Assessment of Soil Seed Bank Dynamics and Regeneration Potential Across Three Different Forest Types in the Himalayan Foothills

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Research Article

Keywords: Biodiversity, Conservation, Regeneration, Soil Seed Bank, Species Diversity

Posted Date: November 25th, 2025

DOI: https://doi.org/10.21203/rs.3.rs-7984952/v1

Additional Declarations: No competing interests reported.

Abstract

This study examines the soil seed bank potential in three forest types in Dehradun district: Sal, Pine, and Mixed Deodar. Soil samples were collected and monitored for seedling emergence to assess their roles in natural regeneration and biodiversity conservation. Species composition, density, diversity indices, and inter-forest similarities were analyzed using statistical and ordination techniques.

A total of 371 individuals from 15 species across 10 families were observed, with herbs being the dominant growth form (66.67%) and Asteraceae as the most represented family (20%). Seed density varied among forest types, with Pine forest having the highest germination potential and maximum seed density of 1291.67 seeds/m² for *Sorghum halepense*. Deodar forest had an intermediate density dominated by *Cassia tora* (638.89 seeds/m²), while Sal forest had the lowest density but supported the highest species richness (10 species) and diversity indices (Shannon = 2.07, Simpson = 0.85). Jaccard's similarity coefficient indicated greater similarity between Sal and Pine forests (0.583), with Deodar showing the least overlap with Sal (0.286). NMDS ordination confirmed distinct community assemblages among the three forest types, with characteristic indicator species identified for each.

These results demonstrate significant variation in soil seed bank composition and regenerative capacity across forest types. Pine forests have dense but less diverse seed banks, mainly dominated by grasses, while Sal forests have balanced and diverse assemblages, supporting broad regeneration potential. Deodar forests exhibit lower diversity due to dense canopy and thick litter layers. The presence of invasive species like *Parthenium hysterophorus* in all sites highlights ecological risks to native regeneration.

Introduction

Based on the Global Forest Watch report (2024), Uttarakhand experienced a loss of 30 hectares of humid primary forest, accounting for 0.13% of its total tree cover loss during the same period. The total area of humid primary forest in Uttarakhand decreased by 0.32% in this timeframe, indicating a concerning rate of forest depletion in the region. Soil Seed Bank Analysis is a valuable tool for comprehending future forest trends and informing conservation strategies.

The soil seed bank serves as a reservoir of viable seeds within the soil, playing a crucial role in plant population dynamics, biodiversity preservation, and ecosystem resilience. It is essential for natural regeneration, species succession, and ecological restoration efforts (Thompson and Grime, 1979; Baskin and Baskin, 2014). Understanding the composition and dynamics of soil seed banks is particularly vital in forest ecosystems, where vegetation recovery post-disturbances relies heavily on the existing seed population.

Roberts (1981) defines the soil seed bank as the collection of viable seeds present in the soil. Baker (1989) further elaborates that this reservoir consists of seeds that have not yet germinated but have the potential to replace adult plants lost due to natural causes, diseases, disturbances, or consumption by animals, including humans. All viable seeds within the soil or mixed with soil debris contribute to the soil seed bank (Simpson et al., 1989).

Large quantities of seeds can remain dormant in the soil for extended periods, and can sprout when conditions are favorable (Warr et al. 1993). Soil seed banks play a crucial role in understanding vegetation history, as the composition of vegetation in terms of plant species is influenced by seed production, dispersal, seed longevity, and soil depth (V. Anju et al. 2022). Seed banks are key determinants of future vegetation, particularly following a disturbance (Warr et al. 1993).

Dehradun, situated in the Doon Valley at the foothills of the western Himalayas, is known for its remarkable ecological diversity. It is located at the meeting point of the Shivalik range, the outer Himalayas, and the Indo-Gangetic plains, creating diverse climatic and soil conditions that support a variety of forest types (Champion and Seth, 1968). The region encompasses moist deciduous forests dominated by sal (*Shorea robusta*), pine (*Pinus roxburghii*) forests, mixed broadleaf forests, and riverine forests, among others. These diverse forest ecosystems exhibit differences in microclimatic conditions, human impact, disturbance patterns, and vegetation structure, all of which impact the composition and abundance of their soil seed banks.

While regeneration studies have been conducted by various researchers, there is limited information available on the diversity of soil seed banks in different forest types in Uttarakhand. The present study aims to address this gap by investigating the soil seed bank diversity in Sal, Pine, and mixed Deodar-dominated forest stands in the Himalayan foothills.

