

Review

Global Review of Soil Seed Banks: Distribution Patterns, Driving Factors, and Implications for Ecological Restoration and Sustainability

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Abstract

Soil seed banks (SSBs) are fundamental resources in terrestrial ecosystems for conserving biodiversity and facilitating the sustainable restoration and long-term stability of ecosystems. As the “genetic and propagule bank” of aboveground plant communities, SSBs play a crucial role in ecosystem regeneration and recovery after disturbances. This study employs a literature review methodology, focusing on the period from 2000 to 2025, and identifies 186 high-quality, peer-reviewed empirical articles. It systematically summarizes the phased advancements in this field, addressing research areas, subjects, technical methods, and conclusions. The analysis specifically highlights the fundamental limitations and deficiencies inherent in traditional research methods, experimental designs, study scales, and theoretical applications. A comprehensive analysis indicates substantial advancement in clarifying the distribution patterns, density dynamics, and response mechanisms of SSBs to natural and anthropogenic disturbances. This study systematically reviews the assessment methods for SSBs (germination trials, physical separation and extraction, and molecular identification) and integrates their spatial heterogeneity in various ecosystems and their response patterns to natural and anthropogenic drivers. Additionally, this study identifies existing research gaps and recommends priority research directions for future investigations. We contend that research on SSBs should be closely integrated with global change ecology, restoration ecology and data science. It holds irreplaceable strategic importance for addressing the escalating global biodiversity crisis, improving the functions and resilience of ecosystem services, and promoting the sustainable management of ecological restoration and biodiversity conservation.

Keywords: soil seed banks; seed bank composition; influencing factors; restoration ecology; sustainable management



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1. Introduction

Seeds represent a critical life-history stage in plants and have historically been a primary focus for ecologists and botanists. The soil seed bank (SSB) denotes a repository of naturally accumulated, mature, viable, dormant, or germinable seeds present in the surface soil and litter layer. It functions as an essential carrier for vegetation regeneration,

community diversity maintenance, and long-term ecosystem sustainability and resilience, allowing plant populations to survive under adverse environmental conditions and underpinning nature-based solutions for sustainable ecological management [1–5]. SSBs are classified into persistent and transient types according to the duration of seed viability in the soil [6]. Persistent seed banks comprise seeds that remain viable in the soil for over a year, whereas species with transient seed banks exhibit shorter retention periods [7]. SSBs, often termed the “evolutionary memory” of vegetation, are crucial in maintaining species diversity, enhancing community stability, and facilitating sustainable ecological recovery, primarily through the “storage effect” and “rescue effect” [8]. At the community scale, SSBs co-regulate, alongside existing vegetation, the pathways of secondary succession after disturbances of varying intensities [9]. Notably, species absent from the extant above-ground vegetation may persist within the SSB, maintaining the potential to re-establish populations when environmental conditions improve [10]. Therefore, they are essential in understanding plant population dynamics and their interactions with the environment [3,11,12].

SSBs are widely recognized as essential propagule reservoirs that support natural vegetation recovery and ecosystem community reconstruction because of their unique ecological roles [10]. Restoration strategies that utilize SSB potentials adhere to essential ecological principles and constitute one of the most effective and nature-based sustainable approaches for conserving native biodiversity, mitigating land degradation, and maintaining ecosystem structural and functional stability [13]. Therefore, a systematic synthesis of existing methodologies, research advancement, inherent limitations, and future development directions in SSB ecology is crucial for fostering theoretical innovation and enhancing nature-based ecological restoration practices aligned with global sustainability goals.

This systematic review conducted an extensive literature search in September 2025, aiming to synthesize empirical advancements and methodological limitations in soil seed bank (SSB) research across global ecosystems. The objectives were to elucidate the spatial distribution patterns and ecological response mechanisms of SSBs and to identify key priorities for future research endeavors. The literature was sourced from both Chinese and international academic databases, specifically two Chinese databases (China National Knowledge Infrastructure [CNKI] and VIP Chinese Journal Database) and two English databases (Web of Science and Google Scholar). The search encompassed publications from 2000 to 2025, utilizing the search string: (soil seed bank OR seed bank OR seed-bank) AND (ecological significance OR spatial distribution OR spatial pattern OR impact factors OR disturbance OR fire OR grazing OR cultivation). Eligible publications were limited to peer-reviewed journal articles, conference proceedings, and dissertations published in English or Chinese, with a primary research emphasis on the ecological functions, spatial patterns, research methodologies, and natural or anthropogenic disturbances related to soil seed banks (SSBs). Studies exclusively addressing canopy seed banks, seed germination physiology, or seed functional traits were excluded, as were abstract-only publications lacking original empirical data and duplicate manuscripts. The initial search yielded 348 records, with 347 unique documents remaining after deduplication. Following a rigorous screening process based on predefined inclusion and exclusion criteria, a total of 186 studies were deemed eligible and included for systematic synthesis in this review.

This review integrates high-quality domestic literature, addressing the geographical bias and data deficiency present in previous reviews, unlike existing Western-dominated syntheses that largely neglect Chinese research findings and regional ecological datasets. Statistical collation indicates that current studies primarily focus on forest [14–16], wetland [17–19], grassland [7,20,21], and agricultural ecosystems [22]. Existing evidence indicates that the spatiotemporal patterns and compositional dynamics of SSBs are influ-

enced by aboveground factors (vegetation structure and topography) and belowground conditions (soil physicochemical properties and microbial communities) [23]. Key drivers include seed functional traits [24], historical vegetation succession [25], microhabitat heterogeneity [26], anthropogenic disturbances [27], seasonal variability [28], and climate change [29].

This study systematically highlights the bidirectional regulatory effects of major disturbance agents in contrast to most previous reviews that oversimplify disturbance impacts. This review presents an optimized stepwise research workflow that integrates recent advancements in molecular and seed ecology, combining traditional physical separation, germination testing, DNA barcoding identification, and single-nucleotide polymorphism (SNP) marker detection to enhance the accuracy, comparability, and repeatability of quantitative SSB investigations. Additionally, this study clarifies the application potential of SSBs in ecosystem restoration and sustainable land management, identifies key research gaps, and delineates five targeted and actionable future research priorities, including the establishment of a global deep SSB research network, developing coupled vegetation–seed bank dynamic models, and establishing a quantitative seed bank restoration index. These refined prospects offer clearer operational guidance than the generalized recommendations presented in most prior reviews. Overall, this synthesis aims to establish a robust scientific basis for ecological restoration and vegetation management decision-making and enhance the standardized and high-quality development of future SSB theoretical and applied research under the framework of global sustainable development.

2. Functions and Ecological Roles of SSBs

SSBs function as essential reservoirs of biodiversity, preserving genetic diversity and facilitating adaptive responses to ecological shifts. Serving as evolutionary archives, these belowground repositories mitigate ecosystems against stochastic disturbances through mechanisms including rescue effects, storage effect [30], and population stabilization [31]. Empirical studies increasingly emphasize their dual function in preserving plant diversity: enhancing gene pools to support evolutionary potential and reducing extinction risks during sudden environmental transitions. Notably, seed bank depletion—especially of key-stone species without local replenishment—erodes ecosystem resilience, lowering thresholds for irreversible regime shifts [32]. This highlights their significance not only as passive “backup systems” but also as dynamic early-warning indicators of ecological fragility.

