**ABSTRACT**

MELO FILHO, Eugenio Feliciano de. Bioindicators for assessing and monitoring *brownfields* resulting from metallurgical industrial activities: a state-of-the-art review. 2024. 47 f. Monografia (MBA em Gestão de Áreas Contaminadas, Desenvolvimento Urbano Sustentável e Revitalização de *Brownfields*) – Escola Politécnica, Universidade de São Paulo, São Paulo, 2024.

Brownfield sites are defined as neglected or underutilised areas that have been previously used for industrial purposes. These sites are often associated with past metallurgical activities and present a significant challenge for environmental management due to the potential impact of potentially toxic elements (PTEs). This paper proposes a literature review of strategies for using bioindicators with a focus on soil assessment and monitoring for contaminated site management and environmental remediation. The systematic review encompassed methodologies, bioindicators selected, characteristics of study areas and evaluated chemical substances. Of the eleven studies analysed, none were conducted in Brazil, underscoring the necessity to expand research in this context. The approaches to the use of bioindicators emphasised the significance of considering the physical, chemical, and mineralogical characteristics of the soil, as well as the successional stage of urbanisation, particularly in metallurgical areas. The review also addressed the complex relationship between EPT concentrations, their bioavailability, and future ecological impacts. It highlighted the need to adapt analytical methodologies based on knowledge about the study area, the bioindicators to be used and the interaction between them. Furthermore, the review showed that soil nematodes, especially those at higher trophic levels, and the order Oribatida are promising bioindicators of soil impacted by EPTs. The difficulties in standardising bioindicators for soil assessment in metallurgical brownfields were highlighted, emphasising the necessity of furthering the comprehension of the effects of EFAs. These outcomes provide a foundation for future research aimed at urban sustainability and the rehabilitation of contaminated areas.

Keywords: Potentially Toxic Element [PTEs]; Environment rehabilitation, Metallurgical industries, Management of contaminated areas, Urban sustainability..

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**LISTA DE SIGLAS**

AI – Inteligência Artificial (do inglês, *Artificial Intelligence*)

CETESB – Companhia Ambiental do Estado de São Paulo

EMI – Índice Eco-Morfológico (do inglês, *Eco-Morphological Index*)

EPT – Elementos Potencialmente Tóxicos (do inglês, *Potentially Toxic Element*)

FDA – Diacetato de Fluoresceína (do inglês, *fluorescein diacetate*)

GAC – Gerenciamento de Áreas Contaminadas

GSRS – Padrões Genéricos de Remediação do Solo (do inglês, *Generic Soil Remediation Standards*)

LBD – Fluxos de Trabalho Baseados em Literatura (do inglês, *Literature-Based*)

NLP – Métodos de Processamento de Linguagem Natural (do inglês, *Natural Language Processing*)

PAH – Hidrocarbonetos Aromáticos Policíclicos (do inglês, *Polycyclic aromatic hydrocarbons*)

QBS – Biológico da Qualidade do Solo (do italiano, *Qualità Biologica del Suolo*)

VI – Valores de Intervenção

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# INTRODUCTION

**Introduction to Evolutionary Rescue in Polluted Environments**

The term *evolutionary rescue* is used to describe the process by which populations facing environmental stress avoid extinction through genetic adaptation. This entails populations restoring positive growth rates, either by adjusting their size or through adaptive mutations (Freitas and Campos, 2024). This phenomenon is of critical importance for the comprehension of species conservation and the evolution of resistance to stressful factors (Wilson, Pennings and Petrov, 2017). The likelihood of evolutionary rescue depends on factors such as the level of environmental stress, population size, and genetic variation (Anciaux *et al.*, 2018). It is notable that evolutionary rescue is frequently driven by soft selective sweeps, whereby multiple adaptive mutations are disseminated concurrently within the population, thereby enabling a rapid response to stress (Wilson, Pennings and Petrov, 2017). Prior exposure to stressors can also influence the probability of evolutionary rescue. For example, previous adaptation to one stressor may increase resilience to new stressors, although it may initially reduce the likelihood of plastic rescue, which is the immediate survival response of an organism to a new stressor through temporary physiological changes (Samani and Bell, 2016). [The degree of parallel evolution between independent populations under environmental stress is influenced by the initial level of maladaptation and demographic factors](https://edgeservices.bing.com/edgesvc/chat?udsframed=1&form=SHORUN&clientscopes=chat,noheader,udsedgeshop,channelstable,ntpquery,devtoolsapi,udsinwin11,udsdlpconsent,udscstart,cspgrd,&shellsig=cde3649ee30036ed9893316a7f065e2262315ce2&setlang=en-US&lightschemeovr=1&udsps=0&udspp=0#sjevt%7CDiscover.Chat.SydneyClickPageCitation%7Cadpclick%7C0%7C5cd0ec12-11ab-4e07-a254-2a1e687232d1). These factors affect the likelihood of evolutionary rescue and the level of parallelism in evolutionary responses (Freitas and Campos, 2024). In light of these considerations, a crucial question arises: whether migration and mutation can enable a population to survive and adapt in a polluted environment despite the pressures exerted by pollution.

