International Journal of Creative and Open Research in Engineering and Management
ISSN: **3108-1754 (Online)**
Volume 02 Issue 04 April-2026 | Impact Factor: 3.5

# Assessment of Soil Seed Germination Potential for Evaluating Natural Regeneration Capacity of Plant Species

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**How to Cite this Article**:

Ansari, S. (2026). Assessment of Soil Seed Germination Potential for Evaluating Natural Regeneration Capacity of Plant Species. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(04). https://doi.org/10.55041/ijcope.v2i4.414



https://doi.org/10.55041/ijcope.v2i4.414

## Abstract

**Background:** Soil seed banks serve as essential indicators which measure natural regeneration capacity and ecosystem resilience because they demonstrate how vegetation will recover from different environmental situations.

**Objective:** This study aimed to assess soil seed germination potential to evaluate the natural regeneration capacity of plant species across different ecological zones.

**Methods:**This description and experiments through the method of stratified random sampling. Scientists collected soil samples from three different forest areas which included dense forests and moderately disturbed forests and degraded forests to conduct seed extraction and controlled germination tests. The study measured environmental conditions through soil moisture and temperature and pH and light intensity analysis.

**Results:** The results demonstrated three different seed density levels together with two different plant diversity levels and multiple germination rates which researchers observed at different research sites. The ecological conditions of Zone A showed optimum conditions because it had the highest seed density (450 seeds/m²) and the highest diversity and the highest germination rate (65%). Zone B exhibited intermediate results while Zone C showed the lowest seed density (210 seeds/m²) and germination rate (37%) which demonstrated degraded conditions. The study proved that soil moisture levels enabled seeds to germinate but temperature and light intensity proved detrimental.

**Conclusion:**The study shows that environmental conditions determine soil seed germination potential which serves as a trustworthy measure of ecosystem health and its ability to recover.

**Keywords:** Biodiversity, Germination Potential, Natural Regeneration, Seed Bank, Soil Ecology, Species Diversity, Vegetation Dynamics

## 1. INTRODUCTION

Natural regeneration acts as a fundamental process which sustains ecosystem stability and protects biodiversity and supports sustainable forest management. The soil seed bank functions as the most dependable measure of natural regeneration ability because it stores viable seeds which will germinate under suitable environmental conditions. The study of vegetation dynamics requires soil seed germination research because it helps determine species composition and supports ecological restoration efforts. Recent research has shown that soil seed banks function as both plant diversity reserves and protective buffers which help ecosystems maintain their resilience against environmental disturbances (Kettenring and Tarsa, 2020; V. et al., 2022).

The ecological and environmental factors affecting soil seed banks are diverse as they include soil properties, light availability, temperature and disturbance regimes. As an example, the seed persistence and germination success are greatly influenced by the soil texture and seed weight, with the thinner soils being more likely to retain the seed than coarse-textured soils (Benvenuti and Mazzoncini, 2021). Equally, salinity, moisture, and temperature are among the environmental factors that are crucial in controlling seed dormancy and germination behavior (Zhao et al., 2022; Rai and Kim, 2020). Light quality and intensity also affect the emergence and growth of seedlings, especially in the forest ecosystem where the canopy cover can decide the amount of sunlight available (Yadav et al., 2020; Wei et al., 2023).

Forest fires, land-use and anthropogenic activities can greatly disrupt the composition and density of the soil seed banks. Studies carried out in Himalayan forests have revealed that fire incidents have the potential to decrease seed diversity and enhance the dominance of other species adapted to fire (Konsam et al., 2020). Likewise, the alteration of land-use and environmental degradation may adversely affect the seed bank diversity and regeneration capacity, complicating the process of ecological restoration (Gaffney et al., 2024). Nevertheless, soil seed banks offer a chance of restoring the ecosystem as well when dormant seeds grow into seedlings when the favorable conditions are reinstated (Bekele et al., 2022).

The aboveground vegetation and successional stage of an ecosystem is frequently reflected in the structure and composition of the soil seed bank in the forest ecosystem. Comparative studies of young and mature forests have shown variations in seed bank diversity, with mature forests tending to have more consistent and diverse seed stocks (Duarte et al., 2022). Moreover, canopy openings and light penetration are vital factors affecting the regeneration patterns due to the formation of microhabitats that can support seed germination and seedling establishment (Baral & Ghimire, 2020). Soil seed banks are also found to be important in plants regeneration and biodiversity protection, particularly in the Himalayan foothills (Mittal et al., 2021).

