or susceptible to a stressor. Toxicological and molecular methods can also be used by introducing a stressor to a plant and then measuring the regulation of genes [141–143]. Conducting research with these plants can serve multiple uses. Facilities, such as biofoundries, use this information to develop standardized, living, bio-based tools that can serve specific functions [156–158]. Chocolate, for example, is prone to cadmium contamination [159,160]. Therefore, scientists at the Earlham Biofoundry are identifying genes to help chocolate exclude cadmium [161]. Community-based biofoundries that investigate the molecular mechanisms of cadmium sequestration hold significant potential for advancing scientific innovation while simultaneously educating the next generation of STEM professionals [146,147] and generating revenue from their contributions. Although not every plant, contaminant, or use for contaminated land was discussed here, there are related yet distinct opportunities depending on the type of contaminant. Alternatively, plants can be selected for phytoremediation based on other ecological functions beyond biofuel production, such as carbon sequestration or erosion control. These functions also have economic values and markets associated with them that can potentially be leveraged at the community level.

4. Conclusion

Political and critical ecology can be used as holistic approaches that emphasize a socio-ecological systems perspective to address environmental and social inequities caused by the structurally racist practice of redlining. The now-defunct policy of designating homes and land in primarily non-white neighborhoods as “hazardous” continues to have an impact on environmental landscapes, urban biodiversity, pollution exposure, health disparities, and economic opportunities, as partially explained by the legacy effect. Today, communities that were graded well by the Home Owners' Loan Corporation are more affluent compared to communities that were graded poorly. Additionally, communities with higher levels of education, employment, and income tend to have more green spaces, cleaner environments, and greater plant biodiversity. The relative abundance of foliage and impervious surfaces, such as concrete and parking lots, in communities directly contributes to their ability to resist minor climate disasters. Major climate disasters have the potential to neutralize large environmental disparities across communities. Absent major natural disasters that redistribute animals, plants, and pollutants, environmental remediation is a mechanism through which air, soil, and water can be made healthier. By focusing specifically on *Plantago* and cadmium as a case study for phytoremediation—an environmental remediation technique utilizing plant-based technology—we described the physical, chemical, and molecular modes of metal tolerance, their potential applications for cleaning contaminated environments, and their potential to financially invigorate communities as part of the growing bioeconomy.

While this current study does not provide a policy recommendation, it encourages multi-disciplinary viewpoints with which to explore environmental remediation and community restoration. Ideally, policymakers, ecologists, sociologists, and community members will be able to discuss the contribution each can make to improve both the environment and the socio-economic status of communities. We encourage readers to explore the current global environmental policies and their socio-economic outcomes, as presented by the Organization for Economic Co-operation and Development, which assesses the social and economic impacts of environmental policies, and consider how local policies and their impacts compare [162–164].

Addressing environmental degradation and the impact of structural racism on community well-being continues to be an ongoing process that requires careful consideration and input from the communities most affected. The hypotheses, framework, and tools presented here offer one approach that should be scrutinized and adapted based on the material conditions of an environment and the community it sustains. The interdisciplinary nature of this approach offers multiple points of entry and inquiry for community organizers, biologists, sociologists, and all those who want to collectively advance environmental equity.

CRediT authorship contribution statement

Alexandria N. Igwe: Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization. **Karlisa A. Callwood:** Writing – review & editing, Writing – original draft, Project administration, Conceptualization. **Delia S. Shelton:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the National Institutes of Health National Institute of Environmental Health Sciences R00ES030398 and R00ES030398-04S1 to DSS, and the Agricultural Microbiomes in Plant Systems and Natural Resources grant no. FLAW-2022-09648/project accession no. 1030620 from the USDA National Institute of Food and Agriculture to ANI.

References

[1] S. Linde, R.J. Walker, J.A. Campbell, L.E. Egede, Historic residential redlining and present-day social determinants of health, home evictions, and food insecurity within US neighborhoods, J. Gen. Intern. Med. 38 (2023) 3321–3328, https://doi.org/10.1007/s11606-023-08258-5.
[2] T. McCall, K. Asuzu, C.R. Oladele, T.I. Leung, K.H. Wang, A socio-ecological approach to addressing digital redlining in the United States: a call to action for health equity, Front. Digit. Health 4 (2022) 897250, https://doi.org/10.3389/fdgth.2022.897250.
[3] N. Lathan, 50 years after being outlawed, redlining still drives neighborhood health inequities, Berkeley Pub. Health (2023).
[4] D.S. Massey, The legacy of the 1968 fair housing act, Sociol. Forum 30 (2015) 571–588, https://doi.org/10.1111/socf.12178.
[5] K.T. Burghardt, M.L. Avolio, D.H. Locke, J.M. Grove, N.F. Sonti, C.M. Swan, Current street tree communities reflect race-based housing policy and modern attempts to remedy environmental injustice, Ecology 104 (2023) e3881, https://doi.org/10.1002/ecy.3881.
[6] J. Casey, P. James, L. Cushing, B. Jesdale, R. Morello-Frosch, Race, ethnicity, income concentration and 10-Year change in urban greenness in the United States, IJERPH 14 (2017) 1546, https://doi.org/10.3390/ijerph14121546.
[7] S. Namin, W. Xu, Y. Zhou, K. Beyer, The legacy of the home owners' loan corporation and the political ecology of urban trees and air pollution in the United States, Soc. Sci. Med. 246 (2020) 112758, https://doi.org/10.1016/j.socscimed.2019.112758.
[8] A. Nardone, K.E. Rudolph, R. Morello-Frosch, J.A. Casey, Redlines and greenspace: the relationship between historical redlining and 2010 greenspace across the United States, Environ. Health Perspect. 129 (2021) 017006, https://doi.org/10.1289/EHP7495.
