

Review

Research Progress on Soil Seed Bank: A Bibliometrics Analysis

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Abstract: The soil seed bank (SSB) is a natural bank of viable seeds in the soil or on its surface. Researches on SSB have accumulated extensively worldwide, but have seldom been visualized and quantitatively analyzed. In this paper, publications related to SSB from 1900 to 2019 were collected from the Web of Science Core Collection database, and reviewed and analyzed using CiteSpace. Annual publications distribution, co-occurrence analysis, collaboration network analysis, co-citation analysis and burst detection were all conducted. The results showed that (1) the number of SSB publications had increased rapidly and is still a hotspot; (2) SSB study is an interdisciplinary field mainly concentrated in ecology, environmental science, and plant science; (3) close research cooperation occurred among European countries which were more influential, whereas the USA was the most active country; (4) soil seed genetic diversity, seed persistence, seed trait, restoration potential and restoration projects, and spatial and temporal variation were the main research areas. (5) R language and linear mixed effects models are currently popular in SSB research. Invasive species, weed control, restoration potential and restoration projects, seed traits (especially seed longevity and dormancy), and SSB responses to environment changes (especially climate change and fire) are newly emerging trends in the research.

Keywords: soil seed bank; bibliometrics; trends; soil ecology; weed management; restoration; invasive species; review

1. Introduction

The germination of mature seeds may be delayed for an indefinite period. During this time, the seeds on the surface of or within the soil are likely to form a soil seed bank (SSB) [1]. SSB studies are important for vegetation dynamics and ecological restoration and management, as normal vegetation regeneration depends on the seeds in the soil [2,3]. SSB was first researched by Darwin, who investigated the seeds in the soil and obtained the first SSB survey data [4]. The first recorded SSB publication on Web of Science occurred in 1918, where the SSB was called “buried seeds” [5]. The term “buried (viable) seeds” was then used until 1976. Vandervalk and Davis first used the term “seed bank”, and defined it as “the amount of viable seed present in the substrate at any given time” in 1976 [6]. In 1977, Happer compared the seed bank with a deposit account in a real bank, which led to the wide use of the term “seed bank” [7]. The first book on SSB, *Ecology of Soil Seed Banks*, was published in 1989 [8].

This book systematically collated and summarized previous research results, and the definition of SSB, referred to the collection of all seeds that live in the soil and on the soil surface, was widely used [8,9]. Until now, large amounts of researches on the SSB have been conducted. Some scholars reviewed part of the studies from various angles. For example, in 2007, Csontos collected and reviewed some SSB studies to provide a methodological synthesis of the seed bank studies and highlight the most important methodological challenges [10]. In 2007, Hopfensperger reviewed 108 articles published between 1945 and 2006 assessing the similarity between SSBs and standing vegetation to understand what mechanisms control community composition [11]. In 2008, Bossuyt and Honnay reviewed 102 SSB studies ranging from 1990 to 2006 to identify consistent trends in SSB characteristics among community types and discussed SSB potential for restoration [12]. Honnay et al., in 2008 reviewed 42 publications regarding habitat fragmentation and 13 publications reporting the genetic diversity of SSB and aboveground plant population, respectively, to find evidence for whether SSB can maintain the genetic variation for the aboveground plant population [13]. In 2018, Kiss et al. reviewed 42 papers globally from the viewpoint of restoration prospects and climate change [14]. Despite these studies, few studies have quantitatively addressed and analyzed the overall structure of SSB research and recent emerging trends in this area.

Bibliometrics is often used as an accurate and presumably objective method to process a large number of references and extract measurable data for the advancement of knowledge through statistics and mathematical analysis [15]. CiteSpace, as a popular tool in bibliometric analysis, provides a series of solutions to explore the potential network relationship between publications and shows advantages in detecting emerging trends and abrupt changes in scientific publications [16]. However, to the best of our knowledge, CiteSpace has not yet been used to analyze the research conducted on SSB. As a great quantity of publications have accumulated but their distribution law and the internal relationships that could be deeply mined were previously unknown, we investigated and analyzed the distribution of publications among years; subject categories; countries/regions, institutions, and authors; the cooperation relationship between countries, institutions, and authors; the major research areas; valuable references; and the emerging trends. Our findings may help researchers in SSB area comprehend the current research state, and identify newly emerging trends in the SSB field.

