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Review Paper

Comparative Resilience of Soil Seed Banks in Restored Wildlife Corridors and Remnant Forests Under Recurrent Disturbance

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Key Words

Disturbance, Functional composition, Landscape connectivity, Seed bank resilience, Species richness.

Abstract

This paper will look at the resilience of soil seed banks in reinstated wildlife corridors and remnant forests during repeated disturbances, with emphasis on the importance of seed banks in ecosystem restoration. The vegetation recovery after disturbances cannot take place without soil seed banks, and the robustness of these seed banks in disturbed landscapes is not well comprehended. The aim was to compare the seed bank density, species richness, diversity, and functional composition of restored wildlife corridors and the remnant forests. The experiment was done in a discontinuous forest environment, having paired restored corridors and remnant forest patches. The samples of the soil and the seed bank properties were measured using a germination experiment under controlled conditions. The frequency and intensity of disturbance were described using historical data and field observations. Statistical analysis revealed significant differences between the two habitats. Seed bank density in restored corridors was significantly lower (1,420 ± 160 seeds m^{-2}) than in remnant forests (2,870 ± 210 seeds m^{-2}; $p < 0.01$). Species richness in corridors (12.4 ± 1.1 species) was significantly lower than in remnant forests (21.7 ± 1.6 species; $p < 0.01$). Shannon-Wiener diversity (H') and evenness (J') were also significantly reduced in corridors ($H' = 1.83 \pm 0.12$; $J' = 0.62 \pm 0.05$) compared to remnant forests ($H' = 2.71 \pm 0.15$; $J' = 0.78 \pm 0.04$). Resistance-recovery indices showed greater resilience in remnant forests ($R_D = 0.87 \pm 0.05$; $R_{H'} = 0.91 \pm 0.04$) than in restored corridors ($R_D = 0.58 \pm 0.07$; $R_{H'} = 0.63 \pm 0.06$). Regression analysis indicated that there was a significant negative correlation between disturbance intensity and seed bank properties, especially in corridors. These results underline the importance of considering the ecological processes in the ground when restoring the areas.

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Introduction

The soil seed banks are important in preserving the dynamics of plant community, resilience of ecosystems, and biodiversity of the landscape at the level of biodiversity. These soil seed banks serve as a time store of vegetative diversity, allowing vegetation to regenerate after disturbance like fire, grazing, logging, invasion of exotic species, and stresses on vegetation due to climate change. In the forested ecosystems, especially in the biodiversity-rich landscape, soil seed banks aid in the process of regeneration by countering the local extinctions and promoting successional patterns. Remnant forests and wildlife corridors are becoming more significant in conservation planning of fragmented landscapes. Restored wildlife corridors will restore isolated patches of habitats, increase the movement of species, and help ecological processes to be sustained in human-altered landscapes. Remnant forests, on the other hand, are relatively unchanged fragments of habitat, which in many cases have historical vegetation structure and ecological memory. Nonetheless, the two systems experience frequent disruptions, such as human-made and natural stressors, which may affect the characteristics of the soil, seed life, species mix, and the ability to regenerate. The comparative resilience of soil seed banks in sites of restored wildlife as compared to those in remnant forests is necessary to assess the long-term performance of the restoration strategies and to forecast ecosystem responses to recurrent disturbance regimes (Achim et al., 2025).

This research will aim to conduct a comparative assessment of the resilience of soil seed banks in restored wildlife corridors and remnant forest ecosystems subjected to recurrent disturbance. The research aims to determine the variation in seed bank density, species richness, and community composition among these two landscape components and to determine the ability of the components to withstand and recover in case of recurring disturbance events. By analyzing seed bank structure and regenerative potential, the research aims to determine whether restored wildlife corridors can develop below-ground resilience comparable to that of remnant forests and to identify ecological factors influencing long-term vegetation recovery in fragmented and disturbance-prone landscapes (Hua et al., 2024).

Though the topic of aboveground vegetation recovery and faunal movement in wildlife corridors has been investigated in many studies, relatively little focus has been given to below-ground regenerative processes, especially soil seed banks (Steel et al., 20234The available studies tend to be biased on an individual disturbance event or a short-term recovery in plant species only, without considering the overall impact of repetitive disturbance on the composition, density, and functional diversity of seed banks. Also, comparative studies involving restored and remnant forests are few, particularly with regard to resilience measures like resistance, recovery ability, and survivability of native species to recurrent stress. The absence of long-term studies, which are integrated, makes it difficult to define whether restored corridors are able to form seed bank features, similar to those of remnant forests, or are more prone to degradation and supremacy of introducing species (Reid et al., 2023).

The hypothesis states that soil seed banks of remnant forests will have higher species richness, species diversity, and dominance of native forest species than soil seed banks of restored wildlife corridors as an indication of higher ecological stability and historical continuity. It is also hypothesized that the restored wildlife corridors have less resilience to repeated perturbations, with fewer seed bank density and an increased proportion of disturbance-tolerant or invasive species (Gibson-Roy et al., 2023). Despite these weaknesses, however, it is hoped that the restored corridors retain operational seed bank properties, which allow partial regeneration and recovery of the ecosystem following frequent disturbance, which implies that the restored wildlife corridors can be employed to offer landscape-level resilience where the restoration sites are properly controlled.