[9] D. Moxley, B. Fischer, Historic HOLC redlining in Indianapolis and the legacy of environmental impacts, J. Pub. Environ. Affairs 1 (2020).
[10] J.S. Hoffman, V. Shandas, N. Pendleton, The effects of historical housing policies on resident exposure to intra-urban heat: a study of 108 US urban areas, Climate 8 (2020) 12, https://doi.org/10.3390/cli8010012.
[11] B. Wilson, Urban heat management and the legacy of redlining, J. Am. Plann. Assoc. 86 (2020) 443–457, https://doi.org/10.1080/01944363.2020.1759127.
[12] C. Estien, M. Fidino, C. Wilkinson, R. Morello-Frosch, C. Schell, Historical Redlining Impacts Wildlife Biodiversity Across California, 2023, https://doi.org/10.32942/X24K60.
[13] C.O. Estien, C.E. Wilkinson, R. Morello-Frosch, C.J. Schell, Historical redlining is associated with disparities in environmental quality across California, Environ. Sci. Technol. Lett. 11 (2024) 54–59, https://doi.org/10.1021/acs.estlett.3c00870.
[14] R. Bullard, Race and Environmental Justice in the United States, Yale Journal of International Law, 1993.
[15] C.J. Schell, K. Dyson, T.L. Fuentes, Roches S. Des, N.C. Harris, D.S. Miller, C. A. Woelfle-Erskine, M.R. Lambert, The ecological and evolutionary consequences of systemic racism in urban environments, Science 369 (2020) eaay4497, https://doi.org/10.1126/science.aay4497.
[16] E.M. Wood, S. Esaian, C. Benitez, P.J. Ethington, T. Longcore, L.Y. Pomara, Historical racial redlining and contemporary patterns of income inequality negatively affect birds, their habitat, and people in Los Angeles, California, Ornithol. App. 126 (2024) duad044, https://doi.org/10.1093/ornithapp/duad044.
[17] P. Mohai, R. Saha, Racial inequality in the distribution of hazardous waste: a national-level reassessment, Soc. Probl. 54 (2007) 343–370, https://doi.org/10.1525/sp.2007.54.3.343.
[18] D.J.X. Gonzalez, C.K. Francis, G.M. Shaw, M.R. Cullen, M. Baiocchi, M. Burke, Upstream oil and gas production and ambient air pollution in California, Sci. Total Environ. 806 (2022) 150298, https://doi.org/10.1016/j.scitotenv.2021.150298.
[19] A. Shkembi, L.M. Smith, R.L. Neitzel, Linking environmental injustices in Detroit, MI to institutional racial segregation through historical federal redlining, J. Expo. Sci. Environ. Epidemiol. 34 (2024) 389–398, https://doi.org/10.1038/s41370-022-00512-y.
[20] United Church of Christ Commission for Racial Justice, in: Toxic Waste and Race in the United States: a National Report on the Racial and socio-economic Characteristics of Communities with Hazardous Waste Sites, 79, 1987.
[21] H.M. Lane, R. Morello-Frosch, J.D. Marshall, J.S. Apte, Historical redlining is associated with present-day air pollution disparities in U.S. cities, Environ. Sci. Technol. Lett. 9 (2022) 345–350, https://doi.org/10.1021/acs.estlett.1c01012.
[22] D.J.X. Gonzalez, A. Nardone, A.V. Nguyen, R. Morello-Frosch, J.A. Casey, Historic redlining and the siting of oil and gas Wells in the United States, J. Expo. Sci. Environ. Epidemiol. 33 (2023) 76–83, https://doi.org/10.1038/s41370-022-00434-9.
[23] L.J. Cushing, S. Li, B.B. Steiger, J.A. Casey, Historical red-lining is associated with fossil fuel power plant siting and present-day inequalities in air pollutant emissions, Nat. Energy 8 (2023) 52–61, https://doi.org/10.1038/s41560-022-01162-y.
[24] C.B. Swope, D. Hernández, L.J. Cushing, The relationship of historical redlining with present-day neighborhood environmental and health outcomes: a scoping review and conceptual model, J. Urban Health 99 (2022) 959–983, https://doi.org/10.1007/s11524-022-00665-z.
[25] E.E. Lynch, L.H. Malcoe, S.E. Laurent, J. Richardson, B.C. Mitchell, H.C. S. Meier, The legacy of structural racism: associations between historic redlining, current mortgage lending, and health, SSM - Populat. Health 14 (2021) 100793, https://doi.org/10.1016/j.ssmph.2021.100793.
[26] A. Nardone, J. Chiang, J. Corburn, Historic redlining and urban health today in U.S. cities, Environ. Justice 13 (2020) 109–119, https://doi.org/10.1089/env.2020.0011.
[27] E.K. Lee, G. Donley, T.H. Ciesielski, I. Gill, O. Yamoah, A. Roche, R. Martinez, D.A. Freedman, Health outcomes in redlined versus non-redlined neighborhoods: a systematic review and meta-analysis, Soc. Sci. Med. 294 (2022) 114696, https://doi.org/10.1016/j.socscimed.2021.114696.
[28] P. Leite, Urbanismo E Dignidade Humana V - Systems Theory, 2016, https://doi.org/10.58079/P368.
[29] Y. Santasombat, *Biodiversity, Local Knowledge and Sustainable Development*. Regional Center for Social Science and Sustainable Development, Faculty of Social Sciences, Chiang Mai University, 2003.
[30] P. Robbins, Political Ecology: a Critical Introduction, third ed., Wiley, Hoboken, NJ Chichester, 2020.
[31] E. Ellis, Anthropocene. the Encyclopedia of Earth, 2013.
[32] E. Andersson, S. Brogaard, L. Olsson, The political ecology of land degradation, Annu. Rev. Environ. Resour. 36 (2011) 295–319, https://doi.org/10.1146/annurev-environ-033110-092827.