2. Materials and Methods

2.1. Search Strategy and Records Collection

The data of this study were obtained from the Web of Science Core Collection using topic search (TS), including search words from the title, abstract, and keywords: (TS = “seed bank” OR TS = “seed banks” OR TS = “buried viable seeds” OR TS = “buried weed seeds” OR TS = soil “viable seeds” OR TS = soil “buried seeds” OR TS = “viable weed seeds” OR TS = soil “weed seeds” OR TS = “soil seed stock”) AND language (English), which included the early and present SSB publications. The time span was from 1900 to 2019. The selected databases were Science Citation Index Expanded (SCI-E) and Social Sciences Citation Index (SSCI); only articles and reviews were extracted. The SSCI database was also selected because knowledge and research on SSB is indirectly linked to issues of social relevance, including natural restoration projects, nature conservation, and land management. A total of 6440 records, including full records and cited references, were all downloaded and exported as a text-based format for further analysis.

2.2. Analysis Tools

CiteSpace (version 5.5.R2) was used to generate the subject categories co-occurrence network, author collaboration network, institution collaboration network, country collaboration network, reference co-citation network, burst detection, and keyword co-occurrence network.

2.3. Parameters in Citespace

CiteSpace has a number of parameters that must be set to output the best result. Combining our new attempts with the methods used in a previous study [17], certain parameters were considered for the current study. For the time slicing method, as about 97.7% of the publications were published after 1990, networks were default set up from 1990 to 2019 with one year per slice. To find the recent trends, we narrowed the time scale from 2010 to 2019 for the burst detection. The time scale was also narrowed for the keyword co-occurrence network, in this case, selected from 2015 to 2019. For node types, we chose “Category” in the subject category co-occurrence network, “Country” in the country collaboration network, “Institution” in the institution collaboration network, “Author” in the author collaboration network, “Reference” in the co-citation network, and “Keyword” in keyword co-occurrence network. For the selection criteria, the top 50 levels of most cited or occurred items from each slice were selected. For the pruning method, all networks used the “pathfinder-pruning the merged network” to maintain the most salient network, except the co-citation network without pruning.

2.4. Network Interpretation Method

Each network consists of nodes and links: the size of a node is proportional to the number of publications (citation counts in co-citation network); the links indicate the relationship between nodes and are proportional to the intensity of the connection. Colors ranged from dark blue to yellow in the network, which are related to the period from 1990 (dark blue) to 2019 (yellow). The magenta ring outside the node indicates betweenness centrality which is used to measure the importance of the position of a node in a network [16].

3. Results and Discussion

3.1. Annual Distribution of Publications

The annual distribution of publications may reflect the development progress of research on SSB. The overall trend of the literature showed growing numbers of publications (Figure 1), indicating that SSB research is expanding and remains a hotspot. However, the growth rate was not even and therefore the time dedicated to SSB research can be roughly divided into four periods:

1. Beginning period (1918–1977): Within this time range, publications per year fluctuated in very low numbers. The average annual number of publications was 0.42, showing that little attention was paid to SSB in this period.
2. Slow growth period (1978–1990): The average annual number of publications in this period rose to 11.08. This is the period when the term “seed bank” was formed.
3. Rapid growth period (1991–2006): With the publication of the first book on SSB (*Ecology of Soil Seed Banks*) [8], the foundational theory study of SSB gradually matured. During this period, the number of publications grew rapidly. A total of 2542 articles were published within 16 years, with an average of 158.88 articles per year.
4. Stable growth period (2007–2019): The growth rate slowed down and the publications reached a peak with 324 publications in 2018. The ratio of SSB publications to all publications has declined since 2006 (Figure 1). Although the number of publications still increased, it did not keep pace with the development of other disciplines. This may be due to the SSB research not enjoying the benefits or without breakthroughs of new methods and technologies, such as molecular biology techniques and other rapid, satisfied and advanced SSB-species-identification methods.