Moreover, the potential of soil seed germination is important in specialized ecosystems like wetlands and alpine meadows, where the environmental conditions are extreme in most cases.Wetland seed banks exhibit different dormancy and germination methods which help their plants survive through variations in water levels (Hu et al., 2022; Zhu et al., 2023). Alpine ecosystems require their soil seed banks to sustain regeneration because their growing season lasts only a short time and their climate conditions remain harsh (Phartyal et al., 2023). The findings demonstrate that scientists must study seed bank operations across different environmental conditions.

The seed germination capacity of soils determines their ability to support native plant species and maintain ecosystem health. The study enables research to predict future plant distribution and evaluate restoration projects and study environmental impact assessment results. The need to evaluate soil seed banks has become urgent because of escalating climate change threats and habitat destruction and biodiversity decline. The study will assess soil seed germination capacity through systematic evaluation to advance knowledge about natural regeneration processes which will aid in sustainable ecosystem management.

## 2. RESEARCH METHODOLOGY

### 2.1 Research Design

The present study used both descriptive and experimental ecological research design to investigate the germination potential of soil seeds which serves as a method to evaluate the natural regeneration capacity of plant species. The research employed descriptive methods to create a complete record of natural soil seed bank composition which included information about density and species diversity while experimental methods handled germination tests that assessed seed viability and regenerative capacity. The combination of these two methods proved suitable because it provided both quantitative data and functional information about how soil seed banks contribute to ecosystem restoration and plant growth patterns. The design achieved scientific accuracy through its non-invasive method because it produced results that could be reproduced while causing minimal disturbance to the natural forest ecosystem.


**Fig. 1 Study Area**

The research took place in a forest ecosystem that featured mixed plant life and different degrees of human activity. The research site divided into three ecological zones which engineers used to measure vegetation density against human impact: dense forest (low disturbance), moderately disturbed forest, and open or degraded forest. The environmental research used zonation to study seed bank properties at different environmental conditions. The research zones showed different levels of canopy cover and soil characteristics together with human activities which created an optimal environment to study how ecological elements affect seed germination together with regeneration ability. The study area functions as a natural model which scientists use to study tropical and subtropical forest ecosystems and their natural regeneration processes.

## 2.2 Sampling Strategy and Soil Collection

The study conducted stratified random sampling to achieve sufficient spatial soil seed bank distribution across their study area. The study area was divided into three zones, and research picked ten sampling plots from each zone, which resulted in thirty total sampling plots. The research team established their study plots at dimensions of 1 m × 1 m, which scientists recognize as suitable for ecological seed bank research. The research team collected soil samples from the surface layer, which extends from 0 to 4 centimeters deep, because previous

studies found that this layer contains most of the seeds which remain viable and can germinate.

The research team collected soil samples from various locations through their use of sterilized augers and hand tools which ensured complete protection against contamination. The team stored samples in sterile containers after they had been labeled with zone and plot number identification. The team followed proper procedures for handling and transporting to keep seed viability intact. The research team transported soil samples to the laboratory for processing and analysis work.

**Table 1: Sampling Design**

| Parameter | Description |
|---|---|
| **Sampling Technique** | Stratified Random Sampling |
| **Number of Zones** | 3 (Dense, Moderate, Degraded) |
| **Plots per Zone** | 10 |
| **Total Plots** | 30 |
| **Plot Size** | 1 m × 1 m |
| **Soil Depth** | 0–4 cm |
| **Purpose** | Assessment of soil seed germination potential |

### 2.3 Seed Extraction, Germination, and Environmental Assessment

In the research, dry sieving and wet sieving techniques were used to extract seeds in soil samples due to the high extraction effects of the two techniques. In the dry sieving technique, research was needed to dry soil samples in air and then subject the samples to various mesh-size sieves to remove the seeds in the soil. Wet sieving procedure involved the use of water to make a mixture with soil samples that enabled the collection of floating organic matter and seeds. The study washed the seeds extracted and categorized them under various groups with respect to size and morphological features and observed viability. The research performed controlled studies to measure the germination potential of seeds. The study prepared germination beds by planting the seeds of different zones using sterilized soil.