Methodology

Study Area

This study took place in Dehradun district, situated between the Himalayas to the north and the Shivalik Hills to the south, with geographical coordinates of 30.3165o N latitude and 78.0322o E longitude. The major forest types in the area include Sal forests at lower elevations, Pine forests at mid elevations, and Oak and Rhododendron at higher elevations.

Site I: *Shorea robusta* (Sal) Forest: Located at latitude 30.37752 N and longitude 77.931215 E, soil samples were collected from the Sal Forest in Manduwala, part of the Dehradun Forest Division.

Site II: *Pinus roxburghii* (Chir Pine) Forest: Coordinates at latitude 30.453615 N and longitude 77.944039 E. Soil samples were collected from the Pine Forest in Koti, within the Chakrata Forest Division.

Site III: Mixed *Cedrus deodara* (Deodar) Forest: Coordinates at latitude 30.4449540 N and longitude 78.076609 E. This study site is located in Mussoorie, which is under the jurisdiction of the Mussoorie Forest Division.

Soil Sampling

In this study, 1 m × 1 m quadrats were randomly placed across the study site to evaluate species distribution and abundance. A distance of 50 meters was maintained between consecutive quadrats to ensure spatial independence and reduce sampling bias. A total of 10 quadrats were established at each study site to provide a representative sample for statistical analysis. Two soil samples were collected from each quadrat—one from a depth of 0–5 cm and the other from 5–10 cm. Therefore, 20 soil samples were collected from each site, resulting in a total of 60 samples across all three sites. In the laboratory, the two depth samples from each plot were combined and thoroughly mixed before being air-dried for 48 hours. Any visible debris, such as stones, twigs, and other extraneous material, was carefully removed during the drying process.

After drying and cleaning, the soil samples were placed in labelled vegetation trays and kept in a controlled setting without existing vegetation to prevent external interference with natural seed germination. No external soil enrichments, such as fertilizers or farmyard manure (FYM), were added to observe the natural regeneration potential of the seed bank. Irrigation was carried out manually, initially every alternate day, and later daily as the summer season progressed and evaporation rates increased to maintain adequate soil moisture.

Data Collection

Seedling emergence was regularly monitored, and the number of germinations from each tray was recorded. Seedlings were uprooted by hand as they reached a stage where species identification was possible, to minimize disturbance and allow other seeds to continue germinating.

Species were identified based on morphological traits such as size, shape, color, and surface texture of leaves and stems. The weekly recording of the number of individuals of each species was conducted over an eight-week period.

Data Analysis

Soil seed bank germination was compared among different forest types using the Kruskal–Wallis test (Kruskal & Wallis, 1952), followed by Dunn's post-hoc pairwise comparisons (Dunn's, 1964). Community structure was evaluated using diversity indices (species richness, Shannon, Simpson, and evenness), and compositional differences were visualized with non-metric multidimensional scaling (NMDS) based on Bray–Curtis dissimilarity. All statistical analyses were performed using R software (Version 4.5.0) with appropriate packages for non-parametric testing, diversity metrics, and ordination. Seed density was calculated as the number of seedlings (viable seeds) per unit area (expressed as seeds/m^2) based on the total number of seedlings that emerged from each soil sample.

Result

Soil seed bank density and morphology of plants

A total of 371 individuals emerged from the soil seed banks of three different forest types, consisting of a total of 15 species, namely *Ageratum houstonianum, Sorghum halepense, Dioscorea bulbifera, Commelina diffusa, Parthenium hysterophorus, Cassia tora, Alysicarpus ovalifolius, Commelina benghalensis, Scindapsus officinalis, Solanum xanthocarpum, Artemisia vulgaris, Lindenbergia indica, Oxalis exilis, Cedrus deodara*, and one unidentified species representing 10 families. The Asteraceae family was the most dominant, with 3 species (20%), followed by Fabaceae and Commelinaceae with 2 species each (13.33%). The rest of the families had only one species each (6.67%). Herbs were the dominant growth form, comprising 66.67% (10 species), followed by climbers at 13.33% (2 species). Dicots accounted for 53.33% (8 species), monocots for 33.33% (5 species), and Gymnosperms for 6.67% (1 species).