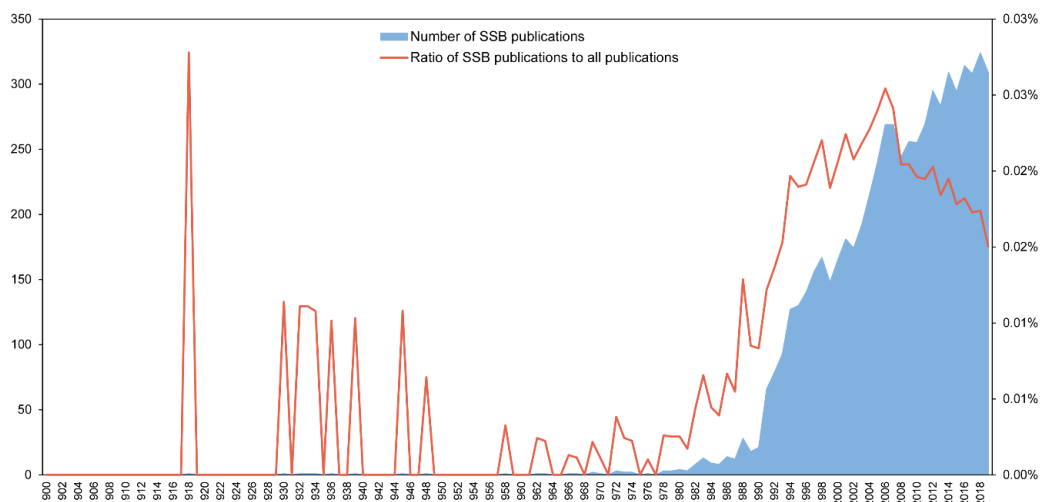


Figure 1. Number of soil seed bank (SSB) publications per year from 1918 to 2019 and its ratio to all publications in Web of Science Core Collection (Science Citation Index Expanded (SCI-E) and Social Sciences Citation Index (SSCI)).

3.2. Distribution of Study Subjects

The subject categories co-occurring analysis identified the main disciplines and their branches. The largest connected network consisted of 62 nodes (Figure 2). The node representing Environmental Sciences and Ecology was the largest with 3125 publications, Ecology (2821) ranked second and Plant Sciences (2570) ranked third, followed by Agriculture (1178), Environmental Sciences (879), Forestry (845), Agronomy (806), Biodiversity and Conservation (490), and Marine and Fresh water biology (304). Several nodes with a magenta ring indicated high centrality, such as Biology (centrality = 0.64), Evolutionary Biology (0.61), Geography (0.48), Cell Biology (0.37), and Genetics and Heredity (0.30). Although the number of publications in these subject categories was relatively low, their high centrality indicated great significance for the expansion of the research fields. In short, SSB is mainly included with the interdisciplinary subjects of ecology, environmental science, and plant science, with agriculture, forestry, biodiversity and conservation, and marine and fresh water biology as the major application disciplines, and biology, evolutionary biology, geography and cell biology as the branches. These results showed that research on SSB has different entry points and its application is diverse.

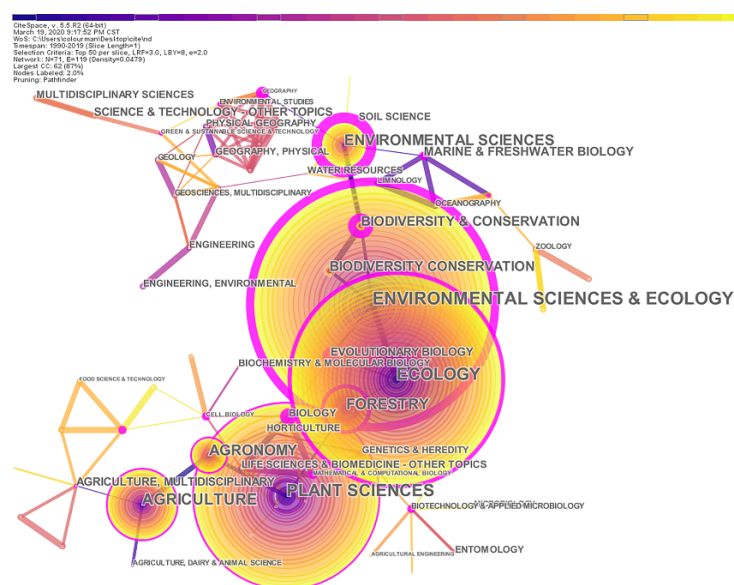


Figure 2. The co-occurring network of subject categories for SSB publications.