This study makes several important contributions to ecological restoration and conservation science:

- Gives a comparative, disturbance-based evaluation of soil seed bank resilience in restored wildlife corridors versus remnant forests.
- Incorporates below-ground ecological indicators in the assessment of corridors, which provides a more comprehensive assessment of restoration success.
- Improves the knowledge of the role of repeated disturbances in determining seed banks and the regenerative ability of fragmented landscapes.
- Produces evidence-based information to guide the design of corridors, their management, and adaptive restoration techniques to be used especially in disturbance-prone forest ecologies.

The paper is divided into several major parts. The Introduction presents the significance of soil seed banks in sustaining ecosystem resilience, as well as the comparison of seed bank resilience during the restored wildlife corridors and remnant forests under recurrent disturbances. The Literature Survey is a review of the literature on the dynamics of seed banks, effects of disturbances, and the effects of restored corridors in increasing landscape connectivity. The section on Materials and Methods describes the study area, the disturbance regimes, the soil sampling design, the methods used to assess the seed bank, and the methods used to analyze the statistics. The results section summarizes the findings in terms of disturbance characteristics, seed bank density, species richness, diversity, distribution of functional groups, and resilience metrics. Lastly, the Discussion explains these findings, compares the resilience of seed banks between restored corridors and remnant forests, and speculates on the implications of these findings for the strategy of forest restoration.

Literature Survey

It is well known that soil seed banks are the key elements of forest resilience, which present a latent pool of propagules that facilitate vegetation recovery after disturbance events.

Research in a variety of ecosystems has shown that the density of seed banks, richness of species, and functional composition have a strong impact on the post-disturbance regeneration patterns. Even now, after a century of disturbance by plantations, endangered Sand Fynbos ecosystems (Rebelo et al., 2025) present convincing data of passively restored ecosystems that still possess resilient soil seed banks that can facilitate the recovery of native vegetation. Nevertheless, the authors also point out that not all functional groups have the same degree of resilience and disturbance-tolerant and pioneer species tend to dominate the initial stages of the recovery process.

Repeat activity, like fire, grazing, and land-use change, may modify seed bank structure by selectively sieving the seed bank species characteristics in terms of persistence, dormancy, and dispersal. The authors show that the recurring exposure of the ecosystem to fire in tropical forests leads to the ecosystems approaching the level of resilience, and further exposure causes the ecosystems to experience limited regenerative capacity as well as habitat loss (Sardinha et al., 2026). The results presented herein highlight the scarcity of research on the functional strength of seed bank presence in terms of cumulative disturbance regimes.

The idea of connectivity with wildlife corridors as a solution to the problem of habitat fragmentation and loss of biodiversity is gaining a greater role in forest landscape restoration. It is stated that repaired interconnectivity promotes ecological flows, animal mobility, and landscape sustainability over time (Hoffmann et al., 2025). Nevertheless, the referenced work also emphasize that structural connectivity, in itself, is not a sufficient condition of functional or regenerative success. Below-ground processes, including soil seed bank dynamics, are rarely integrated into corridor evaluation frameworks.

It is further pointed out that not only are restoration outcomes diverse due to disturbance history, species pools, and management strategies, but also that the results of restoration vary broadly (Resende et al., 2023; Tucker et al., 2023). Although active and passive restoration can restore the forest structure, it has not been established whether the strategies are effective in restoring soil seed banks that are similar to those of the remnant forests. As depicted in (Constantz et al., 2025), continuing restoration pathways of both overstory and understory communities may have a significant divergence, implying that seed banks within the soil can take diverse paths that do not necessarily emerge in the patterns of vegetation at the surface.

Non-forest empirical studies also shed more light on the interactions between restoration and disturbance to determine seed bank resilience. According to the report by Grewal et al., (2026), restored urban meadows have high seasonal and management-dependent seed bank composition, and often, restored sites have lower native species richness as compared to reference systems. Likewise, (Owiny et al., 2026) demonstrate that seed banks in thoroughly degraded mine landscapes are often comprised predominantly of stress-tolerant species unless restoration of facilitative interactions between plants and soil is initiated.

These results can be attributed to the larger successional theory, which suggests that the early-stage restoration habitats are more conducive to opportunistic and generalist species rather than those related to late-successional forest (Poorter et al., 2023). The maintenance of these patterns under repeated disturbance casts doubt on the long-term regenerative ability of restored corridors relative to remnant forests, in which more diverse and functionally balanced seed banks are maintained by stable microclimatic conditions and constant seed rain.

The influences of repeated disturbance on regeneration are becoming progressively known to be non-linear. According to (Marshall et al., 2023), the disturbance frequency and intensity are considered the major limitations of the restoration of the global forest landscape, as the repetition of disturbances may result in the loss of ecological memory in the form of soil seed banks. Similar reports have also been made by (Kewessa & Tolera, 2025) that seedling regeneration and woody species diversity make good predictors of the sustainability of the ecosystem, especially in the forests that are subjected to continuous anthropogenic activities.

Fire-sensitive and tropical wet forests appear especially vulnerable to disturbance-driven seed bank degradation. (Gunatilleke et al., 2023) Highlight that in tropical wet Asia, restoration success is closely tied to the preservation of remnant forest patches that act as reservoirs of biodiversity and propagules. Such reference systems are not present in restored landscapes; without them, the restored landscape runs the risk of overstepping regeneration boundaries that restrict recovery in the long run.