The highest seed density recorded was 1291.67 seeds/m^2 for *Sorghum halepense* in Pine forest, followed by *Cassia tora* with 638.89 seeds/m^2 in Deodar forest. The lowest density recorded was 13.89 seeds/m^2 for *Scindapsus officinalis*, *Solanum xanthocarpum* (in Sal forest), and *Cedrus deodara* in Deodar forest. In the Sal forest, the highest seed density recorded was 166.67 seeds/m^2 for *Ageratum houstonianum*.

Kruskal-Wallis with Dunn Post-hoc

The Kruskal-Wallis test showed a significant variation in soil seed bank germination among the three forest types, and Dunn's post-hoc analysis clarified the pairwise contrasts. The median and IQR values with significance are presented in Table 1. The data was highly skewed, leading to the use of Median with IQR. The results showed that Pine forest had the highest germination potential, forming a distinct significance group ("b"), while Deodar and Sal forests clustered together in group "a," indicating no statistical difference between them. This suggests that the soil seed bank under Pine stands supports significantly greater germination potential compared to Deodar and Sal forests, which maintain relatively lower and similar seed bank germination levels.

Table 1
Median and IQR with significance

	Forest	Median_IQR	Significance
1	Deodar	0 (0–1)	a
2	Pine	1 (0–4)	b
3	Sal	0 (0–0)	a

The violin plot (Fig. 2) indicates that Pine forest soils produced the highest number of germinants per tray, with some replicates exceeding 20 individuals, placing it in a distinct significance group. The wider distribution and higher upper tail in the Pine category suggest a much richer and more responsive soil seed bank compared to Deodar and Sal stands, which show relatively sparse and similar germination densities.

Diversity Indices

The diversity metrics indicate significant differences in soil seed bank composition among the three forest types. Sal forest has the highest species richness (10 taxa), Shannon diversity (2.07), Simpson index (0.85), and evenness (0.90), indicating a well-balanced community. Pine forest has slightly lower richness (9) and moderate diversity (Shannon 1.62; Simpson 0.74), with a slightly skewed community. Deodar forest has the lowest richness (8), Shannon (1.35), and Simpson (0.67), with reduced evenness (0.65), indicating a less diverse and uneven seed bank dominated by a few species. Overall, Sal forest maintains the most diverse and balanced soil seed bank, Pine forest is intermediate, and Deodar forest has the least diverse and even assemblage (Fig. 3).

Similarity among soil seed banks

The Jaccard's similarity coefficient values in Table 2 show that Sal and Pine forests have the highest similarity in soil seed bank, followed by Pine and Deodar forests. The lowest similarity was found between Sal and Deodar forests.

Table 2
Jaccard's Similarity Coefficient of soil seed banks

	Sal	**Pine**	**Deodar**
Sal	1	0.583	0.286
Pine	0.583	1	0.417
Deodar	0.286	0.417	1

Non-metric Multidimensional Scaling (NMDS)

The NMDS ordination (Bray–Curtis) (Fig. 4) shows clear compositional differences in the soil seed bank among Deodar, Pine, and Sal forests, with a low stress indicating a good fit of the ordination. Points representing the three forest types are spatially separated, indicating distinct community assemblages within each forest. Deodar plots (red circles) cluster towards positive NMDS1 values, closely associated with species vectors such as *Lindernia crustacea* and *Lindernia ciliata*. Pine plots (green triangles) are located in the lower central portion of the ordination, showing stronger alignment with species like *Artemisia vulgaris* and *Sorghum halepense*, suggesting these taxa are characteristic of Pine forest seed banks.

Sal plots (blue squares) group on the negative NMDS1 axis, with associations to *Commelina diffusa*, *Alysicarpus ovalifolius*, and *Parthenium hysterophorus*. Species vectors extending outward indicate the strength and direction of each taxon's contribution to community structure, with longer vectors (e.g., *Artemisia vulgaris, Lindernia crustacea*) having a greater influence on ordination patterns. Overall, the ordination confirms that forest type strongly influences seed bank composition, with Pine, Sal, and Deodar supporting floristically distinct assemblages and characteristic indicator species.