3.3. Country/Region Collaboration Status

The country collaboration network can reflect the national attention of SSB research. The largest connected country/region collaboration network consisted of 71 nodes (Figure 3). Among these countries, the USA was the largest contributor, with 1883 publications accounting for 29.24% of the total publications. Australia (770), England (475), Germany (425), and China (404) follow the USA. Combined with Figure 4, we found that North America, Western Europe, East Asia, and Australia were high contribution regions. In terms of centrality, high centrality countries/regions were mainly distributed in Europe (Figure 4), indicating that European countries played a vital role in establishing academic exchanges and cooperation in SSB research. For example, the widely used LEDA-Traitbase (a database of life-history traits of the Northwest European flora) was built by an international group of scientists from nine European countries [18].

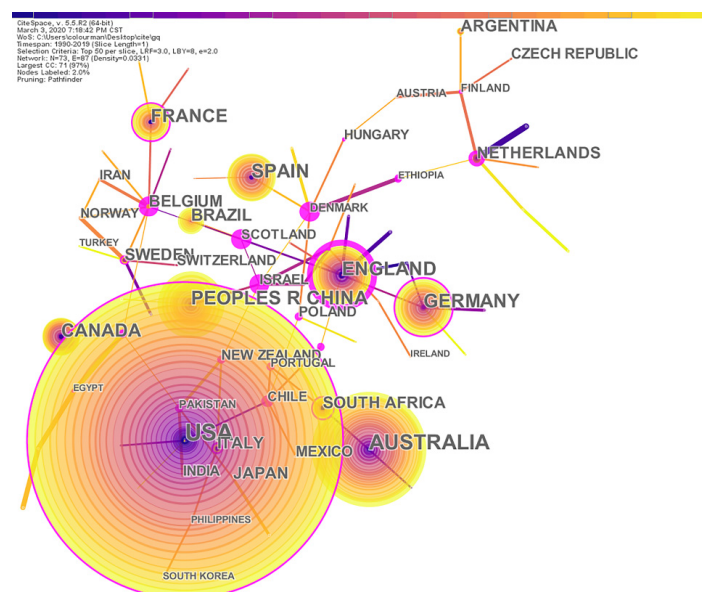


Figure 3. The network of country/region collaboration on SSB research.

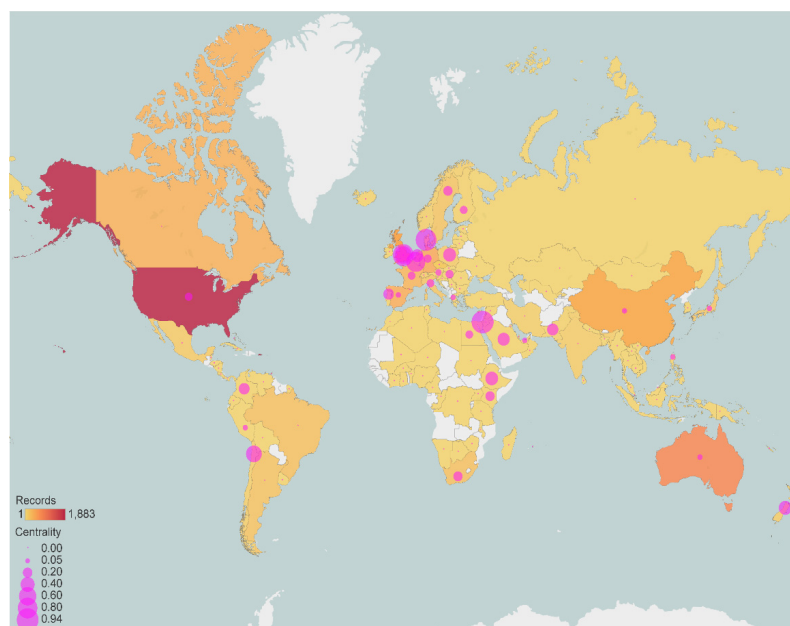


Figure 4. Global geographic distribution (gradient color) and corresponding centrality (purple circular) of SSB publications.