Beyond their immediate ecological roles, SSBs serve as essential repositories for species extirpated from aboveground communities, constituting a fundamental safeguard of ecosystem resilience [31,33]. Through dormant propagules, especially persistent seed banks [33], these reservoirs mitigate extinction risks associated with habitat fragmentation and climatic extremes by maintaining demographic refugia [34] and facilitating post-disturbance recovery, including drought resilience [35]. Notably, high-altitude ecosystems depend on seed bank-mediated regeneration to mitigate against climate-driven community shifts [36]. Empirical analyses indicate that seed banks demonstrate decoupled responses to environmental changes compared to aboveground communities during wetland degradation [37], establishing them as potential recovery templates for impaired systems. This functional divergence highlights their conservation significance: species that are no longer visible in aboveground vegetation frequently survive cryptically belowground, offering viable germplasm resources for targeted, nature-based sustainable ecological restoration.

To synthesize the empirical evidence, SSBs offer three cardinal advantages for sustainable vegetation restoration and long-term ecosystem management:

- (1) Evolutionarily conserved regeneration mechanisms that correspond with ecosystem self-organization principles [22];

- (2) Propagule reservoirs facilitating spatially explicit reconstruction of plant communities [38];
- (3) Protection of locally adapted genetic diversity that stabilizes biodiversity–ecosystem function relationships under environmental stochasticity [39].

Notably, by utilizing in situ ecological memory, these traits collectively alleviate numerous disadvantages resulting from natural disasters and overgrazing, and this attribute has increasingly emerged as a core consideration in the resilience-based ecological restoration framework.

3. Research Methods of SSBs

3.1. Optimal Sampling Timing and Considerations

Sampling time is essential for standardized and credible soil seed bank (SSB) investigations, and the selection of sampling windows is primarily determined by research objectives targeting persistent or transient seed banks. In general, persistent seed bank sampling should be performed after seasonal seed germination and before new seed maturation and seed dispersal, while comprehensive SSB sampling covering both persistent and transient seed pools needs to be conducted before the initiation of seed germination [40]. However, such generalized criteria cannot be universally applied globally, as optimal SSB sampling timing exhibits pronounced biome-specific differences, constrained by regional climatic phenology, plant life forms, and ecosystem characteristics.

Temperate biomes, including temperate regions of Europe, North America, southern Australia, South America, and temperate zones in China, represent the most intensively studied areas for SSB research, with relatively mature sampling protocols. For persistent seed bank investigation in temperate ecosystems dominated by perennial vegetation and summer annuals, sampling is preferably conducted in summer, after the completion of seasonal seed germination and before new seed maturation and seed rain. For a comprehensive SSB assessment covering both persistent and transient seed pools, winter or early spring sampling prior to germination initiation is optimal [41]. Representative regional practices include high-frequency six-week interval sampling in Sheffield, UK, to capture fine-scale seasonal SSB dynamics, and bimodal sampling in May (vegetation green-up stage) and September (vegetation withering stage) in Chinese alpine meadows to quantify annual maximum and minimum seed bank values [42].

Tropical biomes across the Amazon, Southeast Asia, tropical Africa and northern Australia feature distinct wet–dry seasonal alternations and year-round high temperatures, leading to unique SSB phenological characteristics and relatively limited systematic research. Tropical plant seeds generally exhibit shorter longevity, resulting in high species richness but low seed density of regional SSBs. For comprehensive tropical SSB surveys, sampling is recommended at the early or middle wet season, when seed rain is terminated and large-scale seed germination has not yet occurred. Transient seed banks post seed rain are best sampled at the early dry season, while persistent seed bank sampling is conducted at the mid-to-late dry season following seasonal seed germination. In Bawangling, Hainan, triennial sampling is adopted in April, September, and December to track temporal variations in seed quality and community composition [43].

Subtropical biomes, mainly distributed in southeastern China, southeastern America, eastern Australia and parts of South Africa, possess unique dynamic SSB characteristics. Sampling strategies here depend heavily on plant functional types: winter or early spring sampling is suitable for subtropical winter annuals, whereas summer or early autumn sampling applies to summer annuals. For communities co-dominated by both functional groups, multi-seasonal sampling or compromised early-autumn sampling is required to cover phenological differences [44].

Boreal and tundra biomes (northern Siberia, northern Canada and northern Europe) have the least SSB research due to extremely short growing seasons and narrow germination windows, with low seed input and low SSB density maintaining stable vegetation communities [45]. The only feasible sampling window for comprehensive and persistent SSB surveys is the summer thawing period (June–August), before the onset of new seed rain and large-scale germination. Considering that low-temperature conditions in boreal regions often delay seed germination, local snowmelt phenology should be fully considered to adjust the specific sampling time [46]. Overall, biome-specific phenological rhythms and plant functional traits are the core prerequisites for determining rational SSB sampling timing, and no unified sampling scheme is applicable to all global ecosystems.

3.2. Sampling Methods

SSBs exhibit a three-dimensional spatial structure involving horizontal distribution (such as the zonal distribution formed by anemochory and hydrochory of seeds) and vertical depth (seed bank density declines with increasing soil depth), further complicated by temporal variability [47]. Therefore, sampling designs require careful consideration of this spatiotemporal dimensionality, aligned with specific research objectives. Regarding horizontal space, establishing appropriate sampling areas and quantities is essential. Currently, no universally standardized criteria exist for defining optimal plot sizes and sample quantities [47]. Three common methodologies for establishing sampling intensity include the following: (1) utilizing numerous small samples [48]; (2) implementing a small number of large samples; (3) subdividing larger sampling units into smaller subplots. Among these approaches, the deployment of numerous small samples is considered the most statistically robust. Commonly utilized quadrat dimensions include 1×1 m and 50×50 cm [49,50].

Regarding vertical stratification, most studies perform sampling at various soil depths, generally encompassing 0–2, 2–5, 5–10, and 10–15 cm [51,52]. Influenced by specific experimental requirements, sampling profiles may sometimes reach deeper horizons, specifically 10–15 and 15–20 cm [53]. However, viable seed densities in these deeper strata are generally minimal (or exhibit a marked paucity) [54].

Temporally, beyond tailoring sampling strategies to specific seed bank categories (persistent versus transient), sampling frequency must be calibrated to accommodate seasonal dynamics and species-specific phenological traits. For instance, seed dispersal in *Lolium perenne* may commence as early as July, whereas *Carex capillifolia* generally begins shedding in September. Additionally, flora in high-altitude or cryic environments frequently demonstrate accelerated maturation strategies to preempt the early onset of the cold season. Consequently, to obtain a comprehensive temporal profile of the SSB, sampling efforts must be intensified across months and seasons. Indeed, recent evidence suggests that the reported lower diversity in seed banks compared to existing vegetation is frequently a methodological artifact due to insufficient sampling rather than a genuine biological occurrence [30].

Upon establishing critical sampling protocols—including area, depth, and frequency—three distinct spatial strategies are commonly adopted for in situ implementation: random sampling, transect sampling, and frame-supported point sampling. Among these, transect sampling is predominantly preferred in global SSB research because of its simplicity and representativeness. Methodologically, this approach involves establishing linear transects within study plots, where sampling quadrats are placed at predetermined regular intervals.

