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Review

Significance of Soil Seed Bank in Forest Vegetation—A Review

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Abstract: Seed banks present in soils provide information on past/existing standing vegetation and the probable future vegetation of the area. We reviewed 187 articles related to seed banks that were published worldwide from 1859 to 2022 to understand the dynamics of soil seed banks. The heterogeneity and biodiversity of most ecosystems appear vulnerable due to the over-exploitation of soil over the years. The studies on seeds present in soil provide knowledge on species cover, which supports the restoration of degraded areas. An interesting feature observed in most references was that species identified in seed banks do not necessarily represent or reflect the standing vegetation—this is attributed to the varied dispersal mechanisms of different species. The most significant contributions of a seed bank are conservation and the provision of propagules to the ecosystem. These banks are critical for identifying the composition and spatial organisation of understorey plant communities in degraded forests following soil disturbances, such as wildfire, harvesting, and/or logging. Regeneration from soil seed banks enables biodiversity recovery in tropical forests. There has been little understanding of the function soil seed banks play in forest restoration, which is critical to the natural regeneration of forest reserves. The impact of invasive alien species and the associated soil seed banks on vegetation dynamics is poorly researched. With landscape restoration gaining significance in the present decade, it becomes exceedingly important to maintain existing vegetation. It is relevant to India, which has international commitments to restore 26 mha of degraded and deforested land by 2030. This review reveals the importance of soil seed banks and their role in the future maintenance of forest cover.

Keywords: soil seed bank; regeneration; seed dormancy; dispersal; invasive alien species; vegetation

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1. Introduction

A soil seed bank (SSB) comprises the viable seeds on the surface or dormant in the soil [1]. It can also be defined as all the viable seeds present on or in the soil and associated with the litter/humus [2]. In other words, a soil seed bank begins at dispersal and ends with the germination or death of the seed [3]. A soil seed bank is the natural storage of seeds in the leaf litter, on the soil surface, or in the soil of manyecosystems; it serves as a repository for the production of subsequent generations of plants to enable their survival. Seeds frequently persist in the soil as a 'memory' of former vegetation [4]. Seeds are the fundamental part of the ecosystem that reveals the present and history of standing vegetation and future deviation. The buried viable seeds present in soil have practical significance in the conservation of different plant species and invasive alien species management [5]. The study of soil seed banks plays an important role in the natural environment of many ecosystems [6–9]. Since the beginning of modern biology, the presence and crucial role of seed banks in soil have been noticed by many biologists [6,10]. The study of the soil seed bank started in 1859 when Charles Darwin, using soil samples from the bottom of a lake, observed the emergence of seedlings [6]. The first scientific paper on the occurrence of seeds in different soil depths was in 1882 by Putersen [11]. Most ecologists [10,12–14] started their studies understanding the density of living seeds in the soil and the soil seed bank.

During the past decades, there has been a rapid increase in research on soil seed banks in a wide range of plant communities [8]. These studies report on soil seed banks in natural forests from various countries, such as England [9,15,16], Australia [17], Sweden [18,19], New Guinea [20], Singapore [21], Panama [22], China [23,24], Canada [25], Spain [26], Ethiopia [27,28], France [29], the USA [30], Iran [31], Venezuela [32], and Kenya [33]. In India, the soil seed bank studies on different vegetation have been conducted in wastelands and roadsides [34], jhum cultivation [35,36], humid tropical forest [37], grasslands, irrigated and dry land agro-ecosystems [38], tropical dry forest [39], and Himalayan moist temperate forest [40].

This review aims to demonstrate how soil seed banks support forest cover in all types of forests. We looked at publications with studies from as early as 1859 to the present. We organised the 187 articles after examining them to produce the content. We segregated them based on their relevance to the soil seed bank, vegetation, seed dispersal, seed dynamics, and soil microorganisms. We further categorised works on soil seed banks based on the number of seeds and the kind of forest, such as natural, grassland, plantation, and wetland. We analysed the information available globally in different regions and countries that have assessed their forests. We also realise that India has conducted very little work on soil seed banks despite having high biodiversity, in contrast to other nations. With large commitments to the Bonn Challenge, this information would enable Forest Landscape Restoration (FLR) practitioners to develop robust plans to rehabilitate damaged forests and plantations and transform them into secondary forests. The present review is conducted based on the aspects mentioned above.

2. Methods of Literature Search

Online databases were consulted for papers published from the 1850s to 2022. The keywords used to search the papers included “soil seed bank”, “seed bank and soil”, “soil seed bank and India”, “seed bank and wetland”, “seed bank and natural forest”, “seed bank and plantations”, “seed bank and tropics”, “seed bank and temperate”. We obtained more than 300 papers, of which only 187 were relevant to the study as many papers did not clearly provide details on soil seed bank assessment. Out of the 187, 97 papers were finally considered for this review. The data were analysed with regard to the continents in which such studies were undertaken and the vegetation types (agro-ecosystem, grassland, plantations, wetland, and forest) on which they were taken up. Frequency, tables, and charts were used to present the findings.

