

Ecological Zonation Shapes Soil Seed-Bank Density, Diversity, and Species Composition in Chhuhia Ghati, Central India.

Bed Prakash Tripathi¹, Aparna Singh², Dr. Sanjay Singh³,

Dr. Arpita Awasthi^{4*}, Dr. Santosh Agnihotri⁵

^{1-2,4}Govt. Thakur Ranmat Singh College Rewa (M.P),

Newberg Center for Genomic Medicine, Ahmedabad³

⁵Pradhan Mantri College of excellence Govt. Model Science College Rewa (M.P).

arpita.awasthi@ymail.com, dragnihotri.rewa@gmail.com, sanjaybiochem.singh@gmail.com

Abstract: Background: Soil seed banks are important reservoirs of viable propagules supporting natural regeneration, biodiversity conservation, and ecosystem restoration. This study assessed spatial variation in soil seed banks across lower, middle, and upper ecozones of Chhuhia Ghati, Rewa, Madhya Pradesh.

Methods: Field and laboratory investigations were conducted during 2023–2025. Sixty 1 m × 1 m quadrats were sampled from the upper 0–10 cm soil layer. Seed banks were assessed using seed extraction and seedling emergence methods.

Results: A total of 2,307 seeds were recorded. The middle zone had the highest seed abundance (928; 40.23%) and mean density (46.40 ± 9.80 seeds/quadrat), whereas the upper zone showed the highest species richness (46 species). Significant differences occurred in seed density, species richness, Shannon diversity, Simpson diversity, and Pielou's evenness ($p < 0.001$). The upper zone recorded the highest Shannon diversity (2.070 ± 0.313), Simpson diversity (0.850 ± 0.051), and evenness (0.931 ± 0.040). Jaccard similarity was highest between lower and middle zones (53.3%) and lowest between lower and upper zones (28.6%). Dominant species varied among zones.

Conclusion: The soil seed bank showed marked spatial heterogeneity. These findings provide baseline information for biodiversity conservation, natural regeneration, and ecological restoration.

Keywords: Soil seed bank; Species diversity; Seed density; Ecological zones; Chhuhia Ghati; Natural regeneration; Jaccard similarity.

I. INTRODUCTION

Soil is a dynamic and biologically active part of terrestrial ecosystems, providing support to vegetation by its physical, chemical and biological attributes. Soil is also a place of seed banks and realizes viable seeds, which has a significant effect on the persistence of plant population, dynamics of community and regeneration of ecosystem. This reservoir is known as the soil seed bank (SSB) and include viable seeds on the soil surface, in the soil profile and in associated litter or humus layers. Dispersal from vegetation introduces the seed to the soil where it can persist in the soil for years until environmental conditions are appropriate for germination. Thus, the soil seed bank is a significant belowground aspect of vegetation dynamics and can carry a message of past and potentially future vegetation [1,2].

The main ecological value of soil seed banks is as a source of propagules for vegetation regeneration. After disturbances like grazing, fire, cultivation, deforestation, or other environmental changes, viable seeds in soil can help to re-establish populations of plants. Seed banks in the soil can thus act as a source of propagules to restore vegetation when conditions are favourable and to protect the ecosystem from disturbance. The role they play in biodiversity



conservation and ecological restoration has been widely reported since the seed mixture, density and diversity of seed banks can be a valuable source of data on the regenerative potential of an ecosystem [3,4].

Soil seed banks are formed and maintained under the influence of several biological and environmental processes. The number and composition of seeds in the soil is the result of seed production, seed dispersal, seed dormancy, predation, germination, mortality, and persistence. Seed attributes such as size, shape, dormancy and longevity may also affect the likelihood of seed persistence after they enter the soil. Previous research has shown that smaller seeds can be more easily soil incorporated and for some species are more persistent than many of the larger seeds. Biotic and physical disturbances, litter accumulation, moisture and soil properties also contribute to the distribution of seed in the soil profile [5].

Soil seed banks are not homogeneously distributed. However, significant habitat, site and microhabitat differences can result due to variation in vegetation, topography, soils, disturbance history and seed dispersal. Regional scale differences in seed density and species can be significant at larger spatial scales by the presence of ecological gradients. The accumulation and persistence of seeds in soil could be directly or indirectly affected by climatic and edaphic conditions, vegetation structure and/or anthropogenic disturbance. Hence, the estimation of soil seed banks in different ecological zones is relevant for understanding the spatial structure of diversity of plant species in soil and how this diversity relates to environmental heterogeneity in the same area [6].