3.3. Identification Methods

Species taxonomic identification is the fundamental prerequisite for SSB research. Two common methods for species identification are the seed germination method and the

physical separation method (direct counting methods) (Table 1) [54]. The seed germination method is prevalent, with most studies utilizing this approach as it indicates the potential germination capacity of the seed bank [55]. This method eliminates the need for distinct viability assays and capitalizes on the comparative simplicity of identifying seedlings rather than seeds. However, a significant limitation is that experimental conditions rarely concurrently meet the germination requirements of all taxa. Consequently, seeds demonstrating profound dormancy may fail to emerge, resulting in a systematic underestimation of viable seed density in specific communities. Furthermore, the germination process typically necessitates a significant duration, generally spanning 3 to 6 months to conclude [56,57]. Another physical separation method involves extracting seeds from soil utilizing sieves or water flotation separation. This method offers the benefits of expediency and comprehensiveness, rendering it appropriate for large-scale sampling and capable of identifying dormant seeds or those recalcitrant to germination conditions [55]. However, this method requires supplementary viability assays, including tetrazolium chloride staining or germination tests. These additional steps are labor-intensive and, when combined with the lower taxonomic resolution associated with physical seed identification, have relegated physical separation to less frequent application.

Table 1. Comparison of SSB species identification methods.

Identification Method	Description	Advantages	Disadvantages	References
Physical Separation Methods	Methods such as flotation concentration and sieving are used to separate all seeds (viable, dead, dormant, and decaying).	Can separate all seeds from the soil sample.	Labor-intensive, relatively poor accuracy in seed identification, and requires subsequent viability assessment. Less commonly used.	[55]
Seed Germination Methods	Identifies seeds by growing them into seedlings, which are used in over 90% of research studies.	It is easier to identify seedlings, more straightforward and accurate than physical separation.	Germination conditions may not suit all seeds; some seeds may remain dormant, leading to underestimation of seed richness. Time-consuming (3 to 6 months).	[55–57]
DNA barcoding/SNP/SSR markers	DNA barcoding identifies species by sequencing standard gene fragments. SNP achieves high-throughput fine genotyping through single-base differences in the whole genome, while SSR conducts genetic detection using the length polymorphism of simple sequence repeats.	Faster and more accurate	Higher costs and greater technical demands	[56–58]

Recently, advances in molecular biotechnology have introduced DNA barcoding and SNP/SSR markers as effective tools for the taxonomic identification and classification of

SSBs. These molecular approaches have demonstrated superior efficacy over traditional morphology-based or physical separation techniques, providing improved speed and precision, especially for morphologically cryptic taxa [57].

With the rapid development of high-throughput sequencing, environmental DNA (eDNA) metabarcoding and shotgun metagenomic sequencing have further facilitated community surveys of soil seed banks. Nevertheless, both techniques face notable constraints. Metabarcoding is plagued by PCR primer bias and limited phylogenetic resolution, which hamper the discrimination of closely related plant species [58]. While shotgun metagenomics eliminates amplification bias by sequencing total genomic DNA, its performance is weakened by incomplete plant reference genomes and overwhelming non-target microbial reads. More importantly, neither sequencing strategy can distinguish DNA originating from viable germinable seeds versus dead seed debris [59]. Extracellular eDNA can persist in soil long after seed death, such that sequencing outcomes only record historical species occurrence rather than the current viable seed pool.

However, their widespread adoption is presently limited by prohibitive costs and specialized technical prerequisites, which may undermine their feasibility for large-scale spatial assessments [60]. Additionally, taxonomic resolution is significantly dependent on the comprehensiveness of reference sequence libraries; taxa absent from these repositories remain unidentifiable. This limitation highlights the critical necessity for rapid technological iteration and the continuous augmentation of genomic databases [56,61].

Given the existing technological conditions, we advocate for a stratified, multi-method workflow: (1) extracting the seed fraction through physical separation—combining sieving and flotation; (2) performing a preliminary morphological assessment; (3) rapidly assigning taxa through DNA barcoding; (4) elucidating intraspecific variation using SNP markers for species-level accuracy. This integrated protocol achieves an optimal balance among speed, accuracy, and cost, thus enabling broader application in soil seed-bank research (Figure 1).

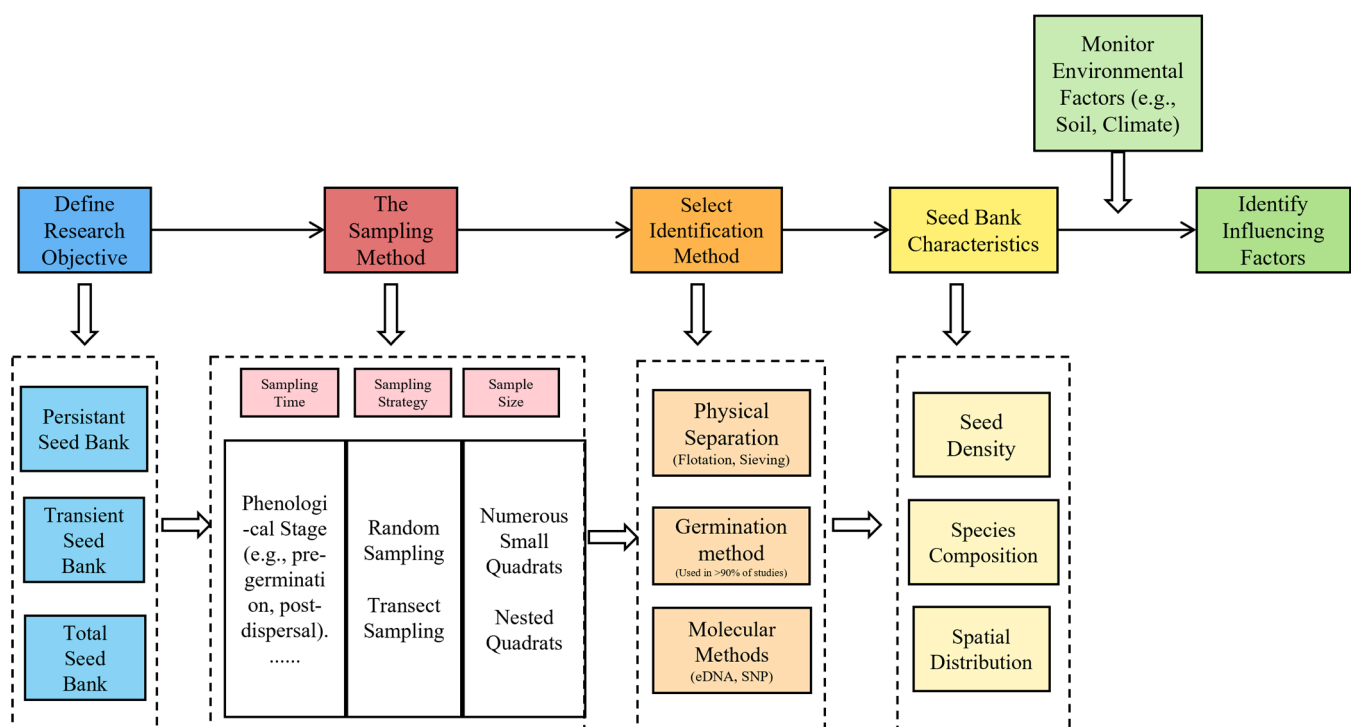


Figure 1. Research flowchart for SSB studies.

4. Spatiotemporal Distribution Patterns

The spatial distribution of soil seed banks (SSBs) is jointly modulated by biotic dispersal vectors and abiotic environmental heterogeneity. In general, SSBs tend to exhibit clustered horizontal distributions rather than uniform patterns, a feature widely observed across diverse ecosystems [62].