The concept of the soil seed bank has been widely adopted in different countries in different ecosystems in America, Asia, and Europe, and the literature available across the continents is presented in Figure 1. There has been an exponential rise in the number of publications over the last 10–15 years. However, this information is still underutilised in the field, with less than 12 percent related to field studies (Figure 2). Furthermore, few studies addressed the importance of soil seed bank assessment in India with its diverse ecosystems. Only 10 out of the 187 papers selected reported studies in India. This review is therefore essential to guide future soil seed bank studies in India and to provide basic information for forest landscape restoration (FLR) activities.

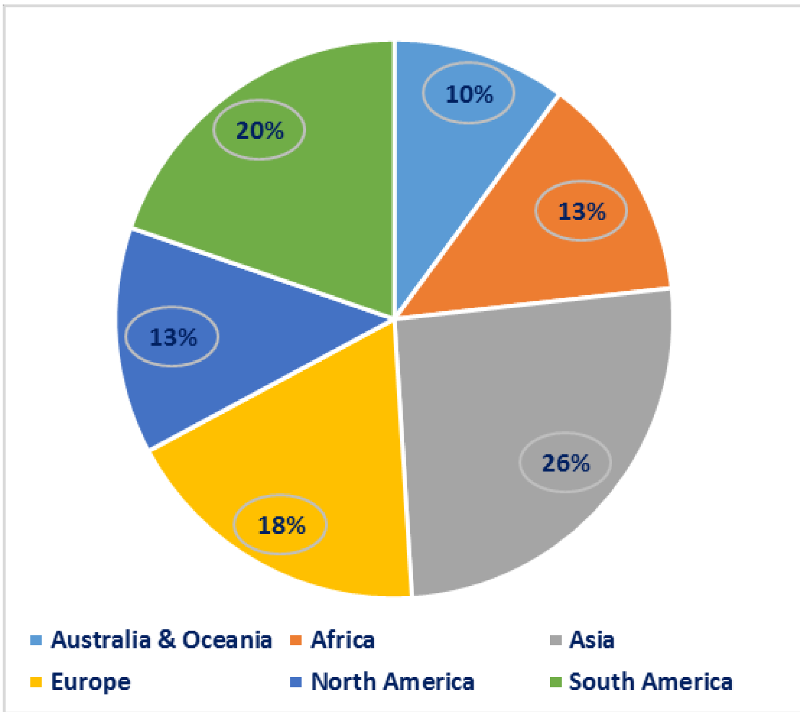

Figure 1. Distribution of soil seed bank-related studies across the globe.

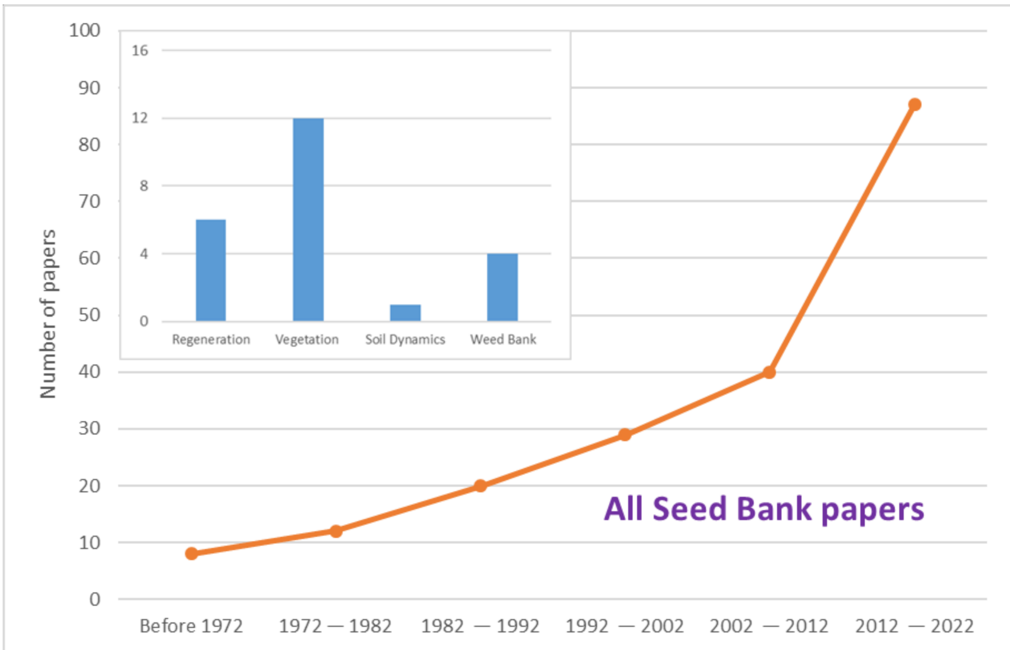

Figure 2. Trend of research in soil seed bank-related aspects. The inset indicates the number of papers with relevance to field-related studies.