Seed density is among the basic parameters of a soil seed bank. Seed density can be correlated with a large propagule bank, but it is not a definitive indicator of ecological regeneration potential. A seed bank may be composed of a large number of seeds from only a few species, or a comparatively small number of seeds from a larger number of species. Therefore, species richness and diversity should be taken into account in order to be able to interpret the seed-bank structure. There are also variations in richness, density and abundance of global seed banks between habitats and localities, and local ecological assessment is important [7].

Species richness is the number of species represented in a community, while diversity takes into account the number and relative abundance of species present in a community. It is common practice to use diversity indices like Shannon–Wiener index or Simpson diversity index for assessing community structure because they complement one another in the distribution of individuals among species. Pielou's evenness also suggests the distribution of individuals among the species present. Together these values give a more complete picture of the extent to which a seed bank is dominated by a few species or if seeds are more evenly distributed among a variety of taxa. This information is especially valuable in assessing the potential of a soil seed bank in natural regeneration and plant biodiversity.

The comparison of the species compositions of the ecological zones is also an important indication of spatial relationships within a landscape. A common measure of comparing the proportion of species shared between communities is the Jaccard similarity coefficient. More similar sites may be due to shared vegetational sources, seed dispersal routes and/or similar environmental factors among neighboring or environmentally similar sites. On the other hand, lower similarity can mean that there are differences in the quality of the habitat, environmental filtering, disturbance history or local species pools. Thus, an integrated evaluation of seed density, species richness, diversity, evenness and similarity can be used to interpret the variation of soil seed banks within spatial gradients at a detailed level.

Another key feature of soil seed-bank ecology is the dynamic between the seed bank and the standing vegetation. The species composition of seeds stored in soil does not necessarily correspond completely with the aboveground vegetation. Species that are not yet common or present in the standing community may be found in the seed bank, and some dominant aboveground species may be underrepresented in the seed bank. This can be due to differences in seed production, dispersal, dormancy, longevity, and environmental conditions for persistence. Soil seed banks can thus serve as a sort of ecological memory bank, holding seeds relics from previous vegetation stages and giving them a chance to grow again in future vegetation stages if the environmental conditions are favorable for germination [1,2,5].

Soil seed bank studies are particularly pertinent in a landscape with strong environmental variation such as that found in differing elevations, topography, vegetation, soil characteristics and disturbance. This variation may affect the



quantity and quality of seed in the soil. Comparing these patterns across ecological zones can help determine zones of higher regeneration and baseline data for biodiversity conservation and habitat restoration. Soil seed-bank assessment is also helpful in understanding vegetation succession as an important source for the early stages of plant community recovery following disturbance, the seed pool that is stored in soil.

Chhuhia Ghati in Rewa district, Madhya Pradesh, India is an ecologically appropriate landscape in which spatial variation of soil seed banks can be studied. It has a varied topography of lower, middle and upper ecological zones, and a variation in the environment and vegetation. The soil in the region are mainly clay and loamy with fine alluvial deposits, and the vegetation is a combination of grassland and forest with annual herbs, shrubs and small trees. The local climate is characterized by a pronounced seasonal variation, mean annual rainfall of 900 to 1100 mm and the mean annual temperature of 10 to 42°C. Such ecological features offer a suitable environment for studying seed dispersal and diversity between different ecological zones.

Although soil seed banks are of ecological significance, there is still a need for information on local soil seed bank composition, density, diversity and morphological variation in order to understand the regenerative potential of heterogeneous landscapes. Thus, the present study was directed towards the study of soil seed bank of Chhuhia Ghati in lower, middle and upper ecological zone. Seed distribution, density, species richness, diversity, evenness, similarity of the species composition and some morphological characteristics of the seeds were considered in the investigation. From the 60 quadrats, a total of 2,307 seeds were evaluated, and the data used to determine the spatial variation in the soil seed bank in the three ecological zones.

Hence the study was set up to describe the spatial variation in the structure of soil seed bank in Chhuhia Ghati and to assess the implications of soil seed bank on plant diversity and natural regeneration in the ecological zones. The study combines quantitative assessments of seed density, species richness, diversity, species similarity and seed morphology to offer a localized assessment of the seed resource of this landscape below ground. These data can help in understanding vegetation dynamics and may be used as an ecological framework for future restoration and natural regeneration projects in the area, as well as biodiversity conservation.

II. MATERIALS AND METHODS

2.1 Study Area

This study was carried out in Chhuhia Ghati in the southern region of the Vindhyan Basin of Rewa district in Madhya Pradesh, India. The study area lies about 25 km South of Rewa town, 8 km South of Govindgarh on Rewa-Sidhi Road at a latitude of about 24°18' N and longitude 81°22' E. The landscape is undulating and can be divided into lower, middle and upper ecological zones. Geology: Clayey beds and shale formations with predominant clay and loamy soils in between with fine alluvial deposits. The vegetation consists of a mosaic of grassland and forest associated species, with annual herbs, shrubs and small trees. The area has a tropical climate and an annual rainfall of about 900-1100 mm and a temperature of 10-42°C during the summer and winter seasons respectively.