Landscape context plays a crucial role in shaping seed bank resilience. The research on forest landscape restoration in Indonesia and Sub-Saharan Africa notes that the closeness to remnant forests positively impacts the natural regeneration of forests by offering the constant supply of seeds and protecting against species extinction (Indrajaya et al., 2022; Owiny et al., 2025). (Millington et al., 2023), Also, prove that forest regeneration, even in the context of human-altered landscapes, can only help biodiversity to the extent that such landscapes remain connected to the intact ecosystem.

The supply and variety of native seed sources are also very important constraints. In turn, (Pedrini et al., 2023) state that the global restoration initiative is currently constrained by a lack of native seeds, which directly results in the composition of the seed bank in the soil in the restored area. This is especially true of wildlife corridors, which can be assisted in regenerating, and which can be short of historical seed bank legacies found in original forests.

All these sources taken together indicate that restored wildlife corridors can provide landscape-scale connectivity and regeneration, but their soils have seed banks of less diversity and are more adapted to disturbance than the soils of remnant forests. These differences are further enhanced by recurrent disturbances that benefit opportunistic species and destroy ecological memory that is stored in the soil. Despite the recent progress of restoration science in comprehending aboveground recovery and connectivity, there have not been explicit comparative studies of soil seed bank resilience of restored corridors and remnant forests under repeated disturbance regimes. This discrepancy implies the necessity of combined research, which would bridge the gap between below-ground regenerative ability, disturbance in the past, and landscape connections. This type of study is important in the determination of whether or not restored wildlife corridors can be functionally equivalent to remnant forests in terms of long-term resilience and ecosystem sustainability.

Materials and methods

Study Area and Site Selection

The study was conducted in a fragmented forest landscape comprising restored wildlife corridors and adjacent remnant forest patches. Restored wildlife corridors were selected based on documented restoration history, minimum corridor age sufficient for seed bank development, and evidence of recurrent disturbance such as grazing, fire, or anthropogenic activity. The sites of the remnant forests were selected to be representative of relatively undisturbed reference ecosystems that had similar soil type, elevation, and climatic conditions. Paired corridorforest sites were set up in the same landscape matrix to have comparability and reduce the effects of confounding the variability of the regional environment.

Disturbance Regime Characterization

To measure recurrent disturbance in each site, a mixture of historical records, field observations, and proxy indicators (fire scars, grazing intensity, canopy openness, and invasive species presence) was used to assess recurrent disturbance. The frequency and intensity of disturbances were classified according to the number of disturbance events within a specified period of time, and their visible ecological effects. This description allowed evaluating the responses of soil seed banks not to singular disturbances but to the pressure of cumulative disturbance, which is closer to the conditions in fragmented landscapes.

Figure 1 shows the difference between the disturbance regimes and the regenerative processes of restored wildlife corridors and neighboring patches of remnant forests in fragmented landscapes. Recurrent disturbances such as fire, grazing, canopy opening, invasive species pressure, and anthropogenic activities are demonstrated to be higher and more intense in restored corridors than in remnant forests.

The figure illustrates the interactions between these disturbance regimes and the seed banks of the soil by changing the seed density, species composition, and the representation of functional groups.

Variations in resistance and recovery curves are also conceptualized, where it is found that seed banks in restored corridors have lower resilience and partial recovery than the higher resistance and stable recovery of remnant forest seed banks. The framework gives a graphical summary of the role of cumulative disturbance pressure in determining the influence on below-ground regenerative capacity and long-term restoration results.