[33] J. Zalasiewicz, M. Williams, W. Steffen, P. Crutzen, The new world of the anthropocene, Environ. Sci. Technol. 44 (2010) 2228–2231, https://doi.org/

10.1021/es903118j.
[34] D.S. Shelton, E.P. Martins, Behavioral variation, adaptation, and evolution, in: J. Call, G. Burkhardt, I. Pepperberg, C. Snowdon, T. Zentall (Eds.), APA Handbook of Comparative Psychology, 2017.
[35] D.S. Shelton, J.R. Alberts, Development of behavioral responses to thermal challenges, Dev. Psychobiol. 60 (2018) 5–14, https://doi.org/10.1002/dev.21588.
[36] M.M. Bell, L.L. Ashwood, I.S. Leslie, L.H. Schlachter, An Invitation to Environmental Sociology, SAGE Publications, 2020.
[37] S. Pierre, The Critical Ecology Lab: Research Towards an Liberatory Anthropogenic Change Episteme, 2023. SY43B-13.
[38] A.E. Patterson, T.M. Williams, J. Ramos, S. Pierre, Building authentic connections to science through mentorship, activism, and community, in teaching and practice, in: Transforming Education for Sustainability: Discourses on Justice, Inclusion, and Authenticity, Springer International Publishing, Cham, 2023, pp. 47–73.
[39] S. Pierre, I. Chu-Jacoby, Theoretical lineage of critical ecology, Critcal Ecol. Lab (2021). https://www.youtube.com/watch?v=LireLlbEyxk&t=506s.
[40] J.R. Kelly, et al., Wild zebrafish sentinels: biological monitoring of site differences using behavior and morphology, Toxics 9 (2021) 165, https://doi.org/10.3390/toxics9070165.
[41] M. Leong, R.R. Dunn, M.D. Trautwein, Biodiversity and socioeconomics in the city: a review of the luxury effect, Biol. Lett. 14 (2018) 20180082, https://doi.org/10.1098/rsbl.2018.0082.
[42] J.R. Nelson-Olivieri, et al., Inequalities in noise will affect urban wildlife, Nat. Ecol. Evol. 8 (2024) 163–174, https://doi.org/10.1038/s41559-023-02257-9.
[43] M.K. Collins, T. Gallo, Legacy effects of housing segregation on urban mammal communities in Washington, D.C., USA, Urban Ecosyst. 27 (2024) 2415–2424, https://doi.org/10.1007/s11252-024-01597-z.
[44] D. Ellis-Soto, M. Chapman, D.H. Locke, Historical redlining is associated with increasing geographical disparities in bird biodiversity sampling in the United States, Nat. Hum. Behav. 7 (2023) 1869–1877, https://doi.org/10.1038/s41562-023-01688-5.
[45] D.H. Locke, B. Hall, J.M. Grove, S.T.A. Pickett, L.A. Ogden, C. Aoki, C.G. Boone, J.P.M. O'Neil-Dunne, Residential housing segregation and urban tree canopy in 37 US cities, npj Urban Sust. 1 (2021) 1–9, https://doi.org/10.1038/s42949-021-00022-0.
[46] H. Akashi, D. Hasui, K. Ueda, M. Ishikawa, M. Takeda, S. Miyagawa, Understanding the role of environmental temperature on sex determination through comparative studies in reptiles and amphibians, J. Exp. Zool Pt A 341 (2024) 48–59, https://doi.org/10.1002/jez.2760.
[47] J.M. Hall, D.A. Warner, Thermal spikes from the urban heat island increase mortality and alter physiology of lizard embryos, J. Exp. Biol. 221 (2018) jeb181552.
[48] J.M. Hall, D.A. Warner, Thermal tolerance in the urban heat island: thermal sensitivity varies ontogenetically and differs between embryos of two sympatric ectotherms, J. Exp. Biol. 222 (2019) jeb210708, https://doi.org/10.1242/jeb.210708.
[49] V. Bókony, E. Balogh, J. Ujszegi, N. Ujhegyi, M. Szederkényi, A. Hettyey, Tadpoles develop elevated heat tolerance in urban heat islands regardless of sex, Evol. Biol. 51 (2024) 209–216, https://doi.org/10.1007/s11692-024-09626-7.
[50] S. Tiatragul, J.M. Hall, D.A. Warner, Nestled in the city heat: urban nesting behavior enhances embryo development of an invasive lizard, J. Urban Econ. 6 (2020) juaa001.
[51] M. Tang, X. Li, Growing disparities in transportation noise exposure across major US cities over time, Transport. Res. Transport Environ. 136 (2024) 104430, https://doi.org/10.1016/j.trd.2024.104430.
[52] O. Hahad, M. Kuntic, S. Al-Kindi, I. Kuntic, D. Gilan, K. Petrowski, A. Daiber, T. Münzel, Noise and mental health: evidence, mechanisms, and consequences, J. Expo. Sci. Environ. Epidemiol. 35 (2025) 16–23, https://doi.org/10.1038/s41370-024-00642-5.
[53] T. Münzel, M. Sørensen, A. Daiber, Transportation noise pollution and cardiovascular disease, Nat. Rev. Cardiol. 18 (2021) 619–636, https://doi.org/10.1038/s41569-021-00532-5.
[54] M. Basner, W. Babisch, A. Davis, M. Brink, C. Clark, S. Janssen, S. Stansfeld, Auditory and non-auditory effects of noise on health, Lancet 383 (2014) 1325–1332, https://doi.org/10.1016/S0140-6736(13)61613-X.
[55] A.C.M. Kok, et al., How chronic anthropogenic noise can affect wildlife communities, Front. Ecol. Evol. 11 (2023), https://doi.org/10.3389/fevo.2023.1130075.
[56] B.W. Berkhout, A. Budria, D.W. Thieltges, H. Slabbekoorn, Anthropogenic noise pollution and wildlife diseases, Trends Parasitol. 39 (2023) 181–190, https://doi.org/10.1016/j.pt.2022.12.002.