2.2 Study Design and Soil Sampling

The investigation was designed in the field and lab to study the composition, distribution, density and diversity of the soil seed bank in the three ecological zones of Chhuhia Ghati. Sampling took place in the 2023-2024 and 2024-2025 growing seasons. Three zones (lower, middle and upper) were chosen to identify ecological variation across the study landscape. Random sampling was used to reduce sampling bias and to ensure that a variety of microhabitats were sampled, such as open grasslands, shaded patches of forest and disturbed areas.

60 quadrats were evaluated in the three ecological zones. Each sampling plot was 1 m × 1 m and soil samples were taken from the top 10 cm of soil where the seed bank was presumed to be concentrated. Soil cores were taken with hand soil auger. Each sample was identified by location, date and depth of sample. Collected samples were air-dried and sieved out the stones, roots and large debris prior to laboratory analysis. To allow for differences in seed deposition and germination potential, the sampling of fields was repeated across seasons. The overall study design and soil sampling procedure followed for soil seed bank assessment are presented in Figure 1.



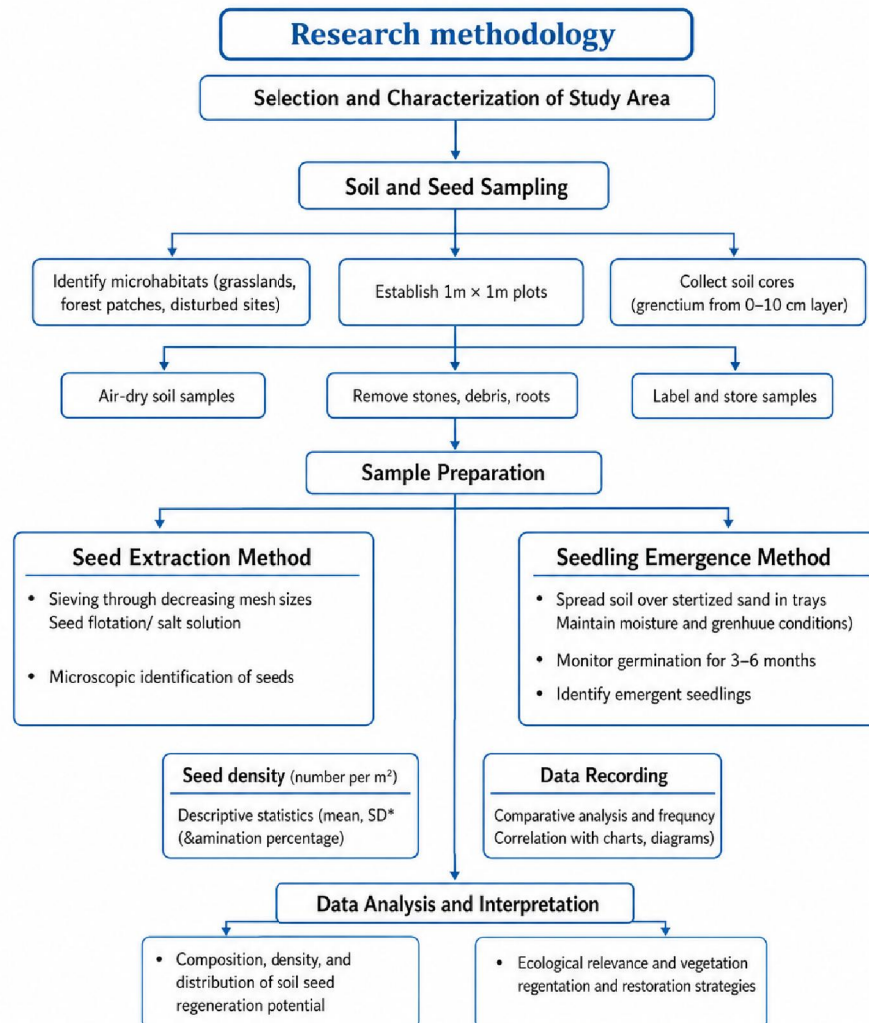


Figure 1. Research methodology and workflow used for soil seed bank sampling, analysis, and interpretation.

2.3 Seed Collection and Assessment

The soil seed bank was evaluated by the seed extraction method and the seedling emergence method (two complementary approaches). The extraction method used was a physical separation of the desired seeds from the soil matrix according to seed size, density and other morphological parameters. Seed germinability was tested by the seedling emergence method under a controlled environment. The use of these approaches allowed assessment of both the composition and regenerative potential of the soil seed bank. The procedures were described by Roberts and in subsequent methodological modifications.