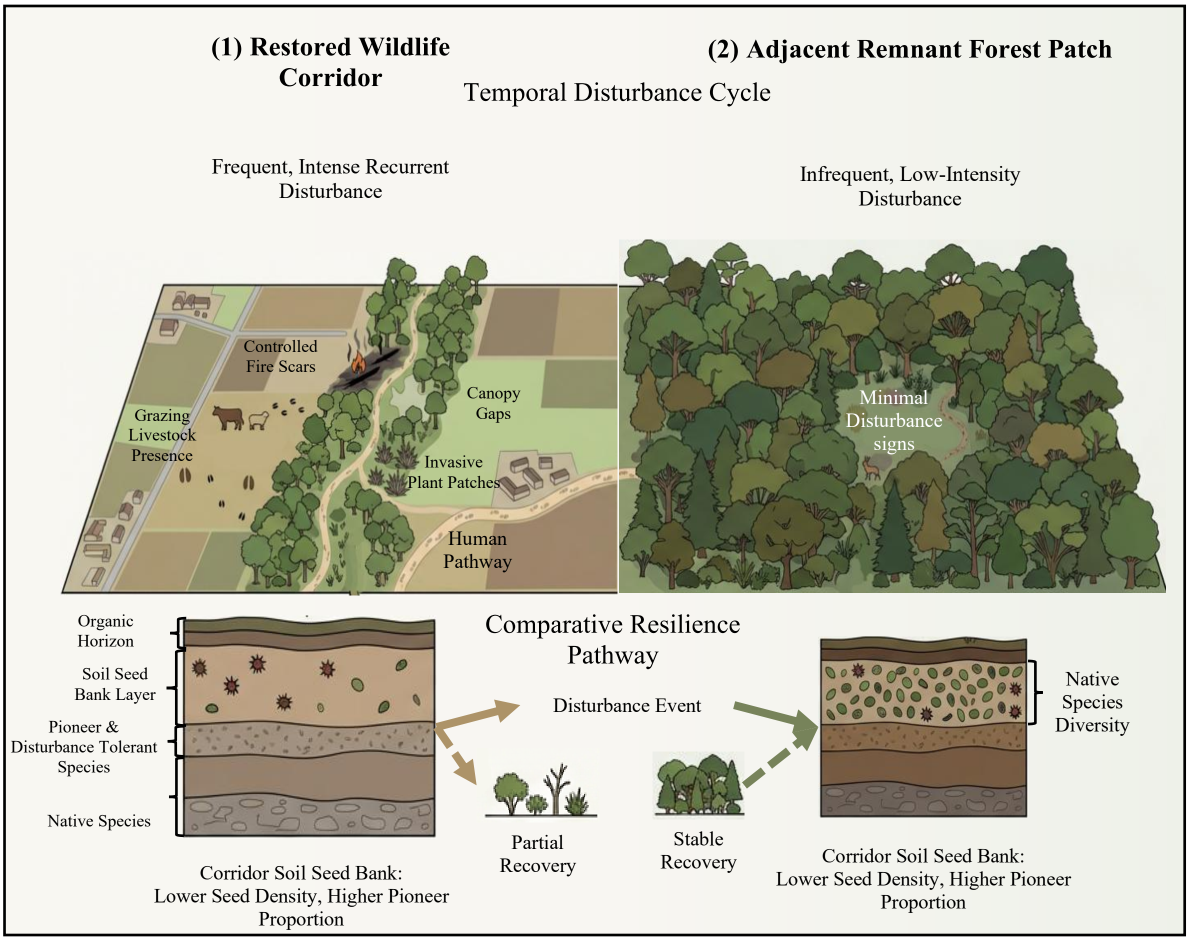

Figure 1: Conceptual Framework Illustrating Recurrent Disturbance Regimes Influencing Soil Seed Bank Resilience In Restored Wildlife Corridors And Remnant Forests

Soil Sampling Design

The pre-monsoon season was selected as the time to sample the soils, and this was before the soils germinated at maximum. At each site, multiple sampling plots were established along transects covering edge-to-core gradients in both restored corridors and remnant forests. Within each plot, soil cores were collected to a standardized depth representing the biologically active seed bank layer. Homogenization of samples within the plot was done to minimize the variability of microsites but maintain spatial independence among the plots. All the soil samples were air dried, sieved to eliminate debris, and kept under controlled conditions before analysis of the seed bank.

Seed Bank Assessment through Germination Experiment

The seedbank of the soil was evaluated by the seedling emergence technique in controlled conditions. Ready samples of soil, having been placed in thin layers on sterile substrate on germination trays, were subjected to uniform light, temperature, and moisture regimes. The identification was done to the lowest possible taxonomic level, counting and eliminating emerging seedlings to avoid competition. The germination test was also maintained until no additional seedling germination would be observed after a certain number of observation cycles, making sure that the viable seed bank is well represented.

Calculations of seed bank density were done by dividing the number of seedlings that germinated by the unit area, which was in units of square meters. The richness of the species was identified as the total number of species per sample, and the community composition was determined using the relative abundance of species.

Functional and Compositional Classification

Based on regional floras and ecological trait databases, identified species were categorized according to functional group (native forest species, pioneer species, disturbance-tolerant species, and invasive species). This classification allowed the assessment of functional resilience by making the distinction between the regenerative power of native forest taxa and the recovery of opportunistic species. Differences in functional composition between restored corridors and remnant forests were used to infer ecological stability and long-term restoration trajectories.

Resilience Metrics and Quantitative Indices

Soil seed bank resilience was quantified using diversity, similarity, and resistance–recovery metrics. Species diversity was measured using the Shannon–Wiener diversity index, calculated as:

$$H' = -\sum_{i=1}^{S} P_i \ln(P_i) \qquad (1)$$

In equation (1), pi represents the proportion of individuals belonging to species I, and S is the total number of species.

Seed bank similarity between restored corridors and remnant forests was evaluated using the Sørensen similarity index:

$$SSI = \frac{2C}{A+B} \qquad (2)$$

In equation (2), C is the number of species common to both habitats, A is the total number of species in restored corridors, and B is the total number of species in remnant forests.

Resilience under recurrent disturbance was assessed using a resistance–recovery index that compares post-disturbance soil seed bank attributes with baseline reference conditions. For each site, seed bank density and diversity measured following exposure to recurrent disturbances were standardized against corresponding reference values derived from remnant forest sites. This index is a composite estimator of a disturbance tolerance and a disturbance recovery ability, where a value near unity is associated with a high resilience and regenerative ability, and a lower value is associated with low resistance to disturbance or incomplete regenerative ability. The resistance–recovery index enabled direct comparison of resilience trajectories between restored wildlife corridors and remnant forests under cumulative disturbance pressure.

Statistical Analysis

By using the proper statistical tests, either parametric or non-parametric, based on the data distribution, seed bank density, species richness, and diversity of the seed bank in restored corridors and remnant forests, a comparative analysis can be conducted. To analyse the variations in the seed bank composition with the change in habitat type and gradients of disturbance, multivariate ordination tools like the non-metric multidimensional scaling tool were used. The significant compositional differences were tested through permutational analysis of variance, with the variation in seed bank structure correlated with the disturbance intensity and habitat category.