Plate 1- Soil sample collection and seed germination

Discussion

This study identified 15 plant species from 10 families, with herbs being the dominant growth form (66.67%), followed by climbers (13.33%). The Asteraceae family was the most dominant (20%), followed by Fabaceae (13.33%). The highest seed density recorded was 1291.67 seeds/m2, while the lowest was 13.89 seeds/m2. Bekele et al. (2022) found 56 species from 27 families, with herbs (78.6%) and the Asteraceae family (20%) being the most dominant, consistent with the current study. Birhanu et al. (2022) observed 2133 species from 27 families, with Asteraceae as the most diverse family, followed by Solanaceae. They also found herbs to be the dominant growth form, with a seedling density of 4637 seeds/m^2. Phartyal et al. (2023) studied the Tungnath Alpine Meadow and identified 13 species (10 dicots, 3 monocots) with an average seed density of 2141 seeds/m^2 at a soil depth of 10 cm. In the present study, 15 species (1 unidentified) were observed, including 8 dicots, 5 monocots, and 1 Gymnosperm. Mittal et al. (2021) conducted a comparative study in Kumaon Central Himalaya Forests, noting the highest emergence of grasses in Pine forests and the lowest in Sal forest soils, while forbs had maximum emergence in Deodar-Oak forest soils.

The greater species richness observed in the Sal Forest (10) may be due to its more open canopy structure, allowing more light to penetrate and supporting a wider variety of understory species. Baral and Ghimire (2020) also found higher seedling density in semi-open *Shorea robusta* forests compared to closed-canopy stands in the Terai Sal forest in Western Nepal. In contrast, the Pine Forest, while dominated by fewer species, had a significantly higher density of *Sorghum halepense*, suggesting potential monoculture formation within the soil seed bank. Several studies have shown a positive impact of forest fires on maintaining plant biodiversity in Pine forests (Kuuluvainen and Rouvinen, 2000; Gorshkov and Stavrova, 2002; Marozas et al. 2007; Konsam et al. 2020).

The Mixed Deodar Forest had lower diversity and evenness, likely due to its dense canopy cover and thick litter layer, typical of coniferous forests. Previous research suggests that soil seed banks in coniferous forests tend to have lower species richness and density compared to deciduous forests (Granström, 1988; Leckie et al. 2000).

Interestingly, the dominant species in each forest type consistently had higher Simpson's and Shannon-Wiener diversity indices, indicating an uneven species distribution with a few species dominating. This trend was also observed in studies by Grime 1988, Dougall & Dodd 1997, and You et al. 2025, showing that species dominance in subtropical forest seed banks can lead to reduced community evenness and diversity.

The current study revealed variations in seed density and diversity indices in the seed soil banks of different forests. Similar findings were reported by Zoghloul 2008, Heydari et al. 2013, Madawala et al. 2016, Tessema *et al*. 2017, Shiferaw et al. 2018, Mmusi et al. 2021, Durate *et al*. 2022, and Zhu et al. 2023 in their respective studies on various forest ecosystems. Factors such as seed size and dispersal, viability, longevity, predator activities, dormancy, light availability, and other environmental conditions influence the density and diversity of soil seed banks (Leck et al. 1989; Whitmore, 1991; Teketay and Granstrom, 1995; Teketay 1998; Matus et al. 2005; Chen et al. 2019; Benvenuti and Mazzoncini, 2021; Zhao et al. 2022).

In the current study, the highest Jaccard's similarity coefficient was found between Sal and Pine forests (0.583), with Pine and Deodar forests showing intermediate similarity (0.417) and Sal and Deodar forests exhibiting the lowest similarity (0.286) in terms of soil seed banks. Bekele et al. (2022) reported a higher similarity in species composition between grassland and shrub land (0.52), followed by forest and shrub land (0.47), while the forest and bare land had the lowest similarity coefficient. Birhanu et al. (2022) noted a very low similarity (0.11) between seedlings emerging from the soil seed bank and the above-ground vegetation. Godefroid et al. (2006) observed a decrease in similarity between vegetation and the seed bank in managed temperate forest ecosystems, with pine to oak plantations showing a decreasing trend.

The widespread presence of invasive species like *Parthenium hysterophorus* in all three forest types indicates a significant distribution and underscores its potential threat to the regeneration of native species. Bajwa et al. (2016) also observed similar patterns, noting the aggressive and competitive nature of *Parthenium hysterophorus* in various forest ecosystems, where it can outcompete native flora, disrupt ecological balance, and reduce biodiversity. The introduction of invasive plant species has a detrimental impact on biodiversity and ecosystem functioning, contributing to global ecological and economic challenges (Fourie, 2012; Gioria et al. 2012; Shiferaw et al. 2018).