Seeds were identified and classified from recovered material based on existing morphological traits and under the microscope. The identified seeds were then used to establish the distribution and abundance of the seeds in each of the lower, middle and upper ecological zones. A total of 2,307 seeds were recorded in the 60 quadrats used in the study.



2.4 Assessment of Soil Seed-Bank Characteristics

To assess the seed-bank structure, quantitative ecological parameters such as seed density, species richness, frequency and abundance were used. The number of species recorded within each ecological zone and at the quadrat level was used to determine species richness. Frequency was the occurrence of a species in the quadrats sampled and abundance was the numerical representation in the appropriate samples.

The Shannon–Wiener diversity index (H') and Simpson diversity index ($1-D$) were used for the species diversity assessment. Pielou's evenness index (J') was used to determine evenness of species. Both of these indices were combined to describe the changes in species richness and relative abundance, and the pattern of distribution of species in the three ecological zones. Similarity of the species composition of the zones was calculated by the Jaccard similarity coefficient. The thesis particularly contained comparisons of seed density, species richness, Shannon diversity, Simpson diversity, Pielou's evenness and Jaccard similarity of the three zones.

2.5 Seed Morphological Assessment

Seed length and seed width measurements were used to compare the morphological variation of recovered seeds. Seed area was also estimated to account for inter-specific difference in seed size. The measurements were combined species-wise for comparison and for descriptive analysis of the seed-size variables. Seed length, seed width, estimated seed area and proportion of each seed-size category in the three ecological zones were thus included in the study data set.

2.6 Statistical Analysis

Soil seed-bank data for each ecological zone was summarized using descriptive statistics. Seed density and diversity related variables were calculated as mean and standard deviations. One-way analysis of variance (ANOVA) was used to evaluate the differences in soil seed density, species richness, Shannon–Wiener diversity, Simpson diversity, and Pielou's evenness between lower, middle, and upper ecological zones. If significant differences were seen, Tukey's honestly significant difference (HSD) post hoc test was performed for pairwise comparison between zones. Similarity of species composition was calculated based on Jaccard coefficient. Analytical tools additionally featured species-wise frequency, density and abundance and descriptive analysis of seed morphological variables.

III. RESULT

Overall distribution of soil seeds across ecological zones

The total number of seeds obtained from the 60 quadrats, equally divided between the three ecological zones (lower, middle and upper), was 2307. The middle zone contained the highest number of seeds (928; 40.23%), followed by the upper zone (748; 32.42%) and lower zone (631; 27.35%). The middle zone had a mean seed density of 46.40 ± 9.80 seeds/quadrat, the upper zone of 37.40 ± 11.90 seeds/quadrat and the lower zone of 31.55 ± 11.09 seeds/quadrat. The upper zone on the other hand had the highest total species richness (46 species) followed by the middle zone (29 species) and the lower zone (17 species).

Table 1. Distribution of soil seeds across ecological zones

Ecological zone	Site	Quadrats	Total seeds	Distribution (%)	Seeds/quadrat, Mean $\pm$ SD	Range	Total species richness
Lower zone	A	20	631	27.35	31.55 ± 11.09	15–57	17
Middle zone	B	20	928	40.23	46.40 ± 9.80	30–64	29
Upper zone	C	20	748	32.42	37.40 ± 11.90	20–68	46
Overall	—	60	2,307	100	38.45 ± 12.41	15–68	—



Comparison of soil seed density

The descriptive analysis revealed that there was a distinct difference in the soil seed density between the three ecological zones. The seed density was maximum in the middle zone (46.40 ± 9.79 seeds/quadrat) and minimum in the lower zone (31.55 ± 11.09 seeds/quadrat). An intermediate mean density of 37.40 ± 11.90 seeds/quadrat was observed in the upper zone. Tukey grouping resulted in a separate zone for the middle zone with the lower and upper zone forming a single homogeneous zone.

The one-way ANOVA showed that seed density was significantly different between ecological zones ($F = 9.317$, $p < 0.001$, $\eta^2 = 0.246$). So, the ecological zone explains about 24.6% of the total variation observed in seed density.

Post hoc analysis revealed that the middle had significantly more seed than the lower (mean difference = 14.85, $p < 0.001$) and upper (mean difference = 9.00, $p = 0.032$) zones. But the differences between the lower and upper zones were not significant ($p = 0.219$).

Species richness across ecological zones

The number of species increased from the lower to the upper ecological zone. The highest mean number of species/quadrat (9.60 ± 3.03 species/quadrat) was found in the upper zone, followed by the middle zone (8.55 ± 2.28 species/quadrat) and lower zone (5.85 ± 1.57 species/quadrat). The species range recorded was 3-9 species in the lower zone, 4-12 species in the middle zone and 6-17 species in the upper zone.