[57] T.W. Collins, S.E. Grineski, Race, historical redlining, and contemporary transportation noise disparities in the United States, J. Expo. Sci. Environ. Epidemiol. (2024) 1–12.
[58] A. Domer, C. Korine, M. Slack, I. Rojas, D. Mathieu, A. Mayo, D. Russo, Adverse effects of noise pollution on foraging and drinking behaviour of insectivorous desert Bats, Mamm. Biol. 101 (2021) 497–501.
[59] K.A. Sweet, B.P. Sweet, D.G.E. Gomes, C.D. Francis, J.R. Barber, Natural and anthropogenic noise increase vigilance and decrease foraging behaviors in song sparrows, Behav. Ecol. 33 (2022) 288–297.
[60] W. Halfwerk, K. Van Oers, Anthropogenic noise impairs foraging for cryptic prey via cross-sensory interference, Proc. R. Soc. A B. 287 (2020) 20192951, https://doi.org/10.1098/rspb.2019.2951.
[61] C. Schmidt, C.J. Garroway, Systemic racism alters wildlife genetic diversity, in: Proceedings of the National Academy of Sciences, 119, 2022 e2102860119, https://doi.org/10.1073/pnas.2102860119.
[62] J.S. Willems, J.N. Phillips, C.D. Francis, Artificial light at night and anthropogenic noise alter the foraging activity and structure of vertebrate communities, Sci. Total Environ. 805 (2022) 150223.
[63] D. Chamberlain, C. Reynolds, A. Amar, D. Henry, E. Caprio, P. Batáry, Wealth, water and wildlife: landscape aridity intensifies the urban luxury effect, Global Ecol. Biogeogr. 29 (2020) 1595–1605, https://doi.org/10.1111/geb.13122.
[64] D. Hope, C. Gries, W. Zhu, W.F. Fagan, C.L. Redman, N.B. Grimm, A.L. Nelson, C. Martin, A. Kinzig, Socioeconomics drive urban plant diversity, Proc. Natl. Acad. Sci. USA. 100 (2003) 8788–8792, https://doi.org/10.1073/pnas.1537557100.
[65] J. Zhai, D.L. Grebner, R.K. Grala, Z. Fan, I.A. Munn, Contribution of ecological and socioeconomic factors to the presence and abundance of invasive tree species in Mississippi, USA, Forests 9 (2018) 38.
[66] T.J. Stohlgren, D.T. Barnett, J.T. Kartesz, The rich get richer: patterns of plant invasions in the United States, Front. Ecol. Environ. 1 (2003) 11–14, https://doi.org/10.1890/1540-9295(2003)001[0011:TRGRPO]2.0.CO;2.
[67] D.G. Gledhill, P. James, Socio-economic variables as indicators of pond conservation value in an urban landscape, Urban Ecosyst. 15 (2012) 849–861, https://doi.org/10.1007/s11252-012-0242-7.
[68] P. Marques, A.T.M. Chin, J.L.W. Ruppert, N.E. Mandrak, The luxury effect in urban aquatic ecosystems: exploring drivers of change, Urban Ecosyst. (2024), https://doi.org/10.1007/s11252-024-01549-7.
[69] H.W. Mielke, C.R. Gonzales, E.T. Powell, Soil lead and children's blood lead disparities in pre-and post-Hurricane katrina New Orleans (USA), Int. J. Environ. Res. Publ. Health 14 (2017) 407.
[70] P.H. Yaukey, Population changes of urban land birds in the three years following the hurricane katrina flood, Nat. Hazards 61 (2012) 1203–1217.
[71] A.C. Peterson, B.M. Ghersi, R. Campanella, C. Riegel, J.A. Lewis, M.J. Blum, Rodent assemblage structure reflects socioecological mosaics of counter-urbanization across post-Hurricane katrina New Orleans, Landsc. Urban Plann. 195 (2020) 103710.
[72] C. Howes, C. Reynolds, Absence of a luxury effect on bird alpha diversity in a rapidly developing African city, but surrounding landscape is key, Landsc. Urban Plann. 213 (2021) 104095.
[73] D.N. Archer, 'white men's roads through black men's homes': advancing racial equity through highway reconstruction, Va. Law Rev. 73 (2020) 1259.
[74] R. Reft, A.P. de Lucas, R. Retzlaff, Justice and the Interstates: the Racist Truth About Urban Highways, Island Press, 2023. See, https://books.google.com/books?hl=en&lr=&id=ovyhEAAAQBAJ&oi=fnd&pg=PP1&dq=Reft,+R.,+de+Lucas,+A.+P.,+%26+Retzlaff,+R.+(Eds.).+(2023).+Justice+and+the+interstates:+The+Racist+truth+about+urban+highways.+Island+Press.&ots=qge6ZjcCA8&sig=peL_G4fFvOr0-pajcn7DUkyGbcg.
[75] K. Otsuki, Procedural equity and corporeality: imagining a just recovery in Fukushima, J. Rural Stud. 47 (2016) 300–310, https://doi.org/10.1016/j.jrurstud.2015.12.012.
[76] L.J. Kulcsar, T. Selfa, C.M. Bain, Privileged access and rural vulnerabilities: examining social and environmental exploitation in bioenergy development in the American midwest, J. Rural Stud. 47 (2016) 291–299, https://doi.org/10.1016/j.jrurstud.2016.01.008.
[77] E. Van Wagner, Law's rurality: land use law and the shaping of people-place relations in rural Ontario, J. Rural Stud. 47 (2016) 311–325, https://doi.org/10.1016/j.jrurstud.2016.01.006.
[78] T. Partridge, Rural intersections: resource marginalisation and the "non-Indian problem" in highland Ecuador, J. Rural Stud. 47 (2016) 337–349, https://doi.org/10.1016/j.jrurstud.2015.12.001.