3. Soil Seed Bank and Standing Vegetation

Understanding the relationship between the soil seed bank and the standing vegetation is important to know the effect of restoration and reforestation and the consequences of disturbance, succession, invasive species, and management techniques [41]. Whipple [42] classified the seed bank based on the relationship between the soil seed bank and the above-ground vegetation. In the first type, plants and their seeds were found in the surrounding soil; in the second type, only seeds were found in the soil; and in the third type, only above-ground plants were found. The study based on above classification shows that

21.4–49% of species were documented in the seed bank, but not found in above-ground vegetation [43]. Many plant communities have shown that seed banks do not resemble the standing vegetation [9]. Grime [44] predicted that disturbance and physical stress interactively influenced the standing vegetation. This leads to a decline in the density of the soil seed bank. In frequently disrupted habitats, the species found in the soil seed bank and the above-ground plant communities are usually similar because the latent seeds are dispersed by several plant generations, potentially over a long period of time. Ma et al. [45] demonstrated the importance of the soil seed bank in conjunction with the grazing disturbance gradient and its interaction with the vegetation of alpine meadows on the Tibet plateau, claiming that 39 species were common to both the vegetation and the seed bank. This indicates that the seed bank species composition and the vegetation are usually similar in frequently disturbed habitats (arable fields) [46]. Thomas [47] and Valbuena and Trabaud [48] also found resemblances between the seed bank species and the above-ground standing vegetation. However, as the plants mature, the discrepancy between the two grows [49]. The soil seed banks between a secondary natural forest and an adjacent big leaf mahogany plantation in the Philippines were examined by Han et al. [50] to understand the seed bank dynamics, the relationship between the soil seed bank and the above-ground vegetation, and the effects of canopy gaps on soil seed banks in a tropical rain forest. They reported that only three species in the secondary natural forest and six species in the big leaf mahogany plantation were commonly found in both the soil seed banks and the above-ground vegetation. Most of the species in the soil seed banks were pioneer or mid-seral species which came from the outside of the stands. The growth status and preparative capacity of the standing vegetation directly impact the species arrangement and changes in the soil seed bank. In addition, the seeds from the SSB support the natural regeneration of new species to produce diversity in forest ecosystems [29,43].

4. Soil Seed Bank and Regeneration

Regeneration is a natural process through which an equilibrium of vegetation is attained. The level of competition is higher amongst members of the same species. In order to examine the current trend in vegetation succession and to obtain insight into the pattern of future vegetation composition, the regeneration studies of individual species and their population structure might be a valuable tool. Seed production, dispersal, the seed bank in the soil, seed germination, and seedling establishment are important aspects of regeneration. In many regions of the world, natural forests and plantations have been the subject of studies on regeneration dynamics [51]. Numerous investigations have been conducted on regeneration in chosen and particular species [52]. Nair provides a thorough description of the studies on natural regeneration. Information on silvicultural practices linked to natural regeneration is also presented [53]. A review of the limitations of natural regeneration and soil seed banks has been conducted by Fox [54]. The process of the development of the stored soil seed bank population is via seed rain. Cheke et al. [55], Uhl and Clark [56], Putz and Appanah [57], Garwood [58], Hopkins et al. [17], and Chandrashekara and Ramakrishnan [37] report that seed rain explains rainforest regeneration more than the soil seed bank when the level of disturbance increases. Thus, more seeds germinate from the seed rain than the seed bank in the subsequent disturbance, as described in the case of a tropical rain forest in Malaysia [57] (Figure 3). Regeneration, the first stage of the establishment of a species, undergoes the process of sylvigenesis and builds up the stand, leading to an increase in population number [59]. The trees of a forest ecosystem mostly have a soil seed-based regeneration pattern. Adequate seed production, effective dispersal, good viability and longevity of seeds, successful establishment of seedlings, and expansive distribution are crucial for sustainable forest management. Therefore, the population structure at each life stage, viz., the adult tree, flower, fruit, seed, seedling, sapling, and pole, determine the structure of the mature tree populations of the future, which is decided by the soil seed bank.

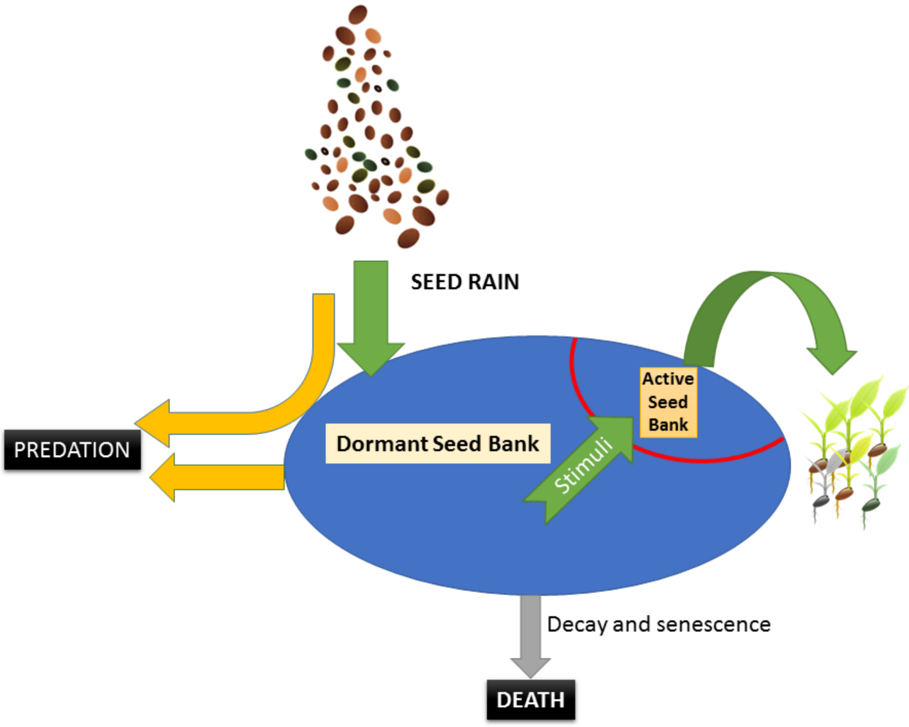

Figure 3. Flowchart for soil seed dynamics in a seed bank (Adapted from Harper, 1977).