A one-way ANOVA showed that there is a significant difference in species richness among zones ($F = 13.320$, $p < 0.001$, $\eta^2 = 0.319$). Post hoc analysis showed that species richness was significantly different between middle, upper and lower zones. There was no statistically significant difference between the middle and upper zones ($p = 0.347$).

Diversity patterns across ecological zones

Overall, the diversity indices increased with the increase in the ecological zone. There was no significant difference between the mean species richness, Shannon–Wiener diversity, Simpson diversity and Pielou's evenness of the upper zone compared to the other zones and showed that the soil seed-bank community in the upper zone was more diverse and balanced. The middle zone had intermediate diversity and the lower zone in general had the lowest diversity values.

Shannon–Wiener diversity

Shannon diversity was lowest in the lower zone (1.463 ± 0.264) and increased through the middle zone (1.726 ± 0.315) to the upper zone (2.070 ± 0.313). ANOVA confirmed significant differences among the zones ($F = 20.829$, $p < 0.001$, $\eta^2 = 0.422$). Significant differences found between all three zones: middle and lower ($p = 0.019$), upper and lower ($p < 0.001$) and upper and middle ($p = 0.002$).

Simpson diversity

Simpson diversity followed a similar pattern, with values of 0.717 ± 0.087 , 0.766 ± 0.082 , and 0.850 ± 0.051 in the lower, middle, and upper zones, respectively. The difference among zones was statistically significant ($F = 16.179$, $p < 0.001$, $\eta^2 = 0.362$). An upper zone was significantly different from the lower ($p < 0.001$) and middle ($p = 0.002$) zones, but the lower and middle zones were not significantly different ($p = 0.103$).

Pielou's evenness

The highest evenness was observed in the upper zone (0.931 ± 0.040), followed by the lower (0.847 ± 0.083) and middle (0.817 ± 0.068) zones. ANOVA showed significant variation among ecological zones ($F = 16.067$, $p < 0.001$, $\eta^2 = 0.361$). The evenness of the upper zone was significantly higher than the lower ($p < 0.001$) and middle ($p < 0.001$) zones, but there was no significant difference between the lower and middle zone ($p = 0.332$).

Table 2. Summary of diversity indices across ecological zones

Ecological zone	Species richness	Shannon–Wiener index (H')	Simpson diversity ($1-D$)	Pielou's evenness
Lower zone	5.85 ± 1.57	1.463 ± 0.264	0.717 ± 0.087	0.847 ± 0.083



Middle zone	8.55 ± 2.28	1.726 ± 0.315	0.766 ± 0.082	0.817 ± 0.068
Upper zone	9.60 ± 3.03	2.070 ± 0.313	0.850 ± 0.051	0.931 ± 0.040

Overall comparison of ecological variables

Statistically significant differences ($p < 0.001$) were found for all major ecological measurements between the three zones. The variable with the highest ecological effect in the evaluated variables was Shannon diversity ($\eta^2 = 0.422$), followed by Simpson diversity ($\eta^2 = 0.362$), Pielou's evenness ($\eta^2 = 0.361$), species richness ($\eta^2 = 0.319$) and seed density ($\eta^2 = 0.246$).

Table 3. Summary of ANOVA results

Variable	Lower zone	Middle zone	Upper zone	F-value	p-value	η^2
Seed density	31.55 ± 11.09	46.40 ± 9.79	37.40 ± 11.90	9.317	<0.001	0.246
Species richness	5.85 ± 1.57	8.55 ± 2.28	9.60 ± 3.03	13.32	<0.001	0.319
Shannon diversity (H')	1.463 ± 0.264	1.726 ± 0.315	2.070 ± 0.313	20.829	<0.001	0.422
Simpson diversity (1-D)	0.717 ± 0.087	0.766 ± 0.082	0.850 ± 0.051	16.179	<0.001	0.362
Pielou's evenness	0.847 ± 0.083	0.817 ± 0.068	0.931 ± 0.040	16.067	<0.001	0.361

Similarity of species composition

The Jaccard similarity analysis showed the highest similarity to be between the lower and middle zones (53.3%) and middle and upper zones (53.1%). The minimum similarity was found between lower and upper zone (28.6%). This means that, based on the thesis data, the middle zone contained a large percentage of species common to both neighboring zones, but the lower and upper zones had a higher percentage of unique species.

Dominant species and seed-bank composition

There was a difference in species dominance with ecological zones. *Holoptelea integrifolia* with 201 seeds, 90% frequency, 10.05 seeds/quadrat and 11.167 abundance was the dominant species in the lower zone. *Hyptis suaveolens* was dominant in the middle zone with 100% frequency, 13.65 density and 13.65 abundance in all the 20 quadrats. *Lantana camara* was the most prevalent species followed by *Hyptis suaveolens*, *Lagerstroemia parviflora*, *Shorea robusta* and *Holoptelea integrifolia* in the upper zone.