3.4. Status of Institution Collaboration

The institution collaboration network can reflect the academic attention in SSB research and help identify activity and influential institutions. The largest connected institution collaboration network consisted of 492 nodes (Figure 5). The node representing the Chinese Academy of Science was the largest with 219 publications, followed by the University of Western Australia (123), University of Kentucky (102), United States Department of Agriculture–Agriculture Research Service (USDA-ARS) (92), the U.S. Forest Service (83), Spanish National Research Council (CSIC) (77), French National Institute For Agricultural (INRA) (73), the University of Queensland (72), the U.S. Geological Survey (69), and the University of Groningen (65), which were the top 10 institutions in terms of publications in SSB research. Among them, four institutions are from the USA, again proving that the USA attaches importance to SSB research. In terms of the centrality, University of Cambridge (0.26), University of Sheffield (0.24), University of Oxford (0.21), and the Spanish National Research Council (CSIC) were above or equal to 0.2. Three of them are in the U.K. and all of them are in Europe, again indicating the strong influence of European countries, especially the U.K. The CSIC is worthy of attention due to its high value received for both publication and centrality.

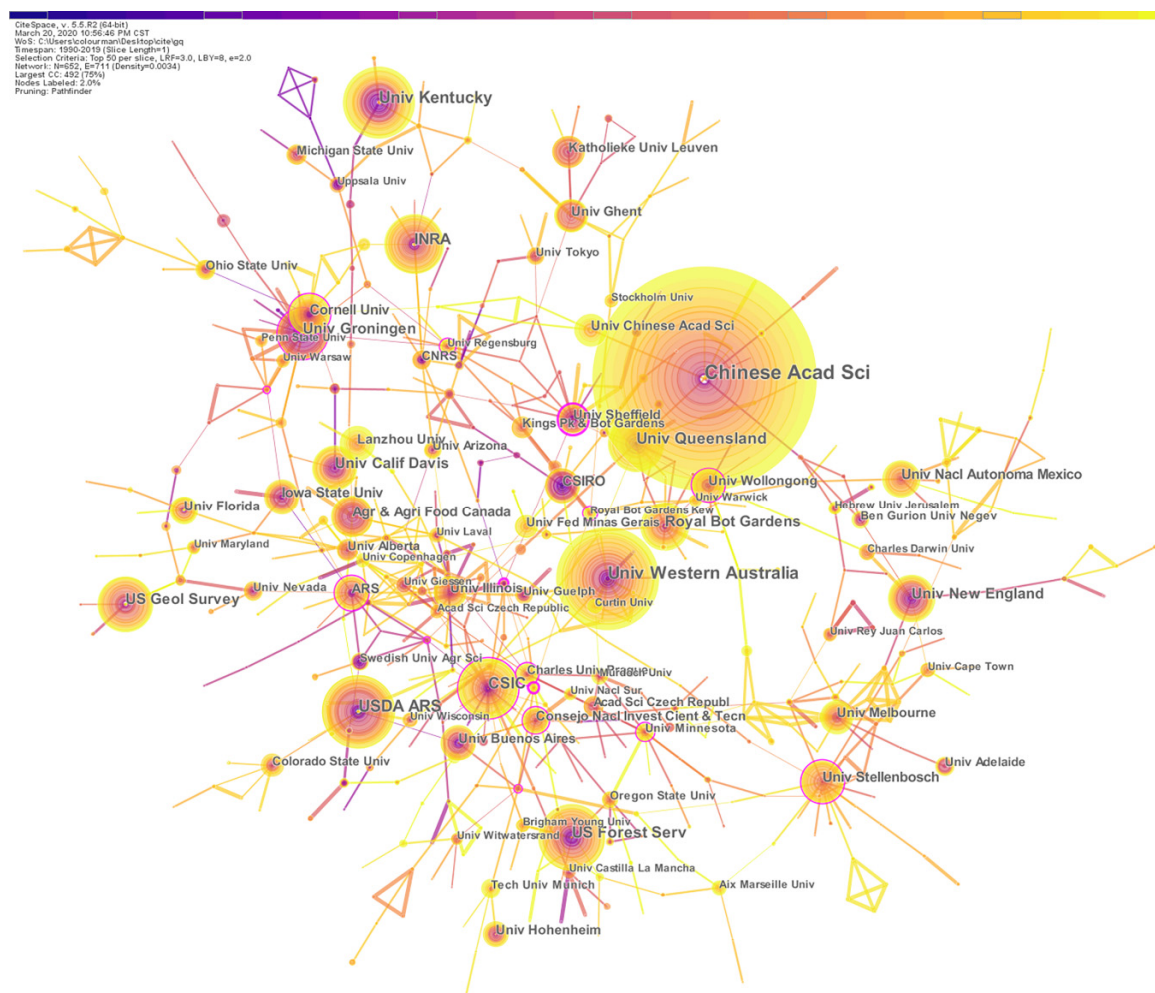


Figure 5. The network of institution collaboration on SSB research.

3.5. Status of Author Collaboration

The author collaboration network can help identify authors with high contribution and reveal the co-operative relationships between the authors. A total of 1033 nodes were obtained; the whole cooperation network was relatively scattered. We enlarged the largest connected cooperation network,