[79] H. Masterman-Smith, J. Rafferty, J. Dunphy, S.G. Laird, The emerging field of rural environmental justice studies in Australia: reflections from an environmental community engagement program, J. Rural Stud. 47 (2016) 359–368, https://doi.org/10.1016/j.jrurstud.2016.04.005.
[80] V. Stull, M.M. Bell, M. Ncwadi, Environmental apartheid: eco-Health and rural marginalization in South Africa, J. Rural Stud. 47 (2016) 369–380, https://doi.org/10.1016/j.jrurstud.2016.04.004.
[81] C.M. Shackleton, N. Gwedla, The legacy effects of colonial and apartheid imprints on urban greening in South Africa: spaces, species, and suitability, Front. Ecol. Evol. 8 (2021), https://doi.org/10.3389/fevo.2020.579813.
[82] Z.S. Venter, C.M. Shackleton, F. Van Staden, O. Selomane, V.A. Masterson, Green apartheid: urban green infrastructure remains unequally distributed across income and race geographies in South Africa, Landsc. Urban Plann. 203 (2020) 103889, https://doi.org/10.1016/j.landurbplan.2020.103889.
[83] Á. Fernández-Llamazares, M. Garteizgogeascoa, N. Basu, E.S. Brondizio, M. Cabeza, J. Martínez-Alier, P. McElwee, V. Reyes-García, A state-of-the-art review of Indigenous Peoples and environmental pollution, Integrated Environ. Assess. Manag. 16 (2020) 324–341, https://doi.org/10.1002/ieam.4239.
[84] J. Vickery, L.M. Hunter, Native Americans: where in environmental justice research? Soc. Nat. Resour. 29 (2016) 36–52, https://doi.org/10.1080/08941920.2015.1045644.
[85] D.N. Pellow, Environmental justice and rural studies: a critical conversation

and invitation to collaboration, J. Rural Stud. 47 (2016) 381–386, https://doi.org/10.1016/j.jrurstud.2016.06.018.
[86] J.L. Rice, J. Long, A. Levenda, Against climate apartheid: confronting the persistent legacies of expendability for climate justice, Environ. Plan. E Nat. Space 5 (2022) 625–645, https://doi.org/10.1177/2514848621999286.
[87] E. Kalita, J. Baruah, Environmental remediation, in: Colloidal Metal Oxide Nanoparticles, Elsevier, 2020, pp. 525–576, https://doi.org/10.1016/B978-0-12-813357-6.00014-0.
[88] P. Borah, M. Kumar, P. Devi, Types of inorganic pollutants: metals/metalloids, acids, and organic forms, in: Inorganic Pollutants in Water, Elsevier, 2020, pp. 17–31, https://doi.org/10.1016/B978-0-12-818965-8.00002-0.
[89] Office of Land and Emergency Management, Superfund Remedy Report, seventeenth ed., 2023, pp. 1–66.
[90] M. Ugrina, A. Jurić, Current trends and future perspectives in the remediation of polluted water, soil and Air—A review, Processes 11 (2023) 3270, https://doi.org/10.3390/pr11123270.
[91] E. Pilon-Smits, Phytoremediation, Annu. Rev. Plant Biol. 56 (2005) 15–39, https://doi.org/10.1146/annurev.arplant.56.032604.144214.
[92] J.-E. Jeong, S.-A. Park, Physiological and psychological effects of visual stimulation with green plant types, IJERPH 18 (2021) 12932, https://doi.org/10.3390/ijerph182412932.
[93] R. Hunter, C. Cleland, A. Cleary, M. Droomers, B. Wheeler, D. Sinnett, M. J. Nieuwenhuijsen, M. Braubach, Environmental, health, wellbeing, social and equity effects of urban green space interventions: a meta-narrative evidence synthesis, Environ. Int. 130 (2019) 104923, https://doi.org/10.1016/j.envint.2019.104923.
[94] W. Guidi Nissim, M. Labrecque, Reclamation of urban brownfields through phytoremediation: implications for building sustainable and resilient towns, Urban For. Urban Green. 65 (2021) 127364, https://doi.org/10.1016/j.ufug.2021.127364.
[95] A. Kafle, A. Timilsina, A. Gautam, K. Adhikari, A. Bhattarai, N. Aryal, Phytoremediation: mechanisms, plant selection and enhancement by natural and synthetic agents, Environ. Adv. 8 (2022) 100203, https://doi.org/10.1016/j.envadv.2022.100203.
[96] R. Meagher, Phytoremediation of toxic elemental and organic pollutants, Curr. Opin. Plant Biol. 3 (2000) 153–162, https://doi.org/10.1016/S1369-5266(99)00054-0.
[97] Z. Ali, H. Waheed, A. Kazi, A. Hayat, M. Ahmad, Duckweed, in: Plant Metal Interaction, Elsevier, 2016, pp. 411–429, https://doi.org/10.1016/B978-0-12-803158-2.00016-3.
[98] J. Okutsu, M.I. Noor, D.S. Shelton, Swimming into view: zebrafish uncover targets, mechanisms, and therapies for cadmium toxicity, Curr. Environ. Health Rep. 12 (2025) 20, https://doi.org/10.1007/s40572-025-00471-0.
[99] A. Kubier, R. Wilkin, T. Pichler, Cadmium in soils and groundwater: a review, Appl. Geochem. 108 (2019) 104388, https://doi.org/10.1016/j.apgeochem.2019.104388.
[100] M. Geron, W. Cowell, C. Amarasiriwardena, S. Andra, K. Carroll, I. Kloog, R. Wright, R. Wright, Racial/Ethnic and neighborhood disparities in metals exposure during pregnancy in the northeastern United States, Sci. Total Environ. 820 (2022) 153249, https://doi.org/10.1016/j.scitotenv.2022.153249.