A soil seed bank initiates regeneration in a natural forest [60,61]. Cost-effective forest regeneration, especially natural regeneration, is one of the keystones in sustainable forestry [62]. SSBs are the reservoir of viable seeds or vegetative propagules that support natural regeneration [63]. Therefore, the study of the soil seed bank is very crucial in conservation asgerminating seeds constitute the future generation [64]. Knowledge of seed bank composition is, thus, essential to understanding the vegetation dynamics. Any natural or anthropogenic disturbance will upset the equilibrium, and the resulting vegetation structure will be determined by the SSB [65]. This enables us to predict the process of natural succession in the area [66]. Information on the impact of plant invasions on the native seed bank and data on the density of seeds in invaded ecosystems are sparse. Information on the invaded and non-invaded plant communities in different habitat types would pave the way for the effective management of the invasives, which would otherwise have a long-standing detrimental effect on the ecosystem.

5. Seed Dispersal, Dormancy, and Germination

A fundamental mechanism controlling the plant's geographical organisation is dispersal. Seed dispersal consists of removing and depositing seeds away from parent plants [67]. Seed dispersion is the process through which a seed spreads its species into other environments. It aids in transferring certain plant groups from one location to another, avoiding competition among individuals of the same species. The benefits of seed dispersal include the capacity to avoid density or distance-dependent seed and seedling death, colonisation to appropriate places that are unexpected in space and time, and a reasonably high likelihood of survival [68]. Seeds can be disseminated by water, fauna, wind, or gravity [69]. This aids in preventing overpopulation and competition for light, water, and minerals. Dispersion allows species to take advantage of new opportunities and to survive if the parent plant's conditions deteriorate [70]. Plants cannot grow without water, light, and space. If the seed falls immediately below its parent plant, it may not obtain the nutrients essential for growth, as the resources are already in use by the parent plant. So, seed dispersal plays a significant role in conserving community diversity [71].

The nature of dispersal implies that the seeds are not dispersed uniformly; rather, as the distance from the parent plant increases, seed dispersal declines exponentially; this is called a seed shadow [69]. A hypothetical relationship between seed dispersal and spread shows that when the distance from a seed source increases, seed density exponentially decreases, along with seedling mortality [72]. Howe [73] found that seeds of pioneer species decreased exponentially as the distance from the parent increased. Therefore, areas near seed sources will have more seeds than the distant ones.

Perera [74] studied the dispersal pattern in the soil seed bank of the tropical semi-deciduous forest of Sri Lanka and observed that wind-dispersed seeds dominate the forest seed bank. The soil seed banks were predominantly of herbaceous species. This dispersal ability of herbs is high due to their light weight [75]. Their small-sized seeds and large quantities dominate the soil seed bank [76]. In contrast, only the tree species assembled long-lived seeds in the soil.

Many temperate and tropical plant species develop fleshy fruits to attract frugivorous animals and birds, which feed on the pulp of succulent fruits [73]. They serve an essential function as seed dispersers in the maintenance and restoration of plant ecosystems. The role of birds in relation to this function is critical, as the spread of seeds over large areas is critical to establishing ecosystems [73,77–80]. Larger fruit-producing species are dispersed by bats and hornbills [81,82]. In human-dominated areas, frugivorous birds perform the crucial tasks of pollination and seed dissemination [83,84]. It would be prudent to use artificial perches to attract frugivorous birds to hasten the recolonisation of forests [85,86]. There have also been investigations on the role of elephants, rhinoceros, Nilgiri martens, monkeys, squirrels, and bears on seed dispersal [87].

Appropriate methods of dispersion can place a seed in the exact location necessary for germination and seedling establishment. There are three key ways in which dispersers might influence the structure and composition of the seed bank. First, dispersers move seeds away from parent plants and decrease the probability that seeds in the bank are close to a nonspecific adult. This is important because natural enemies, such as fungal pathogens and seed predators, often concentrate close to parent plants [88], and dispersal can thus reduce the distance-dependent seed mortality associated with proximity to co-species [89]. Second, by redistributing seeds within the landscape, seed dispersal may alter the spatial aggregation of seeds, leaving fewer 'seed gaps' on the forest floor (e.g., seedless areas under non-fruiting trees) and reducing areas of high local seed density (i.e., under fruiting trees). A disadvantage of seedless patches within the seed bank would be a reduced availability of seeds for seedling regeneration following disturbance and an increase in density-dependent mortality associated with clustered seed deposition patterns [90]. Third, by increasing the movement of seeds within the forest, vertebrate seed dispersers expand the available species pool for any given area and should increase the local species richness of seeds in the soil seed bank.