Conclusions and recommendations

The study revealed significant variations in the composition of soil seed banks among Sal, Pine, and Deodar forests in the Himalayan foothills. Sal forests exhibited the highest species richness and balanced diversity, indicating strong regenerative potential. In contrast, pine forests had the highest seed density but the lowest diversity, while Deodar forests showed low diversity due to their dense canopy and litter accumulation. The presence of the invasive species *Parthenium hysterophorus* poses a threat to native regeneration. To address this, forest management strategies should focus on controlling invasive species, preserving soil seed banks for regeneration, and implementing site-specific restoration techniques. Incorporating seed bank research into long-term monitoring efforts can enhance forest resilience and biodiversity conservation in the area.

Declarations

Funding declaration- No funding was received for the present work.

Consent to Publish declaration- not applicable.

Ethics declaration: Generative AI tool (Chat GPT) was used for language improvement.

Clinical trial number: not applicable.

Competing Interest: There is no competing interest.

Consent to Participate declaration: not applicable.

Author Contribution

Pema Choki Lepcha did filed and lab work (the collection of samples and observation of seedling grwoth) under the supervision of Prabhakar Manori. Primary manuscript written work, Statistical analysis and preparation of figures were done by Prabhakar Manori and Manish Kumar. Manuscript formatting and arrangement of text were collectively done by Viskaspal Singh Rawat, Sandhya Goswami and Anil Kumar Uniyal. All authors reviewed and gave their suggestions for finalizing the manuscript.

Acknowledgement

The authors would like to express their sincere gratitude to the Department of Forestry, Dolphin PG Institute of Biomedical and Natural Sciences, for providing the necessary materials and laboratory facilities required to carry out this study. The authors also acknowledge the support and cooperation of all staff members who contributed to the successful completion of this work. This research did not receive any specific grant or funding from public, commercial, or not-for-profit agencies.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Plate

Plate 1 is available in the Supplementary Files section.