A relatively small number of species (mainly *H. integrifolia*, *H. suaveolens* and *L. camara*) were more dominant in the lower zone. The middle zone, on the other hand, had 29 species recorded but *H. suaveolens* and *H. integrifolia* were quite prominent in the seed bank. There were 46 species in the upper zone with a more even distribution of seeds per species than in the lower zone.

Table 4. Jaccard similarity of species composition among ecological zones

Zone comparison	Shared species	Species union	Jaccard index	Similarity (%)
Lower-Middle	16	30	0.533	53.3
Lower-Upper	14	49	0.286	28.6
Middle-Upper	26	49	0.531	53.1



IV. DISCUSSION

In the present study, it was observed that there exist significant spatial variations in soil seed bank in the three different ecological zones namely lower, middle and upper ecological zones of Chhuhia Ghati. There were differences in seed density, species richness, diversity, evenness, species composition and dominant species, suggesting that the soil seed bank was not evenly spread throughout the study landscape. The spatial heterogeneity is similar to that found in previous studies, where soil seed-banks composition and abundance was found to be affected by vegetation characteristics, environmental conditions, disturbance history and local variation in habitat [8-10]

The highest seed accumulation was observed in the middle ecological zone while the highest species richness and diversity was in the upper ecological zone. This distinction suggests that abundance and diversity of species is not a consistent relationship. It is possible that a high number of seeds are present in a seed bank due to the high abundance of a few dominant species, while a few seeds may be present in another site that have a greater diversity of species. Gomes et al. [11] made similar observations, pointing out that abundance, by itself, is not sufficient to assess the ecological status of a soil seed bank. Birhanu *et al.* [12] also recorded seed-bank composition variation in relation to the vegetation characteristics and Zhou et al. [13] reported the association between seed-bank abundance, diversity and vegetation. The current results indicate that the seed density needs to be interpreted in the context of species richness and diversity, when assessing the ecological importance and regenerative capacity of a soil seed bank.

This difference in the seed density between the middle zone and the others is possibly associated with increased seed input and the retention of seeds from the few species which were well represented. In the present study, the seeds of *Hyptis suaveolens*, *Holoptelea integrifolia* and *Lantana camara* contributed significantly to the seed bank of this zone. Past studies have also demonstrated a significant impact of local vegetation structure and vegetation type on the amount of seeds trapped in the soil. Li *et al.* found significant effects of shrub characteristics despite relatively small fluctuations in species richness and that a few species might make up a large percentage of the whole seed bank. Likewise, Liu *et al.* showed that density of soil seed banks might be affected by vegetation patches and by changes in environmental conditions due to grazing. All of these observations suggest that the higher seed density of the middle zone could be due to a combination of local seed sources, species-specific seed production and persistence.

In contrast the upper ecological zone had the highest species richness and a more complex and even seed-bank structure. The diversity pattern showed that seeds are not concentrated in a few dominant taxa of seeds. This is ecologically significant as a diverse soil seed bank can offer a wider diversity for natural regeneration if conditions are favorable. The same has been pointed out in previous studies, which have also shown that species diversity plays a crucial role in the restoration potential of soil seed banks. Seed banks in soil have been identified as playing a key role in re-establishment of vegetation and restoration of species-rich communities [14]. A diverse seed pool might also give ecological flexibility, as some species may be more sensitive to moisture and light levels, soil types, disturbance etc.

The lower ecological zone exhibited relatively lower species richness and diversity and a higher proportion of the species from a smaller number of dominant species. This trend could be due to variations in local vegetation, seed input, habitat and disturbance history. Previous studies showed that disturbance and land use can affect the makeup and relative abundances of soil seed bank species. An association of soil-stored seed banks with rangeland degradation was reported by Jones and Esler [15] and changes of seed-bank composition and density after deforestation and cultivation were observed by Lemenih and Teketay [16]. The soil seed-bank structure of Chhuhia Ghati is comparable with those found in the above-mentioned studies, and the observed differences could have been related to the environmental conditions or previous disturbance at the site.

Varying diversity and evenness between ecological zones also suggests the presence of different community structures in the soil seed bank. The upper zone exhibited a more even distribution of seed among species, while the lower and middle zones were more dominated by the important species. Such differences are significant because community diversity is not just a function of the number of species, but also of the distribution of individuals among the species. A seed bank with only a few species may be regenerating in great numbers but may not be providing as much to the future floristic diversity as a seed bank with propagules of many species. Thus, the current results support using all four



measures (density, richness, diversity, and evenness) instead of one to evaluate the regeneration potential. The results confirmed the importance of abundance and diversity measures, as expressed in previous soil seed-bank studies, for a complementary ecological analysis.