In the specific context of polluted environments, an understanding of the ways in which populations adapt is of paramount importance for the field of conservation biology. The phenomenon of evolutionary rescue, whereby evolutionary processes serve to prevent extinction in the context of changing environments, can occur through a range of mechanisms. For instance, transgenerational plasticity offers a means of temporary resilience, enabling populations to withstand sudden environmental shifts (Harmon and Pfennig, 2021). It has been demonstrated that certain species, such as the Atlantic killifish, are capable of rapid adaptation to polluted habitats as a result of their large population sizes and significant genetic diversity (Whitehead *et al.*, 2017). Nevertheless, the process of adaptation to pollution frequently results in a reduction in fitness in unpolluted environments. This observation underscores a trade-off between the ability to adapt to stress and overall fitness (Dutilleul *et al.*, 2017). This trade-off is further shaped by mechanisms like frequency-dependent selection, where the fitness of a phenotype depends on its prevalence within the population. Such interactions can significantly influence population persistence, especially when combined with abiotic pressures (Svensson and Connallon, 2019). These studies underscore the complex relationship between evolutionary processes and environmental stressors, highlighting the importance of balancing adaptive potential with associated fitness costs in conservation strategies.

The research on adaptation to polluted environments demonstrates a complex interplay between migration, mutation and selection. In certain cases, adaptive introgression – the transfer of beneficial genes from related species – facilitates rapid evolution. This was observed in Gulf killifish, which developed resistance to toxicants (Oziolor *et al.*, 2019). In contrast, studies on Atlantic killifish have revealed an absence of evidence suggestive of mitochondrial DNA selective sweeps in polluted areas. This finding suggests that population structure is more profoundly influenced by geographic isolation than by pollution levels (Nunez *et al.*, 2018). Theoretical models also indicate that migration can facilitate differentiation in source-sink dynamics, whereby dispersal from a source population to a sink population enhances survival under stress (Mirrahimi and Gandon, 2019). Moreover, populations of rove beetles in polluted areas demonstrate elevated genetic diversity, which could be attributed to augmented mutation rates resulting from oxidative stress or the migration of individuals from neighbouring populations (Giska *et al.*, 2015). These findings highlight the role of gene flow and genetic diversity in enabling populations to adapt to environmental pollution, though mechanisms may vary across species and pollutants.

# OBJECTIVES

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# JUSTIFICATION

Em

# METHODS

## Environment setting

We set up a riverine environment with seashell population A upstream and seashell population B downstream, with the same species in both populations. There is a stable source of pollution between the upstream and downstream, which continuously discharges cyclic hydrocarbon pollutants to the downstream, so there is population decay and mutation in the downstream. However, as the river flows, some individuals from the upstream population migrate downstream, and the downstream population recovers as a result.

## Dynamic changes of population genotypes

We used R studio to model intergenerational changes in genotype of B population. This is modeled by plotting Poisson random variables based on the expected absolute number of wild-type individuals, combining the decay rate of the wild type, the selection advantage of the mutant, and the constant mutation rate, from the number of wild types to the number of mutations as Poisson random variables. We set the initial individual of the wild type as 1000, the mutation type as 0, the environmental carrying capacity as 1000, the decay rate under the influence of pollution as 0.1, the coefficient of natural selection as 0.3, the mutation rate as 0.001, and the migration individual as 3 per generation. It is worth noting that in this process, we must ensure that the coefficient of natural selection is greater than the decay rate, otherwise the population will not recover but tend to extinction.

## Tracking population dynamics as migration numbers change

In order to answer our biological questions, we must track the time it takes for populations to recover to their maximum carrying capacity at different migration levels to see how migration levels affect population recovery and the proportion of different genotypes in the population. After all parameters are set to the above values and run once, we can get the time when the population recovers to the carrying capacity when a specific number of migrations is made. On this basis, the number of migrations was set as a variable, and background values of different pollution levels with decline rates of 0.15 and 0.2 were added to increase the visibility of population changes under different backgrounds. In addition, we tried to test the number of different genotypes in each time period to see which genotype dominated the current population recovery.