Disturbance Regime Characteristics

Wildlife corridors and leftover forest areas that were restored showed obvious differences in the frequency and intensity of disturbances. Corridors that were restored had much greater cumulative disturbance, with evidence of repeated grazing, frequent canopy openings, fire scars at localities, and increased cover of invasive species. Remnant forests, on the other hand, had a relatively low level of disturbance, intact canopy structure, and little anthropogenic impact. The frequency and intensity measures were always greater in the corridor area, and this proved that the habitat was ideal for measuring the seed bank response to a recurrent disturbance regime.

Results

Table 1: Disturbance Regime Characteristics Across Restored Wildlife Corridors And Remnant Forests

Habitat type	Disturbance frequency (events yr^{-1})	Disturbance intensity index (0–5)	Canopy openness (%)	Invasive species cover (%)
Restored wildlife corridors	3.8 ± 0.4	3.9 ± 0.3	42.6 ± 4.1	28.4 ± 3.6
Remnant forests	1.2 ± 0.2	1.5 ± 0.2	18.3 ± 2.7	6.9 ± 1.8

Values are mean ± SE. Disturbance frequency represents cumulative fire, grazing, and anthropogenic events.

Table 1 is a summary of the main disturbance regimes of restored wildlife corridors and remnant forests. The frequency and intensity of disturbance were significantly higher, the canopy was more open, and the cover of invasive species was higher in the restored corridors than in the remnant forest sites, which presented evidence of a more intense and frequent disturbance pressure in the corridor habitats. Remnant forests, on the contrary, had relatively low disturbance levels and more stable structure conditions, which supported their use as reference systems with reduced anthropogenic and ecological stress.

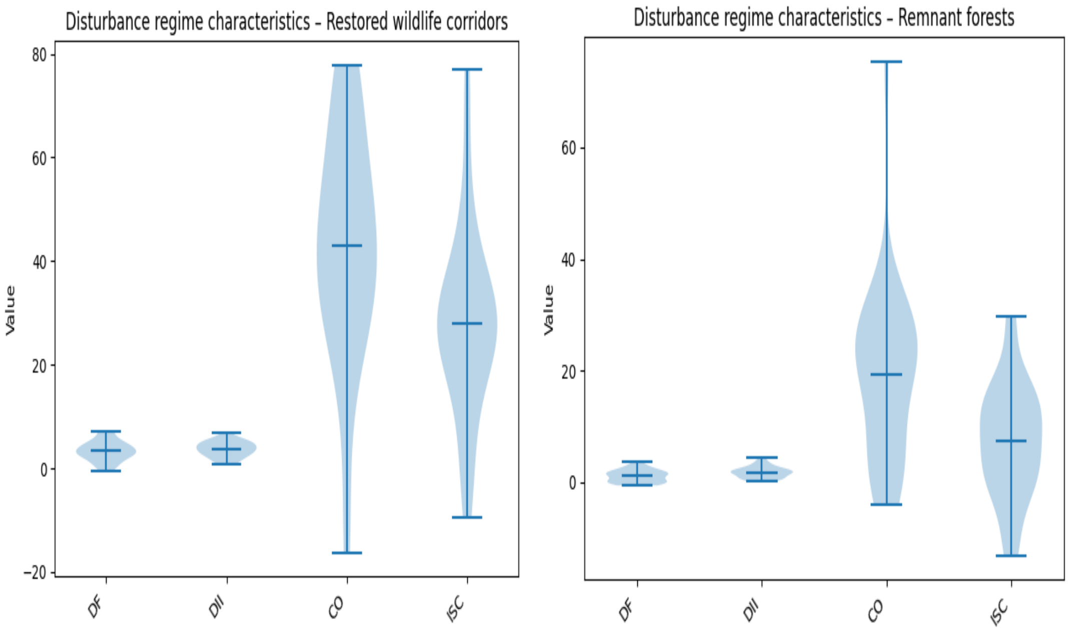

Figure 2: Violin Plots of Disturbance Regime Characteristics in Restored Wildlife Corridors and Remnant Forests

The values in Figure 2 show the distribution of the measures of key disturbances, disturbance frequency, disturbance intensity, canopy openness, and invasive species cover in individual restored wildlife corridors and remnant forests. The values of restored corridors are larger and more varied in all metrics, which implies the presence of frequent disturbances and recurrence, whereas remnant forests exhibit smaller values and distributions, which indicate the structural stability and the slight impact of anthropogenic activity. The data are simulated from mean ± SE values to visualize habitat contrasts.

Soil Seed Bank Density and Species Richness

Soil seed bank density differed significantly between habitat types (Table 2). The density of seeds in restored wildlife corridors was significantly lower than that of remnant forests, but with a high variability among sites of corridors. Remnant forests, on the contrary, were more effectively able to store propagules below ground and had higher regeneration potential due to the fact that remnant forests consistently exhibited higher seed bank densities.

Figure 3 demonstrates the major soil seed bank characteristics: seed bank density, species richness, Shannon Wiener diversity (H′), and evenness (J′) of restored wildlife corridors and remnant forests. Remnant forests always have increased seed densities, increased species richness, increased balanced diversity and evenness compared to restored corridors, or are indicative of more stabilized, and functionally diverse below-ground propagule pools.