[101] X. Li, et al., Evaluation of the cadmium phytoextraction potential of tobacco (*Nicotiana tabacum*) and rhizosphere micro-characteristics under different cadmium levels, Chemosphere 286 (2022) 131714, https://doi.org/10.1016/j.chemosphere.2021.131714.
[102] P. Ashrap, et al., Predictors of urinary and blood metal(loid) concentrations among pregnant women in northern Puerto Rico, Environ. Res. 183 (2020) 109178, https://doi.org/10.1016/j.envres.2020.109178.
[103] Z. Yi, N. Lehto, B. Robinson, J. Cavanagh, Environmental and edaphic factors affecting soil cadmium uptake by spinach, potatoes, onion and wheat, Sci. Total Environ. 713 (2020) 136694, https://doi.org/10.1016/j.scitotenv.2020.136694.
[104] K. Kim, M. Melough, T. Vance, H. Noh, S. Koo, O. Chun, Dietary cadmium intake and sources in the US, Nutrients 11 (2018) 2, https://doi.org/10.3390/nu11010002.
[105] M. Malone, K. Shakya, Trace metal contamination in community garden soils across the United States, Sustainability 16 (2024) 1831, https://doi.org/10.3390/su16051831.
[106] B. Trottier, N. Niehoff, A. Keil, R. Jones, K. Levine, N. MacNell, A. White, Residential proximity to metal-containing superfund sites and their potential as a source of disparities in metal exposure among U.S. women, Environ. Health Perspect. 131 (2023) 037701, https://doi.org/10.1289/EHP11045.
[107] J. Jacquet, E. Benizri, G. Echevarria, C. Sirguey, New insights on glass industry wasteland ecosystems, Environ. Pollut. 315 (2022) 120431, https://doi.org/10.1016/j.envpol.2022.120431.
[108] U.S. EPA, Office of Land and Emergency Management, Data collected includes: (1) Superfund site information from SEMS as of the end of FY2019 and site boundary data from FY 2014 FOIA Request; and (2) population data from the 2015-2018 American Community Survey, 2020.
[109] O. Faroon, A. Ashizawa, S. Wright, P. Tucker, K. Jenkins, L. Ingerman, C. Rudisill, Toxicological Profile for Cadmium, Agency for Toxic Substances and Disease Registry (US), Atlanta (GA), 2012. See, https://www.ncbi.nlm.nih.gov/books/NBK158838/.
[110] R. Heuer, et al., Therapeutic Efficacy of Selenium Pre-treatment in Mitigating cadmium-induced Cardiotoxicity in Zebrafish (Danio rerio), 2024, https://doi.org/10.21203/rs.3.rs-4583781/v1.
[111] Cadmium, European Commision. Retrieved December 10, 2024 (n.d.). from, https://food.ec.europa.eu/food-safety/chemical-safety/contaminants/catalogue/cadmium_en.
[112] D. Shelton, P. Suriyampola, Z. Dinges, S. Glaholt, J. Shaw, E. Martins, Plants buffer some of the effects of a pair of cadmium-exposed zebrafish on the un-exposed majority, Environ. Toxicol. Pharmacol. 107 (2024) 104419, https://doi.org/10.1016/j.etap.2024.104419.
[113] D.S. Shelton, et al., A pair of cadmium-exposed zebrafish affect social behavior of the un-exposed majority, Environ. Toxicol. Pharmacol. (2023) 104119, https://doi.org/10.1016/j.etap.2023.104119.
[114] I. Motairek, Z. Chen, M.H.E. Makhlouf, S. Rajagopalan, S. Al-Kindi, Historical neighbourhood redlining and contemporary environmental racism, Local Environ. 28 (2023) 518–528, https://doi.org/10.1080/13549839.2022.2155942.
[115] S. Rezapour, S. Siavash Moghaddam, A. Nouri, K. Khosravi Aqdam, Urbanization influences the distribution, enrichment, and ecological health risk of heavy metals in croplands, Sci. Rep. 12 (2022) 3868, https://doi.org/10.1038/s41598-022-07789-x.
[116] M. Adom, M. Taher, M. Mutalabisin, M. Amri, M. Abdul Kudos, M.W.A. Wan Sulaiman, P. Sengupta, D. Susanti, Chemical constituents and medical benefits of *Plantago major*, Biomed. Pharmacother. 96 (2017) 348–360, https://doi.org/10.1016/j.biopha.2017.09.152.
[117] M. Vendruscolo, G. Von Poser, A. Henriques, M. Nemitz, Herbal products of *plantago* species: international patents survey, J. Herb. Med. 36 (2022) 100603, https://doi.org/10.1016/j.hermed.2022.100603.
[118] A. Aioub, Y. Zuo, A. Aioub, Z. Hu, Biochemical and phytoremediation of *Plantago major* L. to protect tomato plants from the contamination of cypermethrin pesticide, Environ. Sci. Pollut. Res. 28 (2021) 43992–44001, https://doi.org/10.1007/s11356-021-13853-2.
[119] Z. Webber, et al., Diné citizen science: phytoremediation of uranium and arsenic in the Navajo nation, Sci. Total Environ. 794 (2021) 148665, https://doi.org/10.1016/j.scitotenv.2021.148665.
[120] A. Grammenou, S. Petropoulos, V. Antoniadis, Bioavailability of Cd in *Plantago weldenii* and *Sonchus oleraceus* plants: the effects of a humic and fulvic acids-based biostimulant, Horticulturae 10 (2024) 74, https://doi.org/10.3390/horticulturae10010074.
[121] A. Cakaj, M. Lisiak-Zielińska, A. Hanć, A. Małecka, K. Borowiak, M. Drapikowska, Common weeds as heavy metal bioindicators: a new approach in biomonitoring, Sci. Rep. 13 (2023) 6926, https://doi.org/10.1038/s41598-023-34019-9.