which also included the authors with more publications (Figure 6). Baskin C.C. and Baskin J.M. were the top two authors with 94 and 86 publications, respectively. Hermy (45), Bakker (38), Thompson (38) followed to form the top five contributors. The yellow ring on Baskin C.C., Baskin J.M., Buisson E., and Ooi M.K.J. indicated that they have been the authors with high numbers of contributions in recent years. Though the largest collaboration networks were closely connected, many isolated cooperative networks existed around them, showing that the overall cooperation was loose. Collaboration is an important process in the development of scientific communities [19]; the creation of new collaboration networks will benefit the further development of SSB research by increasing the number of publications and citations.

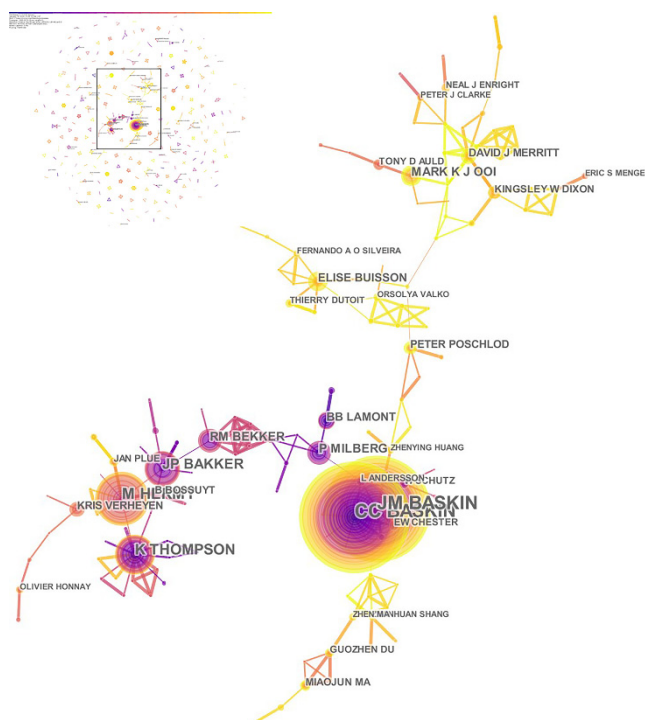


Figure 6. The network of author collaboration on SSB research.

3.6. Reference Co-Citation

Reference co-citation refers to the co-citation relationship when two documents (cited documents) are cited together by a third document (citing document). This analysis can help identify major research areas and find valuable references, and provide a better understanding of the field development. The largest 10 clusters in reference co-citation were visualized, and labelled from the term of title (title of citing document) in log-likelihood ratio (Figure 7). The network had a modularity score of 0.7133, and the mean silhouette score was 0.3791. Modularity score ranges from 0 to 1; clusters are considered well structured when modularity > 0.3. The silhouette score ranges from −1 to 1; the separation of clusters is considered when silhouette > 0.5. The mean silhouette value was relatively low due to the too many small clusters. The largest five clusters were selected for further analysis and their silhouette score was sufficiently high (Table 1). The most active citer in each cluster was selected to represent the cluster. References with top 10 local citation counts, top 10 citation bursts (abrupt increase of citations), and top 10 centrality were selected as valuable references.