When there is little chance of seedling survival under unfavourable ecological conditions, seeds go into dormancy as a protective measure. A dormant seed is one that, when exposed to a combination of environmental conditions that are typically favourable for the germination of a non-dormant seed, cannot sprout within a given time frame. Even under ideal climatic circumstances, seeds occasionally cannot germinate [91]. There are two forms of seed dormancy: primary and secondary, depending on the seed's place of origin. In the former, the seed is naturally dormant, which is further classified as exogenous, endogenous, and combinational dormancy. Some non-dormant and post-dormant seeds experience secondary dormancy when subjected to unfavourable conditions. It can ensure the species' persistence in the form of seeds under harsh conditions, even if the plant population is entirely eradicated. Many elements influence dormancy, including light, water, and oxygen.

Germination of seeds is suppressed by several internal and external factors. Internal factors include the presence of a seed coat (which blocks the penetration of water and oxygen), the presence of biochemical inhibitors in the seed, and an immature embryo. Soil water content and temperature are the most common among external factors [92]. Larger canopy gaps allow more sunlight and heat to the soil surface, which aids better germination in soil-stored seeds [58,93].

A community level study on the germination syndrome can provide valuable insights into the role of selective factors, such as soil moisture, the length of the rainy season, the timing of seed dispersal, the seed dormancy mechanism, and the length of dormancy in controlling the timing of germination. Such studies may also help in understanding how groups of species respond to such factors in their own unique ways. If the future forest developed from the seed bank, it would not have the same role as the former one. This is because of the low diversity of species in the seed bank and the biotic and abiotic changes in the area [65]. Depending on the pattern of land use and the biotic disturbances, the forest communities are reported to vary, and this significantly exposes the forest floor, lowers the soil moisture, and changes the soil nutrient status, thereby adversely affecting the regeneration of many species and influencing the floristic composition of the stand [94].

6. Dynamics of Soil Seed Bank

Soil seed banks comprise all the seeds buried in the soil and those on the topsoil. The soil seed bank plays a vital role in natural ecosystems [58,90,95]. It acts as a reservoir of the natural storing of seed for the regeneration of many plant species [96]. Seed banks are necessary to maintain existing life and growth in diverse habitats, such as grasslands, agro-ecosystems, savannas, deserts, wetlands, sand dunes, ecotones, plantations, and forests. The seed bank of an agro-ecosystem would be less diverse than the seed bank of a forest. Studies of soil seed banks are relatively recent considering their importance as a source of diversity and continued occupation [6]. The seed banks are also a source of hereditary material or evolutionary reminiscence [97]. The seeds of pioneer species are usually present in tropical forest soils, mainly in secondary forests [23]. If seeds are buried too deeply in the soil, they stop working as an effective seed bank.

Tropical soil seed banks show diversified classification. The five soil seed bank strategies promulgated for the tropics are: transient, persistent, pseudo-persistent, seasonal transient, and delayed transient. These begin from the difficult reproductive phenology phases to the seed germination patterns of tropical plants [58]. The pseudo-persistent seed banks seen in tropical forests and cold deserts ensure the presence of a soil seed bank by continued dispersal. Persistent seed banks regenerate without environmental changes and are more often seen in annuals than other life forms. The soil seed bank is the reason for the persistence of annual species, but for perennials, there is a bank of vegetative propagules, such as tubers, rhizomes, and stolons [91]. However, not all annuals produce persistent seed banks. In some communities, perennial woody species produce large seed banks. Generally, small seeds have greater longevity, and the large have lesser longevity in the seed banks [97]. In a warm environment, the activity of seed predation is higher in the lower altitudinal area. In a cold climate, high elevated areas may allow the formation of a persistent seed bank. However, the diversity and richness of ground vegetation differs with changing elevation [75]. Thompson [98] showed that the seed bank density decreases when altitude increases. Ortega and Levassor [99] also suggest that vegetative propagation in a harsh environment at high altitudes is in vogue, with reduced seed production. In addition, when the altitude increases the seed bank richness also increases [100].

Madawala et al. [101] opined that the seeds of herbaceous species dominate the soil seed bank due to the small seed size; small seeds can easily penetrate to deeper soil, allowing seedling development in heterogeneous environments. It also enhances their ability to adapt to the fluctuating climate, increasing their survival [102]. Small and compact seeds persist in soil for a longer period. Yu et al. [103] differentiated four patterns based on the relationship between seed size and soil seed bank.: (1) seed size and weight can predict persistence; (2) seed weight is associated with soil persistence but not shape; (3) there is no relation between seed weight, size, and persistence; and (4) large seed is also persistent but the shape is irrelevant.

The seeds in forest soils are broadly in the range of 10^2 to 10^3 per m^2; for grassland, it varies between 10^3 to10^6 per m^2;and for arable soils from 10^3 to 10^5 per m^2 [97]. This indicates that soil properties influence the density and species richness of seed banks. Soil moisture content affects the quantity and composition of the seed bank. When the physical and chemical properties of the soil are neutral, the establishment of seedlings from the seed bank is assured. If the soil is alkaline, seedling growth is hampered owing to a lack of nutrients. The physical and chemical properties of soil changes based on different seasons also affect the germination of seeds from soil seed banks, thereby influencing the regeneration potential of standing vegetation [104]. Thus, soil property is crucial to the survival of an active soil seed bank and the establishment of new plants.