[122] H. Ltaeif, A. Sakhraoui, J. Castillo, S. Rouz, O. Vicente, Germination and early seedling growth in four *plantago* species in response to Zn, Cu and Fe, EuroBiotech. J. 8 (2024) 32–43, https://doi.org/10.2478/ebtj-2024-0004.
[123] Z. Miszalski, P. Kaszycki, M. Śliwa-Cebula, A. Kaczmarczyk, M. Gieniec, P. Supel, A. Kornaś, Plasticity of *Plantago lanceolata* L. in adaptation to extreme environmental conditions, IJMS 24 (2023) 13605, https://doi.org/10.3390/ijms241713605.
[124] S. Dutta, A. Roy, P. Pramanick, S. Dey, S. Raychaudhuri, Studies on variation of phytochelatin 2 content and metallothionein 2 gene expression in presence of cadmium stress in *Plantago ovata* forsk, African J. Biol.Sci. 3 (2021) 42, https://doi.org/10.33472/AFJBS.3.4.2021.42-49.
[125] A. Cakaj, K. Drzewiecka, A. Hanć, M. Lisiak-Zielińska, L. Ciszewska, M. Drapikowska, Plants as effective bioindicators for heavy metal pollution monitoring, Environ. Res. 256 (2024) 119222, https://doi.org/10.1016/j.envres.2024.119222.
[126] L. Pietrelli, P. Menegoni, P. Papetti, Bioaccumulation of heavy metals by herbaceous species grown in urban and rural sites, Water Air Soil Pollut. 233 (2022) 141, https://doi.org/10.1007/s11270-022-05577-x.
[127] O. Ighodaro, O. Akinloye, First line defence antioxidants-superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPX): their fundamental role in the entire antioxidant defence grid, Alexandria J. Med. 54 (2018) 287–293, https://doi.org/10.1016/j.ajme.2017.09.001.
[128] M. Hasanuzzaman, M. Fujita, Plant oxidative stress: biology, physiology and mitigation, Plants 11 (2022) 1185, https://doi.org/10.3390/plants11091185.
[129] U. Sarker, S. Oba, Catalase, superoxide dismutase and ascorbate-glutathione cycle enzymes confer drought tolerance of *Amaranthus tricolor*, Sci. Rep. 8 (2018) 16496, https://doi.org/10.1038/s41598-018-34944-0.
[130] J. Yuan, R. Liu, S. Sheng, H. Fu, X. Wang, Integrated metabolomic and transcriptomic profiling revealed coping mechanisms of the edible and medicinal homologous plant *Plantago asiatica* L. cadmium resistance, Open Life Sci. 17 (2022) 1347–1359, https://doi.org/10.1515/biol-2022-0501.
[131] N. Mishra, C. Jiang, L. Chen, A. Paul, A. Chatterjee, G. Shen, Achieving abiotic stress tolerance in plants through antioxidative defense mechanisms, Front. Plant Sci. 14 (2023) 1110622, https://doi.org/10.3389/fpls.2023.1110622.
[132] A. Grennan, Metallothioneins, a diverse protein family, Plant Physiol. 155 (2011) 1750–1751, https://doi.org/10.1104/pp.111.900407.
[133] B. Wood, J. Feldmann, Quantification of phytochelatins and their metal(loid) complexes: critical assessment of current analytical methodology, Anal. Bioanal. Chem. 402 (2012) 3299–3309, https://doi.org/10.1007/s00216-011-5649-0.
[134] J. Verkleij, F. Sneller, H. Schat, Metallothioneins and phytochelatins: ecophysiological aspects, in: Y. Abrol, A. Ahmad (Eds.), Sulphur in Plants, Springer Netherlands, Dordrecht, 2003, pp. 163–176, https://doi.org/

10.1007/978-94-017-0289-8_9.
[135] S. Raychaudhuri, P. Pramanick, P. Talukder, A. Basak, Polyamines, metallothioneins, and phytochelatins—Natural defense of plants to mitigate heavy metals, in: Studies in Natural Products Chemistry, Elsevier, 2021, pp. 227–261, https://doi.org/10.1016/B978-0-12-819487-4.00006-9.
[136] A. Vega, N. Delgado, M. Handford, Increasing heavy metal tolerance by the exogenous application of organic acids, IJMS 23 (2022) 5438, https://doi.org/10.3390/ijms23105438.
[137] N. Ubeynarayana, P. Jeyakumar, P. Bishop, R. Pereira, C. Anderson, Effect of soil cadmium on root organic acid secretion by forage crops, Environ. Pollut. 268 (2021) 115839, https://doi.org/10.1016/j.envpol.2020.115839.
[138] S. Lyu, et al., Genome assembly of the pioneer species *Plantago major* L. (plantaginaceae) provides insight into its global distribution and adaptation to metal-contaminated soil, DNA Res. 30 (2023) dsad013, https://doi.org/10.1093/dnares/dsad013.
[139] Y. Pang, Y. Quek, S. Lim, S. Shuit, Review on phytoremediation potential of floating aquatic plants for heavy metals: a promising approach, Sustainability 15 (2023) 1290, https://doi.org/10.3390/su15021290.
[140] C. Delgado-González, A. Madariaga-Navarrete, J. Fernández-Cortés, M. Islas-Pelcastre, G. Oza, H. Iqbal, A. Sharma, Advances and applications of water phytoremediation: a potential biotechnological approach for the treatment of heavy metals from contaminated water, IJERPH 18 (2021) 5215, https://doi.org/10.3390/ijerph18105215.
[141] Y. Zhang, Z. Song, H. Zhao, H. Chen, B. Zhao, Integrative physiological, transcriptomic and metabolomic analysis reveals how the roots of two ornamental *Hydrangea macrophylla* cultivars cope with lead (pb) toxicity, Sci. Total Environ. 910 (2024) 168615, https://doi.org/10.1016/j.scitotenv.2023.168615.