Figures

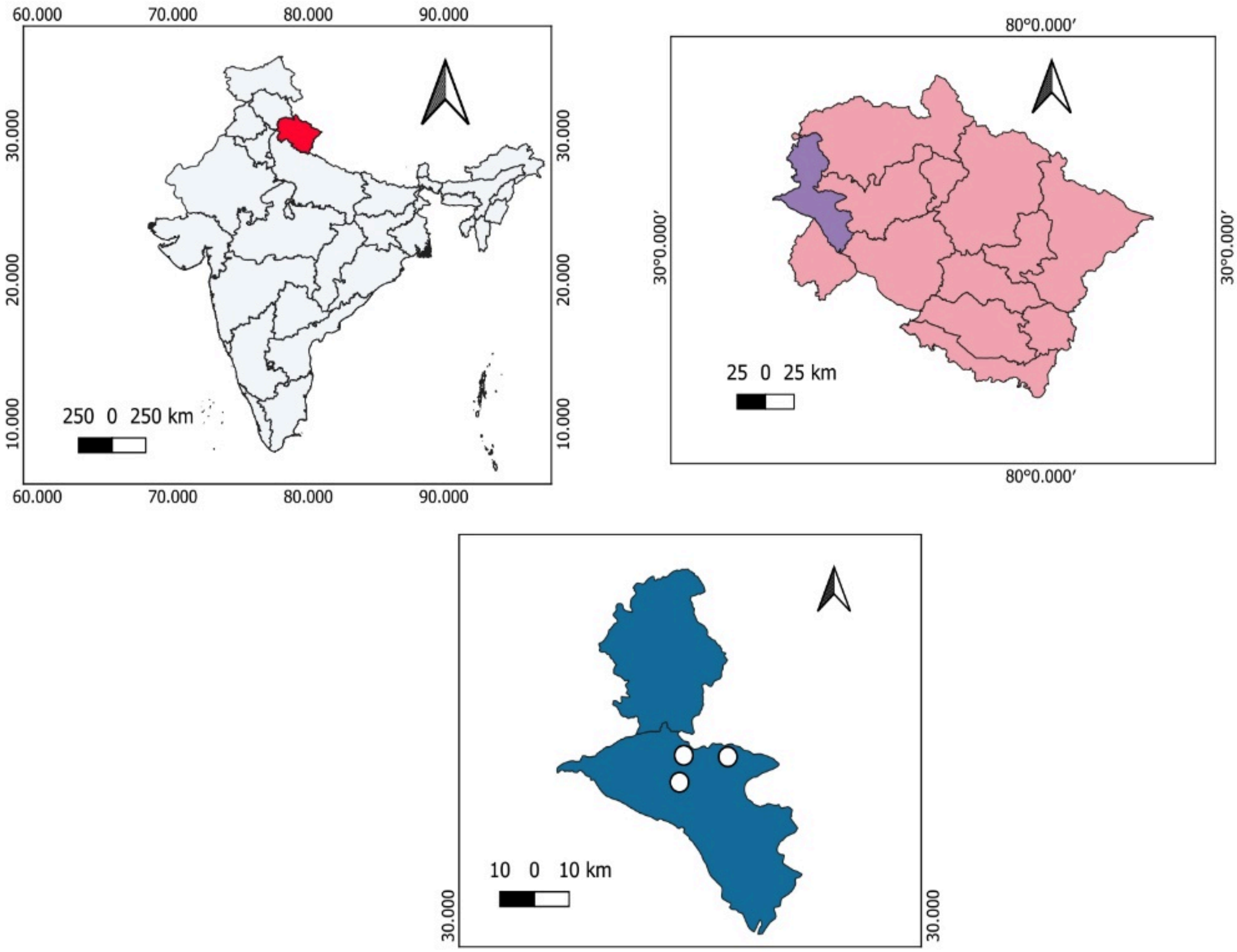

Figure 1

Location map ofViolin plot of Kruskal-Wallis with Dunn’s Post-hoc teststudy site.