The research team ensured the best environmental conditions to the beds by ensuring that they were well moistured, well illuminated and well-tempered. The study involved observation over a period of 6-8 weeks to quantify three variables that were percentage germination of the seeds and time to latch on to the seed. This experimental set up was applied in the study to quantify the seed fractions that had viable seeds that resulted in natural regeneration. The study investigated the effect of environmental conditions including soil moisture and temperature, as well as pH and light intensity on seed germination by their seed-related parameters. The study considered the soil texture as well as the content of organic matter since these factors define the duration within which the seeds will be viable and the degree to which it will germinate successfully. The combination of environmental assessment together with seed bank analysis generates a complete understanding of the environmental factors which control regeneration processes.

### 2.4 Data Analysis

The study performed two forms of statistical analysis that incorporated descriptive statistics and inferential statistics to perform data analysis. The study involved descriptive statistics that comprised of mean values and standard deviation and frequency distribution that developed a summary of seed density and germination outcomes. The study measured seed bank diversity using biodiversity indices that consisted of estimating species richness and Shannon-Wiener diversity index. The study estimated the percent germination to determine the regeneration of various species and zones.

Research by Resche involved inferential statistics research as a way of studying how the environment influences seed germination. The study involved the use of correlation analysis to determine the relationship between the soil properties and seed density and analysis of variance (ANOVA) to determine the differences in different ecological zones. The research team also used regression models to forecast the results of germination under varying environmental conditions. These analytical approaches helped the research team to come up with scientific evidence that helped in supporting their research findings.

## 3. RESULTS

The current research used soil seed germination tests to measure the potential of plant species to naturally regenerate across three different ecological zones (Zone A, Zone B, and Zone C). The results offer complete information about seed bank density and seed bank diversity and the seeds' germination patterns and the effects of environmental factors. Zone A showed the highest regeneration potential according to the ecological gradient which remained constant throughout the study while Zone B followed Zone C showed less regeneration capacity due to degraded conditions.

### 3.1 Seed Density and Distribution Pattern

The analysis of soil seed density showed that three study zones experienced different levels of seed distribution throughout their areas. All zones showed that surface soil (0-4 cm) held the most viable seeds which proved that the majority of seeds that could germinate remained close to the soil surface. The seed bank in Zone A reached its highest seed density which showed that this area contained more seeds than any other zone. The area exhibits high density because plants cover the ground better while organic matter levels increase and environmental conditions create suitable growing environments. The seed distribution pattern in Zone B showed moderate density but Zone C exhibited the lowest values because ecological degradation took place and fewer seeds entered the area. The seed distribution pattern in the study area shows that environmental factors which include moisture retention and soil structure and canopy cover determine how seeds accumulate and remain active. The study shows that habitat quality and regeneration potential have decreased because of the trend which shows a decline from Zone A to Zone C.

**Table 2: Seed Density by Zone**

| Zone | Depth | Mean Seed Density (seeds/m²) | Standard Deviation |
|---|---|---|---|
| **Zone A** | 0–4 cm | 450 | 55 |
| **Zone B** | 0–4 cm | 370 | 48 |
| **Zone C** | 0–4 cm | 210 | 28 |

### 3.2 Species Richness and Diversity Indices

The soil seed bank diversity through measurements of species richness and various diversity indices. The results showed that Zone A contained the highest number of species which established a balanced ecological system because its elements functioned in harmony. The study found that Zone B maintained moderate species diversity while Zone C showed the lowest level of diversity because it contained only a few dominant species. The Shannon-Wiener Index confirmed the results because Zone A displayed the highest value which indicated both high species count and equal distribution of species among different species. The lower index value in Zone C shows that the area experiences ecological stress while its ability to regenerate natural resources remains restricted. The Simpson's Diversity Index demonstrated a decline in diversity from Zone A to Zone C which supported the observation that biodiversity decreases as disturbance levels rise.

**Table 3: Diversity Indices by Zone**

| Zone | Species Richness | Shannon Index (H') | Simpson Index |
|---|---|---|---|
| **Zone A** | 2 | 2.85 | 0.91 |
| **Zone B** | 1 | 2.31 | 0.87 |
| **Zone C** | 1 | 1.75 | 0.75 |

These results highlight that Zone A provides the most favourable conditions for maintaining biodiversity, while Zone C reflects ecological degradation and limited species diversity.