The Jaccard similarity pattern showed that the species shared by the adjacent ecological zones was higher than the lower and upper ecological zones. The middle zone was found to have a significant similarity with both neighbouring zones, indicating that it might be an ecologically intermediate zone in the landscape. The lower and upper zones were less similar, however, relative to the lower, upper and lower, suggesting greater compositional differentiation along the ecological gradient. This variation can be attributed to different seed dispersals, vegetation sources, topographic position, soil conditions and local environmental filtering. Soil seed-bank dynamics may be affected by precipitation amount and timing (Wang *et al.*, 2011 [17]) and soil seed-bank distribution and restoration potential differs by vegetation types (Bekele *et al.*, 2011 [18]). These results tend to confirm that the compositional variations in Chhuhia Ghati are not the consequence of one controlling factor but rather may be due to several environmental and biological factors acting together.

Another important aspect of the present study was the change in dominant species with respect to the different ecological zones. *Holoptelea integrifolia* was the predominant species in the lower zone, *Hyptis suaveolens* in the middle zone and *Lantana camara* in the upper zone. This shift in species dominance provides evidence that ecological conditions not only affect the number of seeds but also the proportion of different seed taxa. The contribution of species to the soil seed bank may vary due to species-specific differences in seed production, dispersal, persistence, dormancy and environmental requirements. Previous studies have shown that environmental factors and plant life forms can interact to determine soil seed-bank composition and richness [19,20]. Therefore, the changes in dominant species are likely to be a combination of local vegetation and environmental heterogeneity.

Morphological variation in seed may also be ecologically important for the distribution and persistence of seed in the soil seed bank for species. Seed size and morphology can affect seed dispersal, burial, soil movements, predation and persistence. Bekker *et al.* [21] found a high correlation between seed morphology and germination and persistence in the soil. Smaller seeds are likely to be better dispersed in soil microsites and may lead to seed banks, larger seeds may have higher nutrient content and thus have a greater chance of establishing seedlings early. Hence, the morphological variation observed during the present study might be an expression of different regeneration and persistence strategies of the species constituting the soil seed bank.

The results of the present study have important implications in the areas of natural regeneration and ecological restoration in Chhuhia Ghati. The soil seed bank is also an important propagule source, in the belowground habitat, but it cannot be evaluated only by the number of seeds present. The middle zone seemed to have a high numerical seed bank, and the upper zone had a wider variety of species and a more even distribution. This means that the ecological value of each zone for future regeneration might vary. While soil seed banks are known to play a key role in the dynamics of vegetation and restoration, the ability of seed banks to restore may differ depending on seed-bank composition and the presence of favorable environmental conditions. Thus, the current results can be used to provide baseline data and information that could aid in future restoration planning, natural regeneration and biodiversity conservation in the study area.

In general, the present study clearly substantiates the high spatial heterogeneity of the soil seed bank of Chhuhia Ghati. Seed abundance, species richness, diversity, evenness, similarity and dominance varied among the ecological zones. Most important, results showed that species diversity was not necessarily related to seed abundance. The combination of density, richness, diversity, species composition and morphological characteristics thus offers a better overall assessment of the structure and ecological importance of soil seed banks.

V. CONCLUSION

In the present study the spatial variation of soil seed bank of Chhuhia Ghati was found to be marked between lower, middle and upper ecological zone. The seed abundance, species richness, diversity, evenness, species composition, and



patterns of species dominance differed clearly, indicating a soil seed bank heterogeneity with regards to the study landscape.

A key result was that it was not necessarily true that more seeds equated to more species or diversity. One ecological zone was more likely to contain a higher number of species while another was more likely to contain a greater diversity of species, with even distribution. This stresses the need for assessment of soil seed banks by means of several ecological factors and not only by the density of seeds.

Also, differences in species composition and species dominance among the ecological zones indicated that local environmental conditions, plant characteristics, seed dispersal, disturbance and persistence strategies of species were important factors. It was also observed that the morphology of the seed varied between species, suggesting that there might be differences in how they disperse and are buried, how long they persist, and how they germinate and grow next.

Altogether, it can be concluded that the soil seed bank is a significant belowground source of plant diversity and natural regeneration in Chhuhia Ghati. The baseline data on the structure and ecological variation of the soil seed bank presented in the study could be applied in biodiversity conservation, habitat management, natural regeneration and future ecological restoration planning in the region.