A number of microorganisms are known to associate with seeds in the bank. However, the significance of the associationis not well studied [96]. Soil microbes have a specific role in seed mortality, plant development, seed protection, and germination [105–107]. They have many ecological values, including contribution to soil structure, quality, and plant disease protection. However, the extent of bacterial and fungal diversity is also unknown.

Canopy gap formation in tropical forests plays a vital role in natural regeneration [108]. According to Godefroid et al. [109], canopy species adjust the understorey environment by changing water and nutrient accessibility, thus modifying the microclimate and quality of the soil litter. Gap creation followed by the removal/destruction of large trees encourages seed germination, seedling establishment, and sapling recruitment [23]. Seedling establishment is a critical life-history stage. At this stage, survival and growth are most sensitive to the microenvironment. Light and soil moisture are the primary limiting factors for tree regeneration [83]. The factors that affect plant regeneration are increased isolation, more light penetration to the ground, changes in soil moisture characteristics, faster decomposition of larger organic matter accumulated on the soil surface, and increased disturbance. The soil seed bank is an important source of forest regeneration [110,111]. Variation in environmental conditions also influences seed bank dynamics in many ways, such as seed production or other life cycle stages. The development and size of a seed bank is affected by the change in soil conditions. The invasion and reproduction of alien species also decides the regenerative potential of a soil seed bank [17].

7. Invasive Alien Species Seed Bank

The invasive alien species seed bank is the reserve of viable invasive seeds present in and on the soil surface capable of replacing other species. Several studies conducted throughout different plant community types disclose that invasive species play a vital role in soil seed banks. Many studies reveal that other than standing vegetation, seed banks contain many invasive alien species and early successional species [112]. An invasive alien species seed bank includes the tubers, bulbs, rhizomes, and other vegetative parts [6]. Most of the invasive alien species can overcome unfavourable climatic environments, such as extreme temperature, humid and dry conditions, and variation in oxygen supply [113]. So, they thrive and disperse thousands of seeds in the soil. These seeds rest in the soil for many years, escape from invasive alien species control, and finally become the source of the future invasive alien species population. Therefore, the study of invasive alien species seed bank dynamics is very important for managing these species in agricultural lands and plantations.

The invasive alien species seed bank consists of new and old seeds that have persisted in the soil for many years. Soil seed bank study has been used as a tool for effective invasive alien species management [114]. Invasive alien species seeds arrive at the soil surface and integrate into the soil seed bank through dispersal by animals, wind, water, and activities during cultivation and harvesting. Some seeds germinate during favorable conditions, establish and contribute more seeds to the soil seed bank, while others fail to germinate or germinate and die or fall to predation. Many of the seeds are dormant or conditionally dormant (depending on soil moisture, temperature, and light availability) in the soil for many years after the dispersal. The seed's peculiar character helpsit to escape from unpredictable environments and invasive alien species control measures. The invasive alien species seeds can be eliminated by repeated and periodical removal of invasive alien species (removal before flowering), which will help to reduce the percentage of seeds in the soil seed bank. However, highly dormant viable seeds persist in soil and their further elimination is difficult. Ecologists are looking for more effective and suitable means to eradicate these highly dormant seeds through multiple stimuli [115].

Around the world, research on soil and invasive alien species seed banks has been conducted in temperate and tropical climates (Table 1). The seedling emergence approach was used to identify seed banks because of its significance for forest management, restoration, and conservation.

Table 1. Studies on size of soil seed bank across the globe in different ecosystems.

Region	Study Location	Ecosystem	Seed Bank (Number of Seeds m^{-2})	References
Temperate	England	Meadow (Permanent)	1235	[116]
	Estonia	Meadow (Permanent)	2362	[117]
	Northern France	Natural forest	2085–8296	[29]
	USA	Natural forest	51–940	[30]
	Canada	Natural forest	475–16,700	[25]
	Southwest England	Natural forest	2937	[9]
	South-central Skane, Sweden	Natural forest	1757	[19]
	Northern Iran	Natural forest	28,931	[31]
	Central England	Planted forest	27,300	[16]
	Southeast England	Planted forest	5847	[15]
	Northern Spain	Planted forest	401	[26]
	South Sweden	Planted forest	30,085	[18]
	USA	Wetland	38,000	[118]
	USA	Wetland	450–394,600	[119]
Tropical	India	Arable field	17,600–17,960	[38]
	China	Meadow (Permanent)	120–1176	[120]
	Northern China	Meadow (Permanent)	20,417–220,831	[1]
	New Guinea	Natural forest	398	[20]
	North Queensland, Australia	Natural forest	588–1068	[92]
	Panama	Natural forest	55–243	[22]
	Singapore	Natural forest	1000	[21]
	Southwest China	Natural forest	4585–65,665	[23]
	Ethiopia	Planted forest	4500–82,600	[27]
	Ethiopia	Planted forest	2300–18,650	[28]
	South China	Planted forest	455–967	[24]
	Venezuela	Planted forest	10–1222	[32]
	Western Kenya	Planted forest	1550	[33]
	Beijing	Wetland	11,575–24,831	[121]
	Southeastern Missouri and West-central Virginia	Wetland	1,440,000	[94]

With awareness of the importance of the soil seed bank in FLRs, studies on similar aspects are on the rise. It is evident that the tropical environments have more studies on the different ecosystems, comprising more than 50 percent of the literature searched (Figure 4). Furthermore, more than 60 percent of the studies focus on plantations and natural forests (Figure 5), to help monocultures to be replaced by secondary forests and to restore the degraded forests back to their past glory.