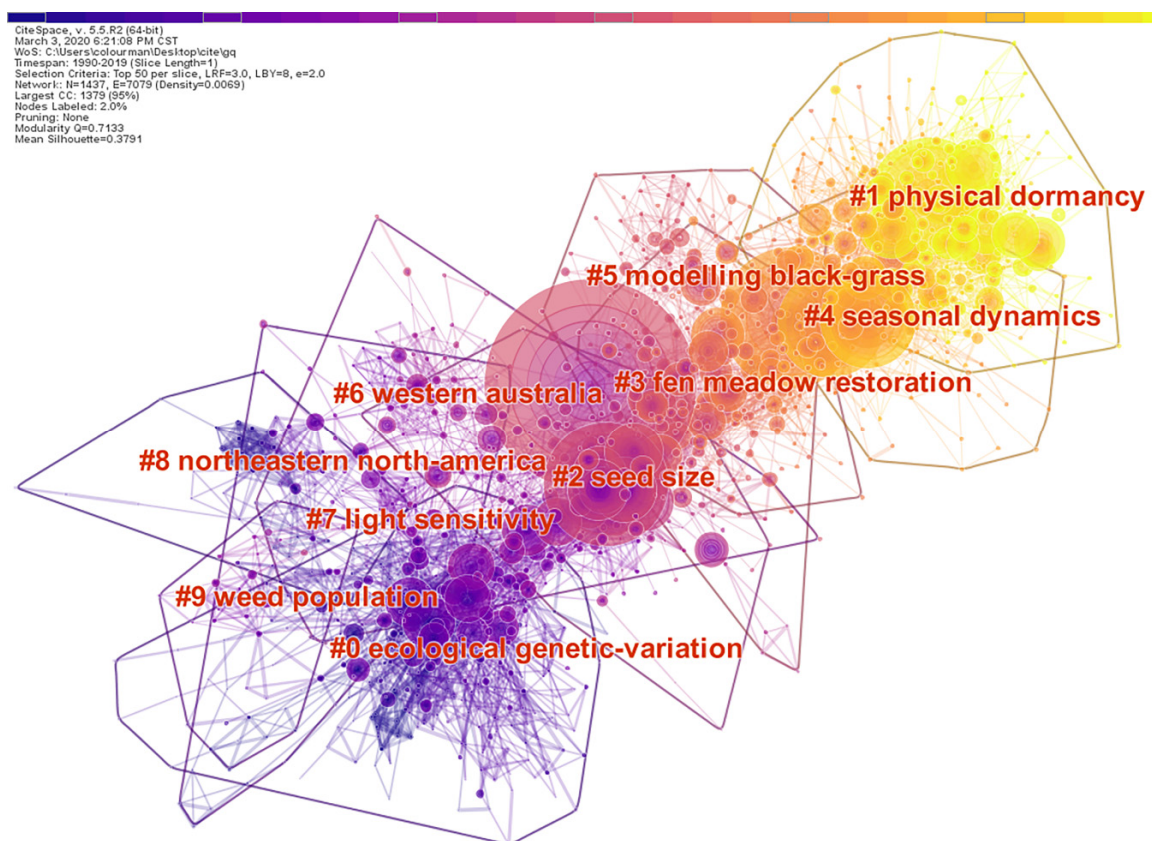


Figure 7. The network of reference co-citation for SSB research.

Table 1. Cluster analysis and feature information for SSB researches.

Cluster ID	Mean Year	Silhouette	Size	Label
#0	1988	0.618	242	ecological genetic-variation
#1	2011	0.669	227	physical dormancy
#2	1996	0.662	179	seed size
#3	2001	0.72	136	fen meadow restoration
#4	2008	0.752	130	seasonal dynamics

Mean year, the average year of publications; Silhouette, the silhouette score; Size, number of references.

The largest cluster (#0) included 242 references and the silhouette score was 0.618, which was considered reasonable (silhouette > 0.5). It was labeled as ecological genetic variation and the average year of publication was 1988, which is the oldest cluster. Some studies found that SSBs of some plants may, in theory, have acted as reservoirs to maintain and restore genetic variation [20–22