Firstly, biological dispersal strategies play a crucial role in determining the fundamental aggregation characteristics of the soil seed bank. Plant species that rely on endozoochory and myrmecochory typically exhibit limited and randomly oriented seed dispersal distances. Consequently, in most natural communities, these seeds tend to accumulate in proximity to the parent individuals, resulting in aggregated spatial structures. This clustered distribution often leads to a variance-to-mean ratio greater than one, which can frequently be modeled using the negative binomial distribution in empirical studies, although it does not represent a universal rule [63]. In contrast, species that disperse seeds via wind are more influenced by airflow direction and the structure of habitat corridors. The seed density of these species generally decreases gradually along spatial gradients, forming continuous linear distribution patterns. These patterns are commonly analyzed using gradient regression and spatial sequence analysis.

Secondly, dispersal processes unique to specific ecosystems give rise to scale-dependent and structurally intricate seed bank patterns within certain biomes. For instance, seed dispersal in tropical forests often displays fractal properties. In particular, vine-facilitated seed dispersal can result in recursively clustered fractal formations at scales ranging from 10 to 100 m, characterized by multiscale self-similar spatial nesting features [39]. These fractal distributions are scale-dependent and predominantly confined to tropical and complex heterogeneous landscapes, rather than being universally present across all ecosystems. Indicators such as fractal dimension and scale threshold are effective tools for characterizing these heterogeneous spatial structures within these specific contexts.

Thirdly, microhabitat filtering significantly contributes to localized seed bank aggregation under specific environmental conditions. In humid ecosystems, soil moisture heterogeneity leads to the formation of discrete seed deposition zones [64]. Notably, riparian buffer zones tend to accumulate buoyant seeds as a result of prolonged soil saturation, thereby creating distinct hotspots of seed density. Conversely, in arid desert systems, wind erosion generates soil micro-depressions that effectively trap seeds. For example, seed density within micro-pit patches of the African Namib Dunes can be three to five times greater than that in adjacent dune interspaces [65]. These microhabitat effects are highly specific to particular ecosystems and cannot be generalized across all landscape types.

Finally, disturbance legacy effects alter SSB horizontal heterogeneity by changing vegetation and soil properties, with varying outcomes. Fire disturbances create patchy vegetation scars and affect soil pH and nutrients, increasing SSB spatial heterogeneity in fire-prone areas [66]. Conversely, grazing and land clearing homogenize vegetation, disrupt natural patches, and decrease seed input, weakening SSB spatial aggregation and reducing spatial autocorrelation. These differences show that SSB patterns depend on the type and intensity of disturbance and the local ecosystem context.

Seed banks exhibit a three-phase vertical structure under gravity-driven sorting: (1) Litter layer (0–2 cm): Transient seeds (90% viability loss/year) of annuals predominate, with density peaking at 12,000 seeds/m² in temperate meadows. (2) Mineral soil (2–10 cm): Perennial seeds (30–50% viability) accumulate in cryoturbated zones, establishing perennial seed banks that endure through glacial cycles [67]. (3) Subsoil (10–30 cm): Paleorelic seeds (viability < 5%) represent a “fossilized” genetic reservoir, activated only during extreme hydrological events [68]. This vertical partitioning mitigates climatic shocks;

for instance, Mediterranean systems preserve 40% of functional diversity in subsoil layers during megadroughts [69].

In the temporal dimension, SSBs exhibit two distinct dynamical regimes: (1) short-term dynamics, characterized by seasonal and diel variation. Seed bank densities frequently increase in spring and autumn when many plants mature and shed seeds, whereas summer and winter generally experience declines due to germination or mortality [70]. Additionally, diel cycles induce 20–30% density fluctuations due to nocturnal seed dispersal by crickets (*Acheta domesticus*) [71]. (2) Long-term dynamics, primarily characterized by interannual to decadal variability. In Mediterranean grasslands, seed bank density decreases by 50% during drought; however, the plant community maintains 75% functional continuity in the subsequent rainy season, attributed to the activation of deep-soil seeds [72]. Conversely, in extreme environments such as Arctic tundra, seed banks may demonstrate significant time lags: cold, deeply buried seed reserves (burial depth > 50 cm) may require 15–20 years to re-establish tundra plant communities after disturbance [73].

5. Natural and Anthropogenic Factors Affecting the Composition and Quantity of SSBs

The SSB comprises seeds from past plant communities, current species, and seeds dispersed from adjacent communities. The first determinant of the SSB is the aboveground vegetation, whereas other factors, directly or indirectly associated with the aboveground vegetation, influence the dynamics of the SSB [74]. These factors include environmental factors, including light, temperature, precipitation, and the physicochemical properties of the soil, which predominantly influence seed longevity in the soil, dormancy, germination, and storage conditions [75]. Furthermore, factors such as plant growth status, phenological stages of flowering and fruiting, animal activity patterns, and even soil microbial activity primarily determine seed yield, dispersal, viability, and subsequent physiological processes [76]. This study examines how natural factor drivers—specifically variations in temperature, precipitation regimes, light, soil physicochemical properties, and fire—and anthropogenic activities, including land-use change, enclosure grazing, and ecological restoration, influence the composition and dynamics of SSBs.

5.1. Effects of Natural Factors on SSBs

Natural factors are fundamental determinants of seed production, germination, and dormancy [77], with early developmental stages, including seeds and seedlings, and the flowering and fruiting periods of plants being particularly sensitive to environmental changes [78,79]. Natural drivers, including temperature, precipitation, light regimes, and soil properties, may primarily influence the species composition and temporal dynamics of SSBs. These drivers operate directly and through complex feedback with plant communities [80] and microbial assemblages [7], thereby controlling seed production, modulating seed germination signals, maintaining dormancy, and, in some cases, accelerating seed decay [81].

5.1.1. Effects of Rainfall on the SSB

Rainfall directly and indirectly regulates SSB dynamics (Figure 2). Direct effects predominantly involve soil moisture-mediated germination. Increased rainfall elevates soil moisture, accelerating germination rates and diminishing seed bank density. This is supported by observations from Mediterranean shrublands, where prolonged rainfall exceeding $100 \text{ L} \cdot \text{m}^{-2}$ over seven consecutive days induces mass seed germination [82]. In salt marshes, germination surges above moisture thresholds (adj. $R^2 = 0.726$) due to salinity dilution, which reduces soil-seed water potential gradients and enhances hydration [83].

Therefore, seed bank size diminishes with increasing annual precipitation [84]. Moreover, although adequate moisture can swell and soften seed coats, enhancing germination, excessive moisture may impede germination by limiting oxygen diffusion or facilitating microbial seed decay [85].