## Effects of pollution degree and mutation rate on population

We also considered competition within the polluted area and the potential for mutation, with the idea that mutants are more resistant to contaminants. Based on the parameters in the method 2, we take the decay rate (under pollution) and the mutation rate as variables respectively to visualize their effects on population dynamics.

# RESULTS

## Intergenerational changes in population size and genotype

As can be seen from the figure 1, after experiencing a low point, the population size that had been gradually dying began to recover gradually, and the mutants began to dominate the process of evolutionary rescue. Under the joint action of migrating individuals and gene mutations, the population gradually recovered to the upper limit of carrying capacity.

A graph with red and blue lines

Description automatically generated

Figure 1. Intergenerational changes in population size and genotype. Black line, blue line, red line means total population size, the number of wild type and the number of mutation type respectively.

## Population dynamics as migration numbers change

After we use the number of migrants as a variable and plot the "time to carrying capacity – mean number of migrants" relationship for three different decay rates, we can see the following results.

A graph of a number of migrants

Description automatically generated

Figure 2. Population dynamics changes with the mean number of migrants at different decay rates. Blue line, red line, purple line means decay rate = 0.1, 0.15 and 0.2 respectively.

At first of figure 2, the population recovered to the carrying capacity significantly faster due to the input of migrants, but with the further increase of the number of migrants, the time to reach the carrying capacity gradually increased. But after a turning point, the rate of population recovery increases with the number of migrants, until the number of migrants in each generation can easily supplement the number of deaths in each generation (it means the number of immigrants and deaths in each generation is almost equal, reaching a steady state).

We hypothesized that in the process of decreasing the speed of reaching the carrying capacity limit with the increase of the number of migrations, the mutation rate was constant, and at the same time, the intraspecific competition and genetic dilution were increased, which made the wild type squeeze the living space of the variant, reducing the efficiency of population recovery and evolutionary rescue. To verify our hypothesis, we made some modifications to the model (increasing the mutation rate to 0.005) to observe the model change.

In figure 3, it is obvious that after modifying the mutation rate, while the time to reach the carrying capacity is greatly shortened and the process of increasing the time to reach the carrying capacity with the increase of the number of migrants is also shortened.

A graph of a number of migrants

Description automatically generated

Figure 3. Population dynamics changes with the mean number of migrants at different decay rates. Blue line, red line, purple line means decay rate = 0.1, 0.15 and 0.2 respectively. (mutation rate = 0.005)

In addition, we also made the number of different genotypes for all migration numbers, and we can conclude from Figure 4 that below a certain threshold value, evolutionary rescue is led by mutants, and after this threshold value, the process becomes wild types-led population recovery.

A graph of a number of migrants

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Figure 3. The number of different genotypes in the above model. Blue line, red line, purple line means decay rate = 0.1, 0.15 and 0.2 respectively. (mutation rate = 0.001)

## Population dynamics change under different pollution degree and mutation rate

We set the mutation rate and decay rate as variables respectively to get Figure 5 and Figure 6, where the upper limit of decay rate is set at 0.3 to ensure that mutation and natural selection can occur, otherwise the population will tend to be extinct.

A graph with a line

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A graph of pollution rate

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# CONCLUSIONS

In this study, we used a series of models to describe the impact of migrants on population dynamics, and compared population dynamics changes under different environmental pressures and variation potential to answer our biological question of "Can migrating individuals promote population recovery when considering the intraspecific competition, environmental pollution and variation potential?"

The results show that migrating individuals can indeed help the evolutionary rescue of the population, but with the increase of migration number, the efficiency of evolutionary rescue will become less due to the action of intraspecific competition and genetic dilution. As the number of migrations reaches the threshold of the wild-type dominant population recovery process, the efficiency of population recovery will be greatly improved, but we can hardly call this process "evolutionary rescue" because natural selection and variation will no longer be the dominant role in population recovery. At the same time, by changing the environmental pressure and the variation rate respectively, we can see that with the increase of environmental pressure, the efficiency of population recovery will significantly slow down or even tend to extinction, while with the increase of the variation rate, the efficiency of population recovery will slowly rise.

Although we got the results we wanted, there were some shortcomings in the study. We do not take into account the interaction of multiple variables, such as the effects of different migration numbers, environmental stress, and mutation rates in a single model. We may take this into account in future studies, and in addition, we need to generalize the model to other environments.

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