REFERENCES

1. Alemu MM. Soil seed bank and natural regeneration of trees. *Journal of Sustainable Development*. 2016 Apr 20;9(2):73-7.
2. Fenner M, Thompson K. *The ecology of seeds*. Cambridge, UK: Cambridge university press; 2005.
3. Mall U, Singh GS. Soil seed bank dynamics: history and ecological significance in sustainability of different ecosystems. In *Environment and sustainable development 2013* Jul 10 (pp. 31-46). New Delhi: Springer India.
4. Viswanath S, Singh RP, Thapliyal RC. Seed bank dynamics of *Buxus wallichiana* in a Himalayan moist temperate forest. *Tropical Ecology*. 2006;47(1):145-8.
5. Levin SA. *Fragile dominion: complexity and the commons*. (No Title). 1999 Jun 3.
6. Suding KN, Gross KL, Houseman GR. Alternative states and positive feedbacks in restoration ecology. *Trends in ecology & evolution*. 2004 Jan 1;19(1):46-53.
7. Suding KN, Hobbs RJ. Threshold models in restoration and conservation: a developing framework. *Trends in ecology & evolution*. 2009 May 1;24(5):271-9.
8. Liu J, Li L, Chen J, Zhang J, Zhu N, Wang C, Luo Y, Xu N, Bao Y, Yan Y. Soil Seed Bank Density Enhanced at Shrub Patches Due to Grazing in a Shrub-Encroached Grassland: J. Liu and others. *Ecosystems*. 2024 Dec;27(8):1143-55.
9. Schutte BJ, Davis AS, Peinado Jr SA, Ashigh J. Seed-coat thickness data clarify seed size–seed-bank persistence trade-offs in *Abutilon theophrasti* (Malvaceae). *Seed Science Research*. 2014 Jun;24(2):119-31.
10. Li X, Jiang D, Zhou Q, Oshida T. Soil seed bank characteristics beneath an age sequence of *Caragana microphylla* shrubs in the Horqin Sandy Land region of northeastern China. *Land Degradation & Development*. 2014 May;25(3):236-43.
11. González-Alday J, Marrs RH, Martínez-Ruiz C. Soil seed bank formation during early revegetation after hydroseeding in reclaimed coal wastes. *Ecological Engineering*. 2009 Jul 1;35(7):1062-9.
12. Dalton RL, Carpenter DJ, Boutin C, Allison JE. Factors affecting soil seed banks of riparian communities in an agricultural ecosystem: potential for conservation of native plant diversity. *Applied Vegetation Science*. 2017 Jul;20(3):446-58.
13. Luo C, Guo X, Feng C, Xiao C. Soil seed bank responses to anthropogenic disturbances and its vegetation restoration potential in the arid mining area. *Ecological Indicators*. 2023 Oct 1; 154:110549.
14. Ma M, Zhou X, Du G. Role of soil seed bank along a disturbance gradient in an alpine meadow on the Tibet plateau. *Flora-Morphology, Distribution, Functional Ecology of Plants*. 2010 Jan 1;205(2):128-34.



15. Jones FE, Esler KJ. Relationship between soil-stored seed banks and degradation in eastern Nama Karoo rangelands (South Africa). *Biodiversity & Conservation*. 2004 Oct;13(11):2027-53.
16. Lemenih M, Teketay D. Changes in soil seed bank composition and density following deforestation and subsequent cultivation of a tropical dry Afromontane forest in Ethiopia. *Tropical Ecology*. 2006;47(1):1-2.
17. Wang G, Lu C, Cheng G, Xiao R, Yang Z, Zhang X. Effects of changed precipitation amount and timing on soil seed bank dynamics in a semi-arid grassland. *Plant and Soil*. 2026 Jan;518(1):763-76.
18. Bekele M, Demissew S, Bekele T, Woldeyes F. Soil seed bank distribution and restoration potential in the vegetation of Buska Mountain range, Hamar district, southwestern Ethiopia. *Heliyon*. 2022 Nov 1;8(11).
19. Shi YF, Wang ZR, Xu BX, Huo JQ, Hu R, Zhao Y, Zhang ZS. Rainfall amount determines annual herb controls over soil seed bank and its similarity with vegetation in the Tengger Desert. *Ecological Processes*. 2022 Dec;11(1):1-1.
20. Zhao Y, Du G, Qi W, An H, Wang L, Luo S, Ma B, Ma M. Role of seed bank in aboveground vegetation regeneration signal ecosystem transition from arid grassland to shrubland with decreasing soil moisture. *Plant and soil*. 2021 Sep;466(1):193-205.
21. Bekker RM, Bakker JP, Grandin U, Kalamees R, Milberg P, Poschlod P, Thompson K, Willems JH. Seed size, shape and vertical distribution in the soil: indicators of seed longevity. *Functional Ecology*. 1998 Oct;12(5):834-42.