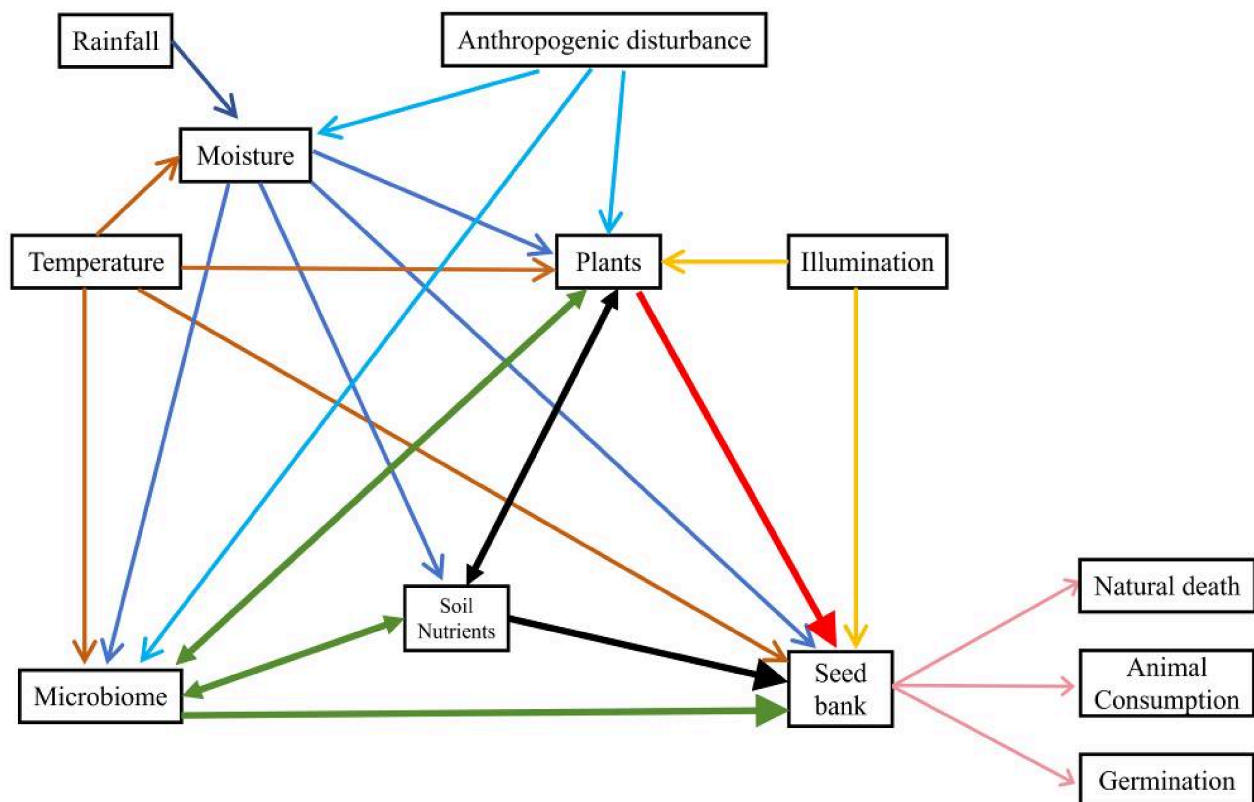


Figure 2. Dynamics and influencing factors of SSBs. Different colors and types of arrows represent the pathways of influence for various factors. The bold arrows indicate the more complex aspects of processes affecting the seed bank, which require greater attention in future research.

Indirect effects function through three pathways (Figure 2): (1) Aboveground vegetation: Precipitation alters plant community structure, affecting seed inputs. For instance, rainfall during the growing season on the Tibetan Plateau increases herbaceous biomass and seed production [86]. However, anthesis-phase precipitation > 40 mm decreases seed set by 50% [87]. Concurrently, increased rainfall can delay plant phenology [88], influencing fruiting time and diminishing seed yield, and reducing seed input into the seed bank in some ecosystems where water is not a limiting factor [89,90]. (2) Soil physicochemical properties: Rainfall governs soil pH through salt leaching (humid regions) or accumulation (arid zones) [91], indirectly affecting seed bank composition through vegetation shifts. Additionally, increased rainfall regulates nitrogen availability [92] and accelerates organic matter decomposition. This benefits invasive species that are resource-efficient and fast-growing and disadvantages slower-growing native species, altering the composition and size of the SSB [93]. (3) Microbial activity: Microbial activity plays a dual role in soil seed banks, acting as both a facilitator of germination and a mediator of seed mortality. On the one hand, beneficial microorganisms, notably plant growth-promoting rhizobacteria (PGPR), play a pivotal role in directly enhancing seed germination and seedling development. Bacterial genera such as *Pseudomonas* and *Azospirillum* contribute to plant growth by facilitating nitrogen fixation, phosphorus solubilization, and the biosynthesis of essential phytohormones, including indole-3-acetic acid (IAA), gibberellins, and cytokinins. For instance, inoculating maize seeds with these PGPR strains has been shown to significantly

improve both germination rates and seedling vigor [94]. On the other hand, environmental shifts such as increased precipitation can favor detrimental microbial processes. Elevated soil moisture promotes the proliferation of pathogenic fungi, leading to seed mold and decay [95]. For sensitive plant species, direct infection by these pathogens is a primary driver of seed mortality; notably, Leishman et al. demonstrated that fungicide treatment in a grassland seed bank increased the survival rate of *Medicago lupulina* seeds from 15% to 43% [96], underscoring the severe pressure fungal pathogens exert on seed survival under wet conditions.

5.1.2. Effects of Temperature on SSBs

The global atmospheric temperature is rising with an increase in greenhouse gases. Increasing atmospheric temperatures are anticipated to modify soil seed-bank dynamics through direct physiological impacts on seeds and indirect feedback mechanisms involving soils and vegetation. Increased soil temperatures frequently accelerate dormancy release and stimulate germination in numerous physiologically dormant taxa, consequently depleting persistent seed reserves [7]. In arid habitats, alpine tundra, and boreal wetlands, experimental warming or natural thermal gradients consistently reduced seed-bank size by enhancing germination or shortening seed longevity [36,84]. Species responses are, however, heterogeneous: elevated soils accelerated emergence in the endangered *Silene diclinis* [97] yet cut *Poaceae* recruitment by 44% and delayed their 50% emergence time from <5 to >8 weeks [36]. Conversely, taxa necessitating extended cold stratification may forfeit a critical dormancy-breaking signal during milder winters, thereby diminishing viable seed pools. Collectively, these studies suggest that warming can deplete or restrict seed banks depending on species-specific thermal thresholds.

Temperature indirectly alters seed banks by modifying soil chemistry, microbial activity, and the aboveground community structure (Figure 2). Warming accelerates organic-matter decomposition and nitrogen mineralization, increasing nitrate and ammonium availability [98]. However, it frequently reduces plant-species richness as competitive dominants proliferate under nutrient enrichment [99]. Such alteration diminishes the diversity and density of seeds entering the soil. Simultaneously, higher temperatures lower soil pH and enhance microbial metabolism, conditions that can promote pathogenic fungi and further erode seed viability [100]. Climate warming is set to restructure the size and composition of SSBs through these coupled pathways—enhanced germination, altered nutrient regimes, and pathogen pressure—resulting in significant implications for vegetation resilience and ecological restoration.

5.1.3. Effects of Light on SSBs

Light regulates soil seed bank dynamics across multiple scales. At the community level, enhanced irradiance advances grassland phenology, increases aboveground species richness, and consequently increases seed rain to the soil [101]. At the seed level, because photons penetrate only a few millimeters into mineral soil, burial depth and seed size determine reception of light signals: Small, deeply buried seeds remain strongly light-dependent, whereas large seeds germinate in darkness and rarely establish persistent banks [102]. This dependence acts as a sieve that maintains seed-bank longevity. Temperature-sensitive species, including *Silene elisabethae*, require light after cold stratification [103]. Light dependence serves as a crucial determinant influencing seed-bank longevity and seed germination rate.