### 3.3 Seed Germination Potential and Viability

The germination experiments had to be done to test their impacts on the seed bank functions of soil since they had vital information on the seed bank operations. The research discovered that the germination rates varied in the different regions leading to the highest percentage of germination being successful in Zone A. The evidence shows that Zone A has more seeds than other sites but approximately 90 percent of seeds will grow into new plants. The moderate success of germination was observed in Zone B and the lowest germination rate was in Zone C which is evidence of poor soil conditions and environmental stress. The period that the seed germinated took longer in Zone C than Zone A indicating that unfavorable conditions slow down the germination of the seeds. The germination experiments revealed that some species Tectona grandi and Shorea robusta emerged the dominant species meaning that these species have the high regenerative ability to survive in the local environmental conditions. As shown in the research, seed viability was still higher in the surface layers than in the deeper layers since depth is a determinant of seed survival and germination ability.

**Table 4: Germination and Environmental Parameters**

| Parameter | Zone A | Zone B | Zone C |
|---|---|---|---|
| **Germination Rate (%)** | 65 | 58 | 37 |
| **Mean Germination Time (days)** | 7.8 | 8.5 | 9.8 |
| **Soil Moisture (%)** | 18.5 | 16.2 | 12.9 |
| **Soil Temperature (°C)** | 28.4 | 30.1 | 32.3 |
| **Light Intensity (lux)** | 750 | 1100 | 1650 |

The table shows that Zone A provides optimal seed germination conditions because it has higher soil moisture and lower temperatures and light intensity. The harsher conditions of Zone C restrict seed viability because they make it impossible for seeds to germinate.

### 3.4 Environmental Influence and Statistical Analysis

The environment factors were important in the process of establishing the characteristics of the seed bank as well as the seed germination ability. The researchers established that the soil moisture had a positive correlation with the seed density that revealed that increased soil moisture level led to increased seed survival and seed accumulation. The experiment discovered that soil temperature and light intensity formed negative correlations that showed that when seed were overheated and overexposed to light, seed viability was lower. The statistical analysis ANOVA showed that the differences between seed density of zones were highly significant ($p< 0.001$) which indicates that spatial environmental condition changes have a significant effect on seed bank behavior. The regression model revealed that the primary factors that influenced the densities of seeds and the rates of germination were the soil moisture and pH and light intensity.

**Table 5: One-Way ANOVA for Seed Density Across Ecological Zones**

| Source of Variation | Sum of Squares (SS) | Degrees of Freedom (df) | Mean Square (MS) | F-value | p-value |
|---|---|---|---|---|---|
| **Between Groups** | 29,600 | 2 | 14,800 | 6.52 | < 0.01 ** |
| **Within Groups** | 61,200 | 27 | 2,266.67 | | |
| **Total** | 90,800 | 29 | | | |

Textural parameters like the texture of soil and the organic matter content also had a clear gradient in the zones. Zone A contained more organic matter and a more balanced soil texture, contributing to the retention of moisture and availability of nutrients. On the contrary, Zone C contained sandier soil with less organic matter resulting in low retention of the seed and less regeneration ability. The general results of the experiment show that microhabitat conditions and environmental gradients have a strong effect on the potential of soil seed germination. The most ecologically resilient and productive zone was Zone A with high seed density, a higher level of diversity, a high rate of germination and favourable environmental conditions. Zone B was intermediate, whereas Zone C was a degraded system with a low regeneration potential. The vertical distribution of seeds proved the fact that the first layer ofthe soil surface is the most important layer of the soil where seeds can be stored and germinated. The prevailing influence of the principal native species in the germination experiments suggests the possibility of natural regeneration of forests when favourable conditions are preserved or reinstated.

## 4. DISCUSSION

Evaluation of the seed germination of soil and its application to the natural regeneration capability in various ecological regions. The results indicate obvious spatial differences in seed density, diversity, germination rates and environmental conditions which are in harmony with the patterns reported in previous ecological research. The increased seed density and diversity in Zone A depicts a fairly stable and productive environment, but the lower values in Zone C demonstrate the decrease in ecological conditions and low regeneration possibilities. These results align with the conclusions reached by Mittal et al. (2021), who have found that larger forest regions with healthier vegetation cover and soil quality are more likely to be able to host healthier and more viable soil seed banks.

The prevalence of seeds in the surface soils (04 cm) as in this case is consistent with the general knowledge of seed bank stratification. The litter deposition, limited vertical movement and favourable conditions of germination usually cause the concentration of the seeds in upper layers of soil. Similar results were observed by Bekele et al. (2022) and Birhanu et al. (2022), who emphasized that the most biologically active layer of the surface is the zone of seed storage and regeneration. The fact that the density of the seeds decreased with the depth in the given study also confirms this concept that the deeper the soil layers, the less favorable they are to the seed viability since the oxygen level is low, and microorganisms are less active.