Table 2: Soil Seed Bank Attributes in Restored Wildlife Corridors and Remnant Forests

Habitat type	Seed bank density (seeds m^{-2})	Species richness (species $sample^{-1}$)	Shannon–Wiener diversity (H′)	Evenness (J′)
Restored wildlife corridors	1,420 ± 160	12.4 ± 1.1	1.83 ± 0.12	0.62 ± 0.05
Remnant forests	2,870 ± 210	21.7 ± 1.6	2.71 ± 0.15	0.78 ± 0.04

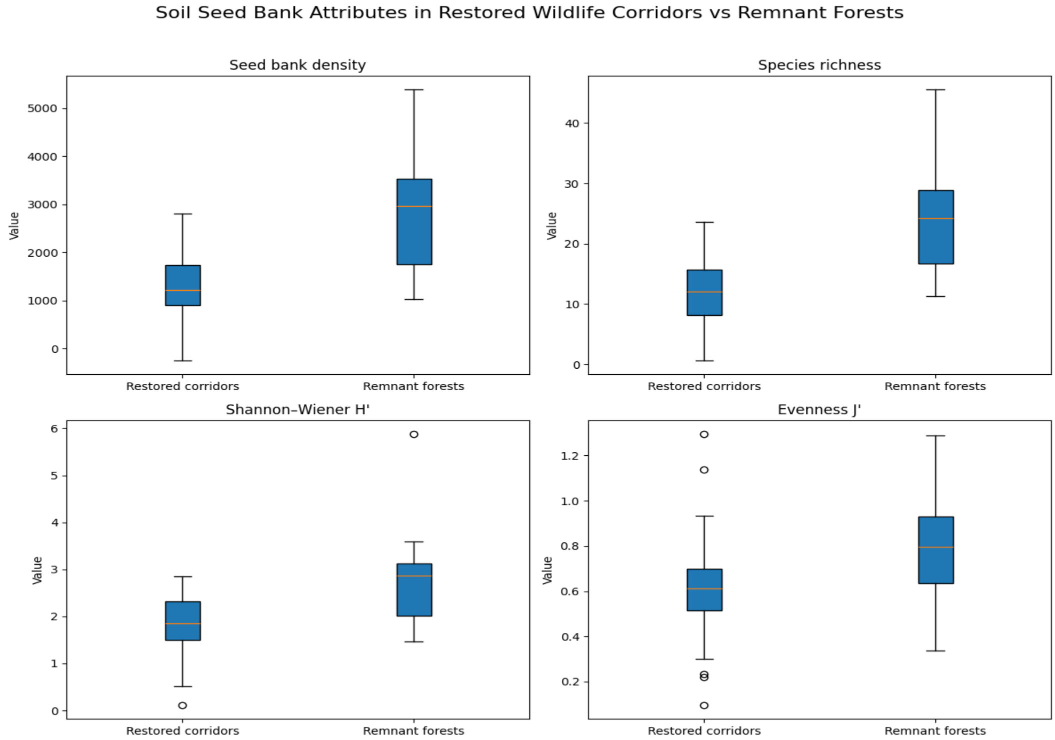

Figure 3: Comparison of Soil Seed Bank Attributes in Restored Wildlife Corridors and Remnant Forests

These patterns are congruent with Table 2, which presents mean ± SE values alone, and finds that restored corridors have viable seed banks but are still relatively depauperate and less evenly distributed than systems in remnant forests.

Richness in the species also showed the same trend, where the remnant forests contained many more species in a sample than the restored corridors ($p < 0.01$). Although the density and richness were lower, restored corridors had viable seed banks that could germinate, indicating the potential to recover partially. Nevertheless, frequent disturbance seemed to limit seed accumulation and persistence compared to remnant forest systems, and species-rich seed reserves were not built up.

Seed Bank Diversity and Community Composition

Seed bank diversity and composition patterns also provided an additional differentiation between restored corridors and remnant forests. Remnant forests had significantly higher Shannon-Wiener diversity and evenness values (Table 2), which is indicative of more complex compositions and more equal distributions of species. Corridor seed banks, in contrast, had less evenness and diversity because there were few, but very abundant taxa.

Multivariate ordination showed strong division among seed bank communities of reconstructed wildlife corridors and remaining forests. Tight groupings of sample remnant forests indicated compositional stability in non-metric multidimensional scaling, and signified larger dispersions in restored corridor samples, indicating higher levels of heterogeneity in the antecedent disturbance. Permutational multivariate analysis established that habitat type and intensity of disturbance were major explanators of seed bank composition.

These findings were found to be supported in community similarity analysis with low similarity between the corridor and remnant forest seed banks (Similarity = 0.46), indicating high compositional divergence and low overlap of species assemblage.

Functional Group Distribution

There was a significant disparity between habitat types as seen in functional classification. Restored wildlife corridors had seed banks characterized by pioneer and disturbance-tolerant species, and invasive taxa were relatively more abundant in the seed bank. Remnant forest seed banks, on the other hand, had a higher ratio of native forest species, including the taxa and shade-sensitive and late-successional species of the forest.

Table 3: Functional Group Composition (%) Of Soil Seed Banks

Functional group	**Restored wildlife corridors (%)**	**Remnant forests (%)**
Native forest species	34.6 ± 4.2	61.8 ± 5.1
Pioneer species	29.3 ± 3.8	18.5 ± 2.9
Disturbance-tolerant species	22.7 ± 3.1	12.4 ± 2.2
Invasive species	13.4 ± 2.6	7.3 ± 1.5

Restored corridors exhibit a succession of early and disturbance-adapted taxa dominance.