In addition, spectral quality and photoperiod further delineate germination timing, including the comparative duration of light and dark periods. In alpine systems, short days of late autumn inhibit germination, whereas long spring days stimulate it in most

physiologically dormant species [104]. However, a few taxa—including *Poa alpina*, *Trifolium pallescens*, and *Anthyllis vulneraria*—light suppresses germination [105]. Accordingly, the interplay of intensity, spectrum, and photoperiod with seed traits dictates the timing and location of seed bank exit, influencing vegetation trajectories.

5.1.4. Effects of Soil Physicochemical Properties on SSBs

Abiotic attributes of the soil matrix—temperature, moisture, pH, and nutrient status—are first-order determinants of seed longevity and germinability, and thus influence the size and composition of SSBs [106]. Soil acidity consistently enhances persistence: in grasslands, viable-seed density declines logarithmically with increasing pH because alkaline conditions favor soil-borne pathogens that erode viability, whereas germination is largely pH-insensitive [2]. Moisture exerts a bimodal influence. Prolonged inundation generates anoxic microsites that preserve long-lived hydrochorous species and suppress overall richness, whereas moderate drying elevates oxygen availability and extends longevity but—when severe—reduces vertebrate dispersers (birds and rodents) and indirectly depletes the bank [107]. Overall, soil moisture and pH are fundamental drivers of seed bank dynamics, influencing seed longevity, species richness, and interactions with microbial communities.

Additionally, research has demonstrated that nitrogen (N) deposition has significant and previously unrecognized detrimental effects on the SSB within one of Europe's most extensive and species-rich acidic grassland ecosystems [108]. Specifically, 13 years of experimental nitrogen deposition resulted in reductions in species richness and abundance of the seed bank, negatively impacting three major functional groups: forbs, sedges, and grasses. Although aboveground flowering vegetation demonstrated signs of recovery 44 years post-cessation of nitrogen deposition, the seed bank demonstrated no signs of recovery [109]. These findings indicate that nitrogen deposition exerts a more significant and lasting impact on grassland seed banks compared to the visible plant community. Therefore, nitrogen deposition diminishes the diversity of seed banks and hinders the long-term recovery of ecosystems.

5.1.5. Effects of Aboveground Vegetation on SSB

To ensure species succession, plants frequently propagate through seeds to mitigate their survival risks, thereby maintaining long-term species existence [110]. Annual and perennial plants typically adopt distinct reproductive strategies. Annual plants primarily propagate through seeds, whereas perennial plants can reproduce multiple times based on their underground roots. Therefore, the species composition and density of seed banks are closely associated with the species composition of surface aboveground vegetation [111]. The SSB density is positively correlated with the overall plant density, or subordinate species density in the aboveground plant community. This result was demonstrated in a previous study by O'Connor and Pickett in African tropical savannas [112]. An increased density of subordinate species correlates with greater reproductive branches and seeds by aboveground vegetation, thereby increasing the number of seeds entering the soil and consequently increasing the density of the SSB. However, the association between SSB composition and aboveground vegetation is influenced by the intensity of external disturbance. Numerous studies have demonstrated that, after severe disturbance, SSBs may exhibit minimal resemblance to the current vegetation; instead, they often remain more closely associated with previously established (pre-disturbance) communities, indicating legacy effects and delayed compositional turnover [113]. Therefore, the association between aboveground vegetation and the SSB is essential in understanding seed bank dynamics, with plant density and reproductive strategies playing significant roles.

5.1.6. Effects of Fire on SSBs

Fire, as a natural ecological disturbance, primarily affects the SSB by restructuring it and modifying its germination potential. Fire, as an intense perturbation, exerts two opposing effects—consumption (seed destruction) and activation (dormancy breaking)—on the seed bank. Therefore, the post-fire SSB typically demonstrates alterations in dominant species (favoring fire-resistant seeds) along with a spatial redistribution of seeds (increased density in surface layers and migration to deeper soil). These changes provide the seed source and the catalyst for vegetation succession following fire.

The intensity of fire exerts dual effects on SSB density composed of different seed categories. (1) Destruction and consumption: Fire can directly consume seeds in the SSB, especially thin-coated seeds located in the surface layer. Research demonstrates that fire predominantly diminishes seed bank density in the 2–5 cm soil layer, whereas deeper layers, below 5 cm, experience minimal impact. A single burn in tropical savanna preserves substantial reserves, allowing the bank to completely recover within 1 year [114]. Furthermore, studies have demonstrated that the density of viable seeds in the soil often diminishes following a fire, and the richness (number of species) of the seed bank may decline, primarily due to embryo death caused by high temperatures [115]. (2) Activation and Stimulation: The heat generated by fire and smoke (especially karrikin compounds) can induce seed germination by breaking dormancy. The thermal shock compromises the impermeability of hard seed coats, facilitating water imbibition. Moreover, chemical stimulants in smoke can induce germination. Consequently, fire frequently significantly increases the proportion of germinable seeds within the seed bank, indicating that the active seed fraction may increase relative to the total, even if the overall seed bank density diminishes [116].

Fire can significantly change dominant species composition and species richness within the SSB, as it frequently eliminates the seed reserves of pre-fire dominant perennials (broadleaf shrubs), thus freeing recruitment space for fire-tolerant herbaceous and annual species [117]. Accordingly, post-fire seed banks often exhibit a shift in dominant taxa from broadleaf species to grasses or shrubs, or from perennial species to annuals. Furthermore, fire frequently mitigates seed dormancy, leading to a significant enhancement of species richness during the first post-fire year. This surge is attributed to the removal of fire-sensitive seeds, while fire-tolerant or newly dispersed seeds are stimulated to germinate [118].

5.2. Effects of Anthropogenic Disturbance on SSBs

Human disturbance has become a primary regulator of SSBs, primarily influencing them through its effects on aboveground vegetation [119]. In the grasslands of northern China, grazing, mowing, and fencing constitute the primary land-use regimes [120]. Each modifies plant reproduction, litter inputs, and microclimate in distinct ways, resulting in distinctive signatures within the buried seed pool. Intensive grazing suppresses flowering of palatable taxa and curtails seed rain, filtering the bank towards unpalatable or grazing-tolerant species [121]. Mowing imposes uniform senescence and diminishes stature, narrowing functional diversity and favoring early-maturing annuals. Conversely, prolonged fencing enhances standing biomass and litter, and disturbance-induced alterations in soil texture, temperature, and moisture further interact with pathogens to modify dormancy loss and persistence [122]. These intertwined pathways explain the divergence of seed-bank responses across land-use practices and highlight the necessity of incorporating disturbance history into predictions of community resilience and restoration planning.

5.2.1. Effects of Grazing Disturbance on SSBs

Grazing restructures SSBs through three interacting pathways. First, herbivores serve as seed vectors: grazing animals facilitate seed dispersal through their feces and fur [123], thereby improving spatial connectivity among fragmented populations while depositing propagules into novel microsites formed by trampling and wallowing [124]. Light-to-moderate disturbance enhances seed burial and fosters persistence, contributing to the establishment of a larger persistent seed bank [125], as evidenced by increased seed-bank richness under conservative stocking in Swedish grasslands [126]. However, severe trampling compacts soils beyond critical thresholds, diminishing porosity and oxygen diffusion to levels that hinder germination and increase pathogen-mediated mortality [85].