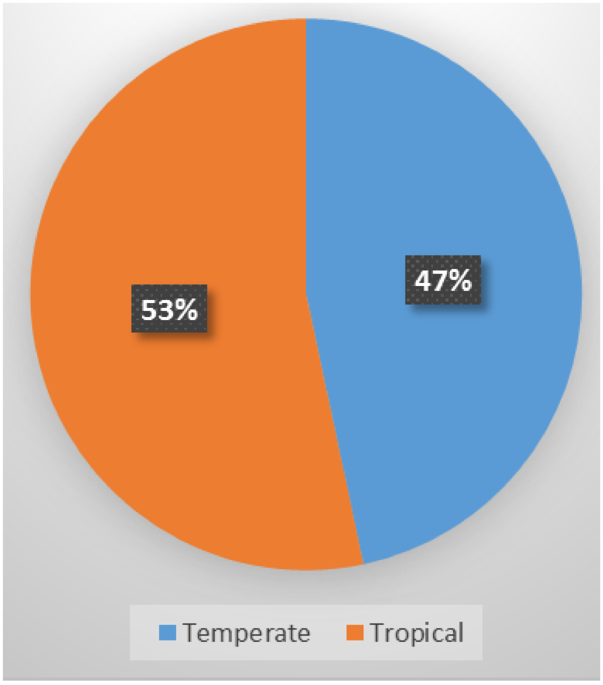

Figure 4. Soil seed bank studies related to ecosystem types in the temperate and tropical regions.

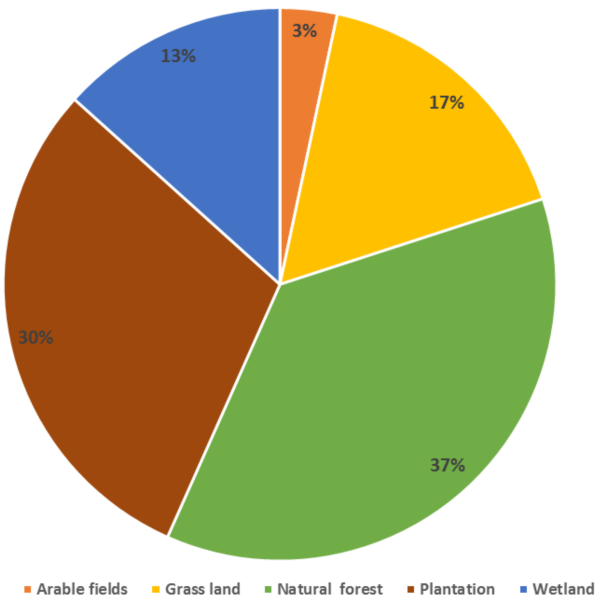

Figure 5. Pie chart depicting the proportion of soil seed bank studies in different ecosystems.

In the current investigation, we observed that the density of soil seed banks in different forest communities and within the confines of the same type of ecosystems vary. Table 1 shows that diverse ecosystems had varying densities of seeds. The forests recorded a higher density than the grasslands within a region (e.g., China). Similarly, in the temperate regions in the USA, e.g., the natural forests had low density, while the wetlands had a higher seed density. Comparing two meadows in China revealed a drastic difference in seed densities. Thus, we cannot attribute specific values to seed banks from different ecosystems, regions, or ecosystems. It depends on the composition of the forests, the climatic and soil conditions, the vegetation of the past, and the disturbances in the study sites. Under normal conditions, grasslands generally store more seeds as 90% of the vegetation in grasslands is herbs, and their small, compact seed size facilitates ease of burial. Seed mass, shape, and persistence correlations may not hold true across communities or habitats because different species may have distinct life histories and seed attributes. Furthermore, the aspects of dispersal and predation play a significant role in determining the soil seed bank density. Grasslands are prone to easy disturbances due to their open nature, hence the low numbers. Further research is needed on the mechanisms underlying the patterns and the correlations between seed mass, form, and persistence in various flora.

Furthermore, the occurrence of soil seed banks is influenced by the diverse ecosystems' soil conditions and climatic conditions. Small and compact seeds are most abundant in humid areas. In contrast, arid regions are more likely to have an abundance of large-seeded species with long-lasting seed banks. Wetland ecosystems exhibit large seed densities in both tropical and temperate regions of the globe. Survivorship is high in these wetlands due to minimal anthropogenic disturbances to the soil surface. Furthermore, most seeds tend to move to deeper strata, ensuring their survival. Natural forests constantly have varying numbers of seeds as each forest may have different climatic conditions. The type of ecosystem also influences the seed bank. A wet evergreen soil seed bank may have less diversity as the seeds are recalcitrant and lose viability once the favourable moist conditions change.