[142] L. Liang, M. Ze, J. Yang, Q. Xu, C. Du, X. Hu, M. Dong, L. Zou, T. Qi, Physiological and transcriptomic response reveals new insight into manganese tolerance of *Celosia argentea* linn, J. Hazard Mater. 465 (2024) 133079, https://doi.org/10.1016/j.jhazmat.2023.133079.
[143] J. Ge, et al., Transcriptome analysis reveals candidate genes involved in multiple heavy metal tolerance in hyperaccumulator *Sedum alfredii*, Ecotoxicol. Environ. Saf. 241 (2022) 113795, https://doi.org/10.1016/j.ecoenv.2022.113795.
[144] S. Misra, K.G. Misra, Phytoremediation: an alternative tool towards clean and green environment, in: S. Shah, V. Venkatramanan, R. Prasad (Eds.), Sustainable Green Technologies for Environmental Management, Springer, Singapore, 2019, pp. 87–109, https://doi.org/10.1007/978-981-13-2772-8_5.
[145] Z. Wei, Q. Van Le, W. Peng, Y. Yang, H. Yang, H. Gu, S.S. Lam, C. Sonne, A review on phytoremediation of contaminants in air, water and soil, J. Hazard Mater. 403 (2021) 123658, https://doi.org/10.1016/j.jhazmat.2020.123658.
[146] L. Molina, A. Segura, Biochemical and metabolic plant responses toward polycyclic aromatic hydrocarbons and heavy metals present in atmospheric pollution, Plants 10 (2021) 2305, https://doi.org/10.3390/plants10112305.
[147] W. Qin, J. Zhao, X. Yu, X. Liu, X. Chu, J. Tian, N. Wu, Improving cadmium resistance in *Escherichia coli* through continuous genome evolution, Front. Microbiol. 10 (2019) 278, https://doi.org/10.3389/fmicb.2019.00278.
[148] H. Wang, et al., Mapping and identifying candidate genes enabling cadmium accumulation in *Brassica napus* revealed by combined BSA-seq and RNA-seq analysis, IJMS 24 (2023) 10163, https://doi.org/10.3390/ijms241210163.
[149] E. Woźniak-Gientka, A. Tyczewska, Genome editing in plants as a key technology in sustainable bioeconomy, EFB Bioecon. J. 3 (2023) 100057, https://doi.org/10.1016/j.bioeco.2023.100057.
[150] M. Gallo, The Bioeconomy: a Primer, 2022, pp. 1–33.
[151] National Academies of Sciences, Engineering, and Medicine, Safeguarding the Bioeconomy, National Academies Press, Washington, D.C., 2020, https://doi.org/10.17226/25525.
[152] A. Cortés, Abiotic stress tolerance boosted by genetic diversity in plants, IJMS 25 (2024) 5367, https://doi.org/10.3390/ijms25105367.
[153] S. Mahapatra, D. Kumar, B. Singh, P. Sachan, Biofuels and their sources of production: a review on cleaner sustainable alternative against conventional fuel, in the framework of the food and energy nexus, Energy Nexus 4 (2021) 100036, https://doi.org/10.1016/j.nexus.2021.100036.
[154] Y. Su, X. Wang, C. Liu, G. Shi, Variation in cadmium accumulation and translocation among peanut cultivars as affected by iron deficiency, Plant Soil 363 (2013) 201–213, https://doi.org/10.1007/s11104-012-1310-8.
[155] Visiongain, Biofuel industry market is projected to grow at a CAGR of 7.6% by 2034: visiongain, Global News Wire (2024). See, https://www.globenewswire.com/news-release/2024/03/27/2852952/0/en/Biofuel-Industry-market-is-projected-to-grow-at-a-CAGR-of-7-6-by-2034-Visiongain.html.
[156] M. Holowko, E. Frow, J. Reid, M. Rourke, C. Vickers, Building a biofoundry, Synthetic Biol. 6 (2021) ysaa026, https://doi.org/10.1093/synbio/ysaa026.
[157] A. Moffat, A. Elliston, N. Patron, A. Truman, J. Carrasco Lopez, A biofoundry workflow for the identification of genetic determinants of microbial growth inhibition, Synthetic Biol. 6 (2021) ysab004, https://doi.org/10.1093/synbio/ysab004.
[158] N. Hillson, A procedural framework for benchmarking biofoundry capabilities, ACS Synth. Biol. 12 (2023) 3778–3782, https://doi.org/10.1021/acssynbio.3c00491.
[159] H. Blommaert, et al., From soil to cacao bean: unravelling the pathways of cadmium translocation in a high Cd accumulating cultivar of *Theobroma cacao* L, Front. Plant Sci. 13 (2022) 1055912, https://doi.org/10.3389/fpls.2022.1055912.
[160] T. Godebo, et al., Occurrence of heavy metals coupled with elevated levels of essential elements in chocolates: health risk assessment, Food Res. Int. 187 (2024) 114360, https://doi.org/10.1016/j.foodres.2024.114360.
[161] G. Grilli, T. Cantillo, S. Ferrini, J. Richardson, K. Turner, C. Di Maria, J. Erazo, J. Azcárate, F. Di Palma, Perspectives on a bio-economy Development Path for Colombia: Cacao Farming for Peace Building and Rural Development, 2022, https://doi.org/10.6084/M9.FIGSHARE.19368212, 32436026 Bytes.
[162] Assessing the Social and Economic Impacts of Environmental Policies: Key Findings from OECD Research, 2022.
[163] OECD, Environmental Justice: Context, Challenges and National Approaches, OECD, 2024, https://doi.org/10.1787/57616eb4-en.
[164] H. Canton, Organisation for economic Co-Operation and Development—oecd, in: The Europa Directory of International Organizations 2021, Routledge, 2021.