Second, selective herbivory acts as a filter on plant communities, favoring the prevalence of taxa that are either unpalatable or tolerant to grazing. Species with annual and biennial life cycles, which are distinguished by their rapid growth, significant reproductive investment, and small seeds that are easily buried, tend to thrive under conditions of intermediate disturbance. These species contribute a greater quantity of seeds to the seed bank in comparison to perennial species. Additionally, intensive grazing during the flowering period can diminish seed rain by 70–90% through direct consumption of reproductive structures of palatable plant groups [127,128] or by activating compensatory resource allocation to vegetative regrowth at the expense of sexual reproduction [129]. The resulting compositional changes cascade into altered seed-bank structure: palatable grasses decline, and toxic or prostrate forbs expand, fundamentally reshaping regeneration potential.

Third, livestock modify edaphic conditions through nutrient deposition and physical disturbance. Grazing alters soil microbes, soil fertility, and nutrient cycling by introducing nutrients from livestock dung and urine, which increases nitrogen availability 2–5 times, promoting nitrophilous ruderals and suppressing stress-tolerant specialists [130]. Simultaneously, hoof action increases soil hardness, surface roughness, heterogeneity, and diminishes soil moisture, potentially decreasing the probability of seed infiltration into the soil [131]. These soil feedbacks interact with plant life-history traits to determine which species persist as seeds versus establish as adults. Grazing functions as a multiscale filter whose net effect on seed banks depends essentially on stocking density, seasonality, and site moisture: enhancement under light, rotational regimes, but depletion under chronic overgrazing.

5.2.2. Effects of Grazing Exclusion on SSBs

Grazing exclusion has significantly transformed grassland ecosystems globally [114]. A potential strategy to enhance SSBs has been proposed [55]. The effectiveness of grazing exclusion depends on the duration of the exclusion [132] and grazing pressure outside the enclosures, which regulates propagule supply [133]. Short-term fencing (<5 years) frequently increases seed-bank density and vegetation cover by alleviating plants from defoliation and trampling [121]. Extended exclusion, however, allows competitive dominants to accumulate litter, inhibit recruitment, and diminish seed-bank richness and diversity indices [55]. Therefore, the benefit for vegetation of long-term grazing exclusion in restoring degraded grassland is questionable.

The seed bank is further influenced by (i) initial degradation status and soil fertility [109,132]; (ii) precipitation regime, which regulates plant growth rates and thus the optimal fencing length. Consequently, large seed banks are characteristic of ungrazed semiarid rangelands but diminish steeply with increasing herbivore density [134]. In areas of low primary productivity, prolonged exclusion may be necessary to restore biomass, whereas in mesic, fertile sites, rotational grazing can more effectively restore diversity than permanent fencing. These findings caution against universal prescriptions: fencing should

be time-limited and combined with adaptive, low-intensity grazing to balance productivity gains with long-term biodiversity conservation.

5.2.3. Effects of Mowing on SSBs

Mowing exerts contrasting effects on grassland seed banks dependent on cutting regime and soil depth. Occasional mid-season cutting can enhance seed-bank richness by maintaining a diverse standing flora and decreasing litter accumulation [135,136]. Conversely, early, late, or repeated cuts truncate flowering periods, reduce seed bank density and richness by inhibiting seed production [121]. Decreased litter simultaneously increases near-surface irradiance, promoting germination and further depleting seed reserves. Research demonstrated that slight changes in seed density at 0–2 cm depth were observed, but seed density decreased at 2–5 and 5–10 cm depth under mowing, suggesting that impacts of mowing on seed density are evident in deep soil, not at the surface [136]. Furthermore, these dynamics of SSBs caused by mowing counteract the passive enrichment of seeds by nitrogen deposition, especially for grasses whose diaspores accumulate at depth [136,137]. Mowing serves as a bidirectional filter by preserving biodiversity under conservative schedules while depleting persistent seed banks when cuts are either mistimed or excessively frequent. This underscores the necessity for management strategies tailored to specific mowing regimes.

5.2.4. Complex Role of Fertilization, Tillage, and Construction in Shaping Seed Bank Dynamics

Fertilization and soil tillage are essential factors affecting SSBs [108]. Fertilization enhances plant sexual reproduction by supplying extra nutrients; however, it can shift the aboveground community toward highly productive grasses, which contribute poorly to persistent seed banks [136,138]. Frequent tillage disrupts the vertical spatial distribution of seed banks, and the species composition in rotational cropping systems significantly differs from that in fallow periods [139].

Furthermore, activities including road construction directly and indirectly affect SSBs by altering aboveground vegetation, soil structure, and chemical properties. These alterations subsequently affect the species composition, density, dynamics, and spatial distribution patterns of seed banks [140]. A study conducted in a typical steppe grassland in Ningxia reveals that contour trenching significantly enhances SSB density, though it does not significantly affect diversity indices. As recovery progresses, seed bank density initially increases and subsequently decreases before increasing again [141]. Overall, anthropogenic factors, including fire, fertilization, tillage, and construction activities, have different and complex impacts on SSBs, depending on the intensity and nature of the disturbances. For effective ecological restoration, it is essential to implement scientifically informed management strategies to leverage the beneficial impact of these disturbances on SSBs.

5.3. Other Influential Factors Shaping SSBs: Succession, Burial Depth, and Litter Cover

Numerous additional factors affect the SSB. First, the stage of succession significantly impacts the seed bank. Research has demonstrated that seed density in the seed bank diminishes as succession progresses. Early successional species typically generate large quantities of seeds, whereas species in subsequent successional stages contribute less to the seed bank [142]. In early successional stages, increased light facilitates a higher germination rate in seed bank samples, whereas in mid-successional stages, this effect diminishes as light intensity increases. Conversely, light has little to no impact on seed germination from the late successional stage [143].

Second, burial depth is essential in SSB viability. A direct association exists between the depth of seed burial and the potential for seed germination. Generally, seeds buried at

greater depths demonstrate increased longevity, as deeper burial diminishes the likelihood of seeds reaching the surface [144,145]. However, seed banks at various depths exhibit differences in seed composition and germination rates, primarily due to changes in soil conditions such as temperature, moisture, and light availability. These conditions modify the physiological processes of seed dormancy, activity, longevity, and germination, affecting the overall seed bank [146].

Third, litter cover is a significant factor influencing the SSB. In grassland ecosystems, thick litter layers, resulting from enclosures or light grazing, can physically isolate fallen seeds from the soil, reducing seed density. However, litter functions as a protective layer, altering microhabitats and influencing soil microbial communities, thereby affecting the seed decay rate and overall seed density in the soil [147,148]. Overall, the SSB is influenced by various factors such as successional stage, burial depth, and litter cover, which interact to influence seed density, longevity, and germination dynamics.

6. Research Limitations

Despite significant advancements in SSB ecology, existing research still exhibits notable deficiencies and knowledge gaps, which may impede our comprehensive understanding and accurate prediction of seed bank functions amidst global change, thereby constraining evidence-based decision-making for long-term ecosystem sustainability and nature-based sustainable restoration. These constraints can be classified into four interrelated dimensions: Methodological limitations, spatiotemporal scale restrictions, incomplete theoretical systems, and insufficient practical transformation.