Herb and grass seeds make up the majority of seed bank contents. Consequently, the species with more seeds tend to create enduring seed banks in the soil. As a result, environmental influences are just as significant as innate seed features in determining the correlations between seed mass and persistence. Therefore, managing these species is challenging.

8. Significance of Soil Seed Bank

Ecology plays a major role in the field of conservation biology due to a decline in the number of endemics and rare species and a parallel increase in alien species, resulting in the degradation of global biodiversity [122]. One of the most efficient ways to manage and conserve degraded ecosystems is to conduct a detailed study on soil seed banks. These studies are critical to understanding the secondary succession of plants [123]. The regeneration potential of any ecosystem can be predicted by the soil seed bank of the area as it provides the reminiscence of the previous flora present there. Soil seed banks are the ecological footprints of past vegetation which existed for many years. Hence, the relevance of such studies will increase in the coming years as these studies support the conservation of plant diversity and vegetation dynamics. Seed banks can play a vital role in local diversity maintenance through their storage behaviour [124]. The conservation of different ecosystems worldwide, with the help of vegetative propagation and buried seeds, provides information on future flora prediction, there storation of natural ecosystems [63], and the better management of invasive species in agro-ecosystems [6].

The restoration of plants can be conducted by focusing on the self-regeneration of native species [64]. According to Pugnaire and Lazaro [125], the soil seed bank is a crucial element of the dynamics of vegetation, affecting both the flexibility and the resistance of ecosystems. In any ecosystem, the life is retained by the un-germinated or dormant seeds present in or on the soil [126]. A better understanding of seed banks is essential to finding out the role of ecosystem functioning and developing the management plans of ecosystems [127]. There are chances of disappearing ground vegetation due to high grazing, mining, and other human interference. The recovery of these species is very difficult even if the disturbance pressure is greatly reduced; however, it can be facilitated through the soil seed bank [126].

In general, disturbances in plantations and seed banks have an impact on the re-establishment of secondary succession. The restoration of vegetation in any ecosystem occurs mainly due to persistent seeds in the soil and the seasonal seed rain [128]. Tree seed germination from the soil seed bank is very low because of the recalcitrant nature of the seeds. Compared to other ecosystems, planted and natural forests show a very low germination percentage from the soil seed bank. This is because herbaceous plants dominate the soil seed banks of natural and planted forests [116]. In such a situation, the restoration of natural forests can be achieved through in situ and ex situ preservation of seeds by knowing the viability period for the existence of biodiversity in a future generation [6].

9. Prospects and Perspective of Soil Seed Banks

A soil seed bank is a key factor for counteracting local extinction of plant species. Soil seed banks are critical to the long-term survival of individual species and plant groups in all agro-ecosystems across the globe. Soil seed banks are integral to ecosystem stability, serving as a reservoir with regeneration potential in many plant assemblages. The composition of new plant recruitment can be predicted using soil seed banks. Species withstand times of harsh weather by amassing a big seed bank. This technique preserves species' variety while preserving information on their dynamics and structure. Soil seed bank research has piqued the interest of many people due to its importance in plantation repair and restoration, biological variety preservation, vegetation succession and diffusion processes, and other areas. Seed banks, as an important component of population dynamics, are also a source of genetic material and historical recollection. Genetic variety in seed banks may be a source of long-term population stability or divergence among populations. Without a soil seed bank, plant establishment is hampered during primary succession. In contrast, a well-stocked soil seed bank allows for the rapid emergence of species-rich ecosystems during secondary succession. Therefore, the only way plant life is encouraged on disturbed sites following any significant rapid re-vegetation caused by wildfire, extreme weather, agricultural activities, and timber removal is through the seed bank already existing in the soil. Furthermore, there is a need for additional seed bank data in invasion ecology. This would help characterize the species-specific and habitat-specific impacts of invasives. It would also throw light on the causes of the degradation of the vegetation, whether it was there before or appeared as a result of it.

10. Conclusions

Many natural ecosystems, including forests, are suffering because of the fast rate of deforestation, land use changes, and land cover changes. This practice risks the benefits of forest resources and the potential for biodiversity. Natural forests struggle to regenerate, driving the extinction of the most valuable land resources on the planet. As it is crucial to sustainable development, forest regeneration, and ecological restoration, the protection of soil seed banks and natural regeneration potentials needs addressing by supporting policy, strategy, and action plan frameworks. The majority of plant regrowth comes from seeds that are already present in the soil. Research along these lines is pertinent today as it supports landscape restoration activities. Of the 187 scientific papers reviewed, only 5.40% were from India. Research on soil seed banks provides information such as historical knowledge of lost forests, current species composition, and future regeneration patterns for the region for the effective restoration of species. The dynamics of the invasive species seeds would help us understand the reasons for the degradation and to assess their roles as either drivers of environmental degradation or sources of associated bioresource benefits. It would also help with the control of invasive species if detrimental to the ecosystem, the restoration of the damaged forest ecology, and the transformation of monoculture into secondary forests. This study provided a foundation for ecological restoration strategies in different ecosystems, a vital element for sustainable development.

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