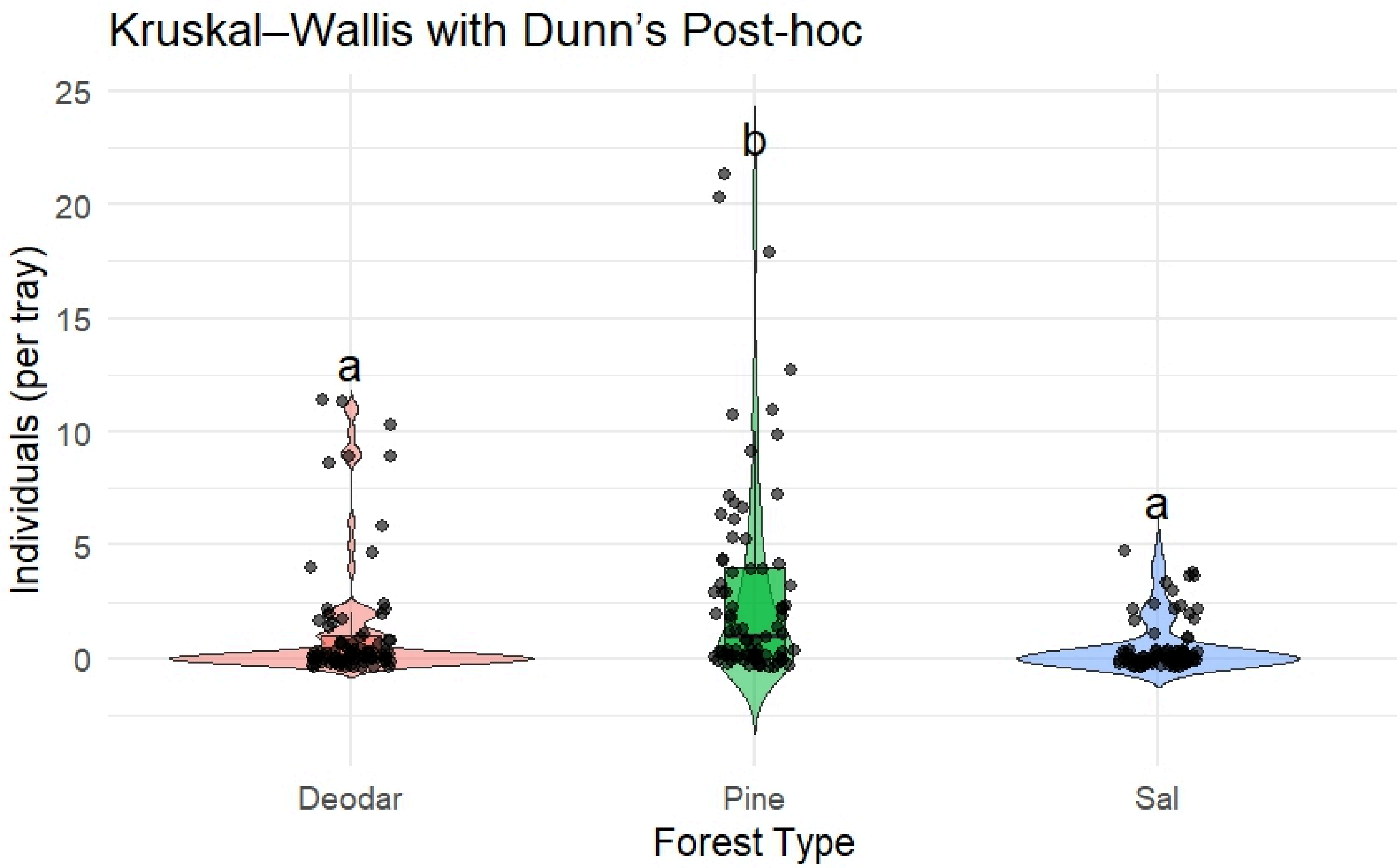

Figure 2

Violin plot of Kruskal-Wallis with Dunn's Post-hoc test

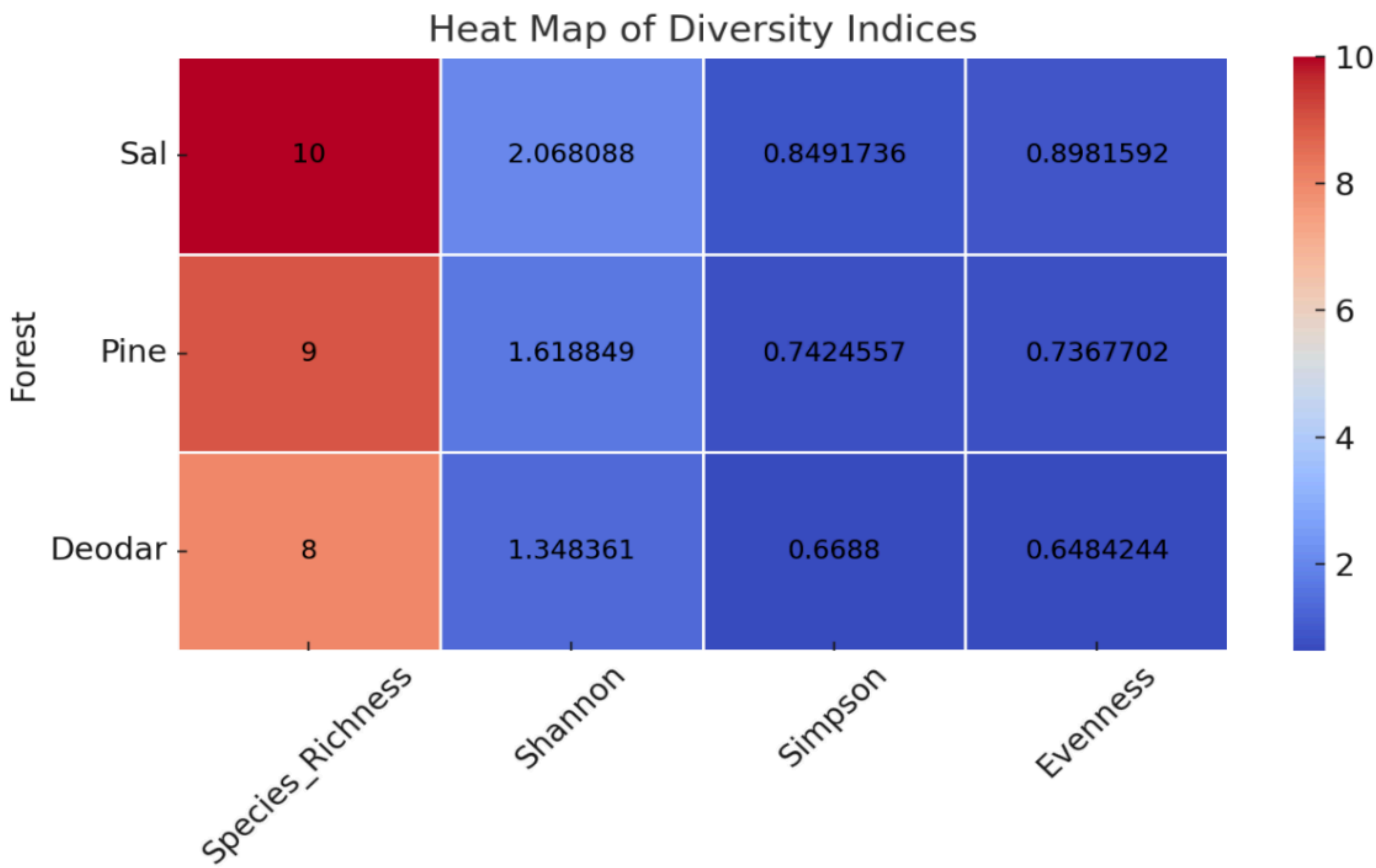

Figure 3

Heat Map of Diversity Indices