The soil seed banks of restored wildlife corridors and remnant forests differed in functional group composition. Native forest species were more abundant in remnant forests (61.8%) than in corridors (34.6%), whereas pioneer, disturbance-tolerant, and invasive species were proportionally higher in restored corridors. This pattern reflects the influence of habitat disturbance and successional stage on the soil seed bank structure, shown in Figure 4 and Table 3.

These trends imply that repeated disturbance selectively concentrates seed bank structure in corridors to benefit rapid-germinating and disturbance-tolerant species, and curtails the survival of forest-dependent species. Remnant forests also had higher functional redundancy, which led to a higher level of ecological stability and resilience.

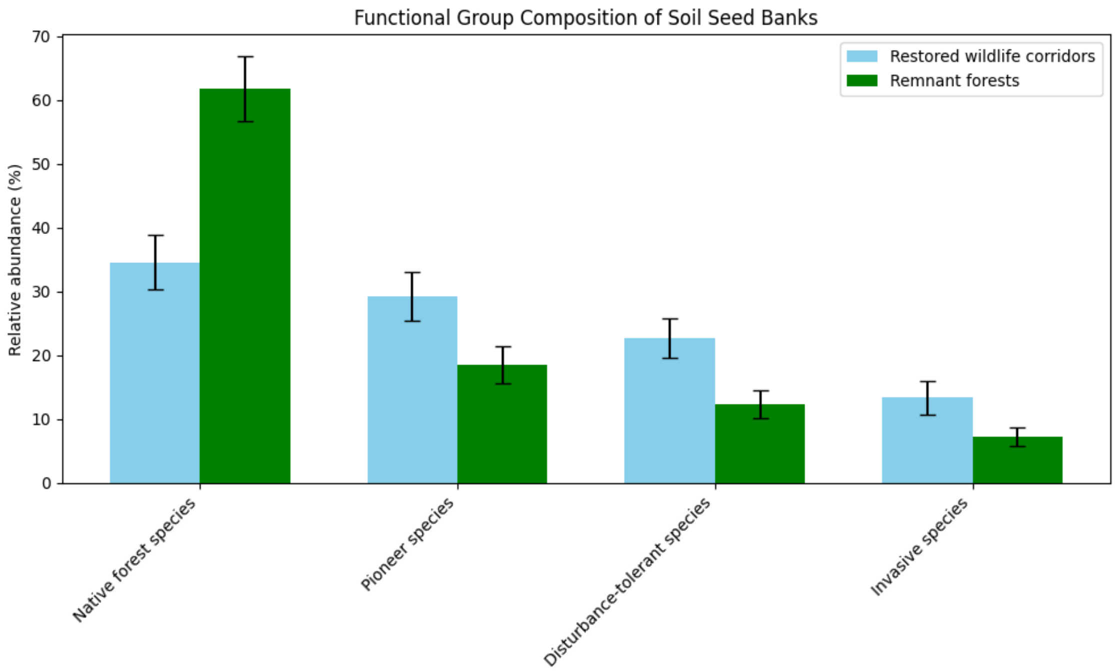

Figure 4: Functional Group Composition of Soil Seed Banks in Restored Wildlife Corridors and Remnant Forests

Resistance and Recovery Metrics under Recurrent Disturbance

The analysis of resistance-recovery indices showed opposite recovery projections of restored corridors as compared to the remnant forest. Remnant forest seed banks were highly resistant, with few reductions in density and diversity with exposure to disturbance. The recovery indices were near unity, which revealed stable regeneration ability.

Conversely, restored corridors exhibited less resistance and partial recovery, and post-disturbance seed bank indices were significantly smaller than the reference. Even though a recovery was noticeable, especially in the pioneer species, frequent disturbance restricted the re-establishment of a diverse and functionally balanced seed bank. Resilience under recurrent disturbance was further assessed using a resistance–recovery index, expressed as:

$$R=\frac{D_{post}}{D_{pre}} \quad (3)$$

In equation (3), Dpost represents seed bank density or diversity following disturbance exposure, and Dpre represents baseline or reference values derived from remnant forest sites. Index values approaching 1 indicate high resilience with strong resistance and recovery capacity, whereas values substantially below 1 reflect reduced resistance or incomplete recovery under recurrent disturbance.

Table 4: Resistance–Recovery Indices (R) For Seed Bank Attributes

Habitat type	Density resistance (R_D)	Diversity resistance ($R^{H'}$)
Restored wildlife corridors	0.58 ± 0.07	0.63 ± 0.06
Remnant forests	0.87 ± 0.05	0.91 ± 0.04

Values closer to 1 indicate higher resistance and recovery capacity.

In Table 4, soil seed banks in remnant forests exhibited higher resistance in both density (R_D = 0.87) and diversity ($R^{H'}$ = 0.91) compared to restored wildlife corridors (R_D = 0.58; $R^{H'}$ = 0.63), indicating that remnant forests are more resilient to disturbances than restored corridors.

Relationship between Disturbance Intensity and Seed Bank Resilience

Regression analyses demonstrated a significant negative relationship between disturbance intensity and seed bank density, richness, and diversity. An increase in the frequency and magnitude of disturbances correlated with the dwindling representation of native species and the rise in the prevalence of disturbance-tolerant taxa. The latter trends were stronger in the case of restored corridors, which suggests that the corridor seed banks were more sensitive to cumulative disturbance pressure. The combination of these findings suggests that although restored wildlife corridors still house viable seed banks in the soil, the corridor seed banks are repeatedly disrupted, limiting their ability to become resilient compared to remnant forests, which may limit long-term restoration success.