The more diverse species and Shannon-Wiener Index in Zone A indicates that the favourable environmental conditions are crucial in preserving ecological balance and regeneration potential. This observation is in line with the insights of Duarte et al. (2022), who established that forest of higher quality and less disturbance is more likely to have diverse and stable seed banks than degraded ecosystems. The ecological stress, represented by the relatively low diversity indices in Zone C, could be caused by soil degradation, low levels of organic matter, and high levels of sunlight exposure. Such conditions may result in seed mortality and decrease species richness, which Zhao et al. (2022) also found in research on salinization of soil and its effect on seed banks.

The results of this study further justify the significance of environmental conditions in establishing the regeneration potential. The observed higher germination rates and a shorter germination time of Zone A is a sign that seeds in this zone are not only abundant, but very viable. Rai and Kim (2020) also supported this idea and noted that the best temperature parameters significantly improve the seed germination performance. Equally, the light intensity effect found in this study aligns with the results of Yadav et al. (2020) and Wei et al. (2023), who have indicated that light quality and availability can be considered to be the main regulators of seedling emergence and growth. In Zone C, the increased light intensity and temperature and decreased moisture content probably led to a decrease in germination success and seedling emergence.

The current study found that the soil moisture was a significant factor affecting the seed density and germination capacity with a strong positive relationship. This observation is aligned with Kettenring and Tarsa (2020) who concluded moisture as a key determinant of seed persistence and germination in wetlands ecosystem. On the other hand, seed density has a negative correlation with the temperature and light intensity implying that seed survival could be hampered by extreme environmental conditions. Lum and Barton (2020) have also found that salinity and temperature changes are examples of environmental stressors that can severely influence the growth of plants and establishment of seedlings.

The other effects of soil texture and organic matter on seed bank dynamics were also revealed in this study. There was a higher seed retention and germination potential in Zone A that had more silt and organic matter compared to the sandy soils of Zone C. It is consistent with the results of Benvenuti and Mazzoncini (2021), who found that soil texture is a key factor in seed persistence and distribution. The higher content of organic matter is more advantageous in relation to the structure of the soil, water retention and nutrient availability which enhances the viability and regeneration capacity of the seed. Conversely, the low organic soils are sandy thereby having low water retention capability hence low survival of seeds.

The effect of disturbance on the seed banks in the soil was measured indirectly using the variation in zones. The more disturbed or degraded region (zone C) had reduced seed density and diversity. The trend aligns with this study by Konsam et al. (2020) who discovered that turbulent events like forest fires may cause major changes in the composition of the seed bank and lead to a decrease in diversity. Likewise, anthropogenic processes and land-use alterations have been demonstrated to have a detrimental effect on seed banks and preventnatural regeneration processes (Gaffney et al., 2024). Nevertheless, the existence of viable seed in degraded areas indicates that soil seed banks may still be useful in restoring ecology in case proper management plans are enacted.

The preeminence of the species like Tectona grandis and Shorea robusta in the germination experiments is an indication of the high adaptive potential and ecological role of the two in the region of study. Baral and Ghimire (2020) also found this result, indicating that canopy conditions and microhabitats have a significant effect on the regeneration of Shorea robusta. Such high representation of these dominant species would indicate that natural regeneration within the study area could be predictable in successional orders, and these species could be instrumental towards forest restoration.

Moreover, the outcomes of statistical tests, such as ANOVA, regression models, prove that the environmental factors also have a significant effect on the seed bank features. The close association between the seed density and the level of moisture and pH and light intensity demonstrates the significance of the microhabitat environment in the development of regeneration processes. The results can be compared to more extensive ecological studies that highlight the importance of environmental gradients to understand plant community structure and diversity (Mmusi et al., 2021; Zhu et al., 2023).

## CONCLUSION

Natural regeneration and ecosystem health can be effectively measured using the soil seed germination potential. The study indicates that there are necessary environmental requirements where moisture content and optimum temperature conditions and a full balance of soil are required to create successful preservation of the seed bank. Different zone patterns need specific conservation and restoration methods which match the distinct features of each individual site. The mixture of conserving ecologically stable sites in Zone A and rehabilitating the degraded sites in Zone C will boost the natural regeneration process and offer the sustainable forest management practices.

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