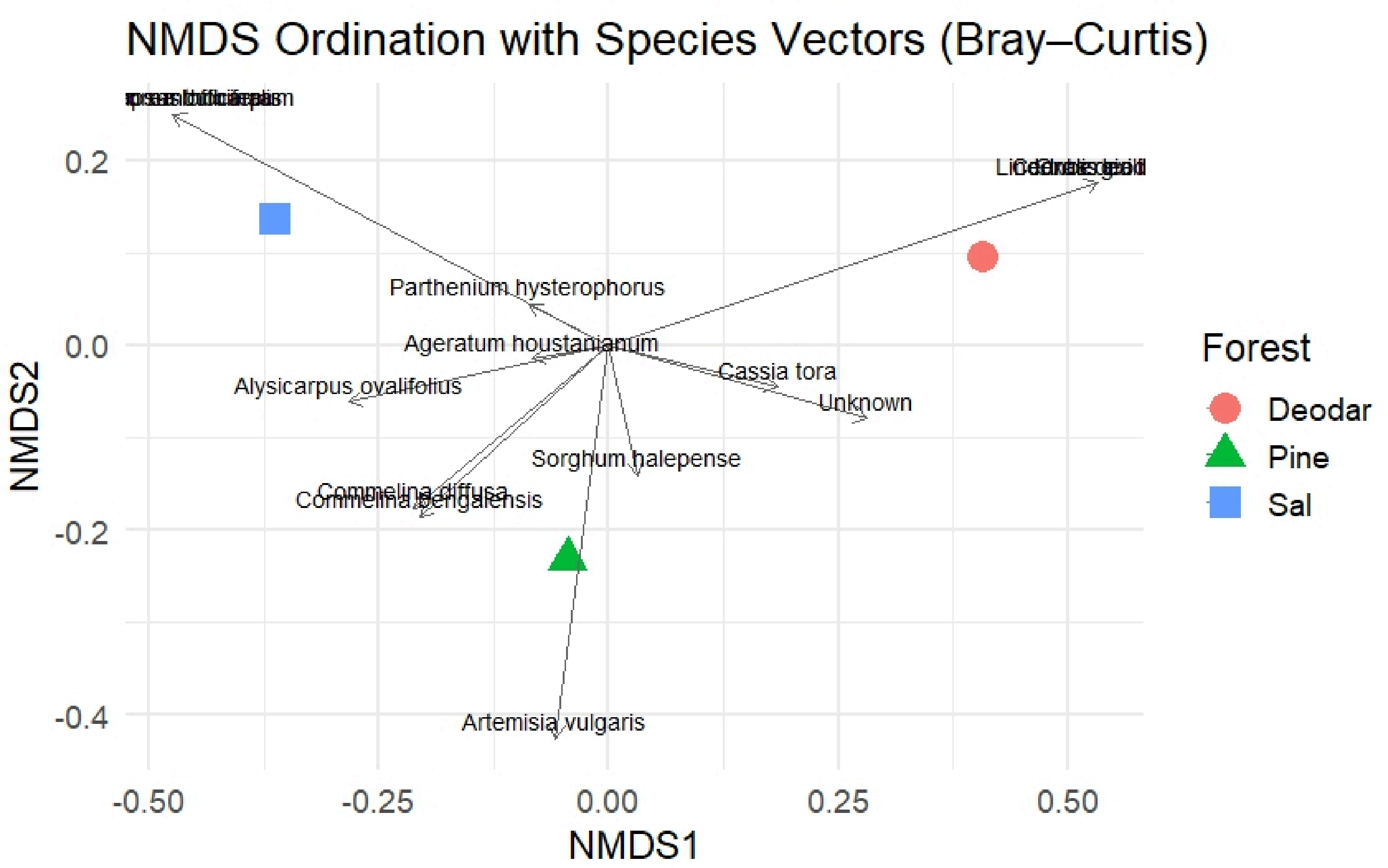

Figure 4

NMDS Ordination with Species Vector (Bray-Curtis)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Plate1.png