Discussion

The contrasts in the disturbance regimes were very clear in restored wildlife corridors, as well as in remaining forests. Restored corridors experienced substantially higher disturbance frequency (3.8 ± 0.4 events yr^{-1}) and intensity (3.9 ± 0.3 on a 0–5 scale) compared to remnant forests (1.2 ± 0.2 events yr^{-1}; 1.5 ± 0.2 intensity). The difference in canopy openness was greater between corridors (42.6 ± 4.1% and 18.3 ± 2.7% in remnant forests, respectively) and invasive species cover being significantly higher in corridors (28.4 ± 3.6% and 6.9 ± 1.8% in remnant forests, respectively), which suggests that these habitats are affected by disturbances, including grazing, canopy openings, and local fires, more often and more intensively. Violin plots verified larger variability in disturbance measures of corridors, whereas remnant forests exhibited slender distributions of disturbance that portrayed structural stability (Figure 2). Soil seed banks reflected habitat differences in disturbance regimes. Seed bank density in restored corridors (1,420 ± 160 seeds m^{-2}) was significantly lower than in remnant forests (2,870 ± 210 seeds m^{-2}; $p < 0.01$). Species richness similarly followed this trend, with corridors supporting 12.4 ± 1.1 species per sample, compared to 21.7 ± 1.6 species in forests ($p < 0.01$).Shannon–Wiener diversity (H′) and evenness (J′) were also reduced in corridors (H′ = 1.83 ± 0.12; J′ = 0.62 ± 0.05) relative to forests (H′ = 2.71 ± 0.15; J′ = 0.78 ±

0.04), indicating lower compositional complexity and less equitable species distribution. These results demonstrate that, although the restored corridors have viable seed banks, repeated disturbance reduces their density, richness, and functional balance (Figure 3; Table 2). The multivariate ordination indicated a marked distinction between the corridor and forest seed bank communities. The Non-metric multidimensional scaling (NMDS) indicated that the remnant forest samples were tightly clustered, indicating compositional stability, whereas the corridor samples were widely spread, which indicated high heterogeneity under recurrent disturbance. Through functional group analysis, pioneer (29.3 ± 3.8%) and disturbance-tolerant species (22.7 ± 3.1 %) were found to dominate corridors, and more invasive species were found (13.4 ± 2.6 %), whereas there were more native forest species in forests (61.8 ± 5.1 %) and fewer early-successional or invasive taxa (Figure 4; Table 3). Resistance–recovery indices revealed that remnant forest seed banks exhibited higher resilience, with density resistance (R_D = 0.87 ± 0.05) and diversity resistance ($R^{H'}$ = 0.91 ± 0.04) closer to 1, indicating minimal reductions under disturbance. Conversely, seed bank density and diversity recovery after disturbance were less apparent in restored corridors (R_D = 0.58 ± 0.07; $R^{H'}$ = 0.63 ± 0.06), which indicated that seed bank resistance to disturbance was not fully recovered (Table 4). The results of regression analysis indicated that the intensity of disturbance significantly correlated negatively with seed bank properties, with the rising disturbance levels corresponding with decreased representation of native species and augmentation of disturbance-tolerant taxa, mostly in corridors.

Conclusion

This study demonstrates that disturbance regimes strongly regulate soil seed bank structure, diversity, and resilience in restored wildlife corridors relative to remnant forests. Restored corridors experienced significantly higher disturbance frequency (3.8 ± 0.4 events yr^{-1}) and intensity (3.9 ± 0.3), greater canopy openness (42.6 ± 4.1%), and elevated invasive species cover (28.4 ± 3.6%) compared with remnant forests. These disturbance patterns were manifested in significantly different seed bank density (1,420 ± 160 seeds m^{-2}), species richness (12.4 ± 1.1), and diversity (H′ = 1.83 ± 0.12) of the corridors compared with remnant forests (2,870 ± 210 seeds m^{-2}). Community composition patterns also showed that there was a huge dissimilarity among habitats (similarity = 0.46), where corridors had a greater prevalence of pioneer, disturbance-tolerant, and invasive species, whereas remnant forests had a higher fraction of native forest species (61.8 ± 5.1%). The same findings (resistance-recovery indexes) confirmed that lower resilience in corridors (R_D = 0.58; $R^{H'}$ = 0.63) than in remnant forests (R_D = 0.87; $R^{H'}$ = 0.91) is a sign that shows incomplete recovery under recurrent disturbance. Collectively, these results suggest that although the corridors have viable seed banks, the corridors cannot regenerate as quickly as remnant forests because recurrent disturbance limits regenerative capacity and prevents the convergence of these conditions. Further studies should focus on long-term monitoring measures that can be used to assess the temporal recovery patterns of seed banks are subjected to less disturbance pressure. To examine the hypothesis that reducing the intensity of disturbance is possible to improve seed bank density, seed bank diversity, and seed bank resistance index, such improvements require experimental management interventions, including grazing exclusion, fire regulation, and the invasion of invasive species. By combining vegetation dynamics above ground with seed bank estimation below ground, predictions of success in restorations will be enhanced. Lastly, both functional trait-based analyses and landscape-scale analyses might determine disturbance thresholds beyond which the seed banks cannot be restored in the corridors, and this knowledge can be applied to adaptive management to restore the corridors in a resilient manner.

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