(1) Methodological constraints and sampling bias

Two conventional strategies, germination assay and physical separation, dominate current seed bank investigations, and each possesses inherent technical biases. Methodological inconsistencies among studies may cause significant numerical deviations, suggesting potential obstacles for global meta-analysis and unified model construction. Furthermore, existing research presents evident spatial imbalance. Most surveys focus on accessible, minimally disturbed regions, whereas biodiverse tropical and subtropical ecosystems remain underrepresented. For instance, regional evidence signifies that 5.4% of local SSB publications stem from domestic research in India, despite its high biodiversity [149]. Additionally, most investigations predominantly examine the 0–10 cm topsoil, whereas deep SSBs are largely neglected, potentially underestimating their potential contribution to long-term ecosystem recovery following severe disturbance [150]. Global datasets further reveal uneven spatial coverage: research hotspots are concentrated in North America, Europe, and Australia, whereas data from Africa, South America, and parts of Asia remain scarce [151]. This geographic imbalance may create uncertainties in large-scale pattern simulation and trend prediction.

(2) Spatiotemporal scale bottlenecks and mechanistic ambiguity

Most long-term monitoring depends on space-for-time substitution or short-term observations lasting under 5 years, which may inadequately account for interannual fluctuations and slow ecological variables regulating seed bank dynamics. Current findings are predominantly based on small plot-scale surveys, and cross-scale mechanisms driving regional or global seed bank patterns remain poorly understood. Existing global analyses indicate that fire effects differ significantly across ecosystem types, indicating positive responses in Mediterranean regions but adverse impacts in tropical forests [152]. However, the primary factors contributing to these divergent results, including fire frequency, intensity, and soil physicochemical alterations, have not been clearly clarified. The interactive dynamics among seed banks, soil microorganisms, and edaphic conditions are insufficiently

understood. Most relevant studies only report correlational patterns, leaving critical gaps in understanding how microbial communities influence seed persistence and germination, and their coupled responses to ongoing climate change, key knowledge gaps for forecasting terrestrial ecosystem sustainability under global environmental change.

(3) Inadequate integration with mainstream ecological theories

The incorporation of SSBs into comprehensive ecological frameworks remains limited, potentially resulting in a gap between theoretical understanding and empirical observation. Within ecosystem resilience and alternative stable state theories, the functional role of SSBs is generally underestimated. Conventional theoretical analyses of ecosystem degradation often emphasize variables such as aboveground vegetation and soil properties, whereas seed banks and bud banks, which serve as critical slow variables offering ecological memory and restoration capacity, are frequently neglected [153].

(4) Weak translation toward conservation and restoration practice

Although numerous studies have demonstrated the restoration potential of SSBs, relevant theoretical findings are underutilized in practical management. In severely degraded landscapes, including abandoned mining areas and degraded grasslands, local seed bank reserves are frequently depleted, signifying that natural regeneration alone cannot ensure effective vegetation recovery. Current restoration-oriented evidence remains limited, and targeted techniques for seed bank activation, topsoil transplantation, and litter regulation lack systematic verification. Ineffective collaboration between ecologists and management departments may further restrict the practical implementation of existing research outcomes [154].

7. Future Directions

To overcome the above limitations and enhance the utilization of SSB resources amidst global change, future studies could focus on five targeted research orientations: methodological optimization, standardized database development, cross-scale model integration, theoretical framework enhancement, and interdisciplinary policy integration.

- (1) Promoting methodological integration and technological progress is crucial for future research endeavors. Subsequent studies should consider the integration of traditional germination assays with molecular techniques, such as environmental DNA (eDNA) sequencing and metabarcoding, to facilitate cross-validation between phenotypic and molecular datasets. In addition to molecular identification, remote sensing offers a viable approach to extrapolate plot-scale seed bank observations to broader regional landscapes. Concurrently, the application of machine learning and AI-assisted ecological modeling can automate the processing of multi-source datasets, mitigate taxonomic identification biases, and predict seed bank distribution across diverse habitats. This integrated workflow, encompassing multiple technologies, is anticipated to enhance the accuracy, comparability, and reproducibility of seed bank identification and viability assessments.
- (2) Establishing global deep SSB networks and standardized databases. It is essential to extend sampling beyond the conventional 0–10 cm topsoil layer and systematically examine deep seed bank characteristics at depths up to 1 m or more. More research attention is warranted on understudied tropical, arid, and subtropical regions, as they may enrich global datasets and yield novel insights for macroecological and biogeographical research to inform equitable global biodiversity conservation and sustainable development planning.
- (3) Developing integrated aboveground–belowground dynamic models. Future vegetation models must comprehensively integrate seed bank dynamics, including seed

rain input, germination, mortality, and dormancy transitions. Parameterizing these belowground components may enhance the capacity to predict vegetation succession, biodiversity turnover, and ecosystem responses to multi-disturbance regimes, providing quantitative support for adaptive sustainable ecosystem management under climate change.

- (4) Integrating SSBs into alternative stable state theory. Quantifying a unified Seed Bank Recovery Index along degradation gradients may aid in identifying ecological thresholds and evaluating ecosystem resilience. Integrating seed bank indicators into theoretical models can yield more scientific references for restoration target setting and pathway optimization.
- (5) Conducting cross-ecosystem comparison and enhancing policy integration. Seed bank formation and maintenance strategies appear to differ greatly among forests, grasslands, wetlands, and deserts. Cross-system comparative analysis may aid in revealing generalizable adaptive mechanisms under climate change. Moreover, establishing seed bank priority conservation networks could support reasonable resource allocation and enhance targeted biodiversity management, bridging ecological research with sustainability-oriented land-use policies and regulatory frameworks.

8. Conclusions

The soil seed bank (SSB) serves as a vital repository of evolutionary memory and germplasm for plant biodiversity, playing a crucial role in maintaining ecosystem stability, enhancing resistance to disturbances, and facilitating vegetation restoration. By leveraging its storage and rescue functions, the SSB mitigates the limited resilience of aboveground plant communities and provides nature-based solutions for the rehabilitation of degraded ecosystems. To date, research on SSBs has predominantly focused on forests, wetlands, grasslands, and croplands. The current research framework employs a stratified spatiotemporal sampling strategy coupled with integrated identification techniques, including traditional germination trials, physical separation, DNA barcoding, and SNP markers. This comprehensive approach elucidates the species composition, seed density, and spatiotemporal dynamics of seed banks, characterized by horizontal aggregation, vertical stratification, and temporal fluctuation. The abundance and community structure of seed banks are influenced by climatic, edaphic, fire, and vegetation conditions, as well as anthropogenic disturbances such as grazing, enclosure, and cultivation, through direct regulation of seed dormancy and indirect modification of seed sources and microhabitats.

Despite advancements in the study of soil seed banks (SSBs), significant challenges persist in the field. A major issue is the absence of a standardized methodological framework, with many studies neglecting the consideration of deep soil seed reserves, thereby introducing notable sampling biases. Furthermore, the complex interactions among various environmental factors are insufficiently quantified, and the mechanisms of cross-scale responses remain inadequately understood. Additionally, theories related to SSBs have not been effectively integrated into mainstream ecological paradigms. Concurrently, empirical findings are seldom converted into practical restoration strategies, thereby limiting the applicability of seed bank research in real-world scenarios.

Future research should standardize technical protocols, develop global databases for deep soil seed banks, and create integrated models and restoration metrics. Cross-ecosystem comparisons will enhance theoretical frameworks and inform regional disturbance management. This review has limitations: many studies are observational, limiting causal inference; small samples weaken statistical reliability; inconsistent conditions hinder conclusion extrapolation; and selection bias may be present. These uncertainties should be considered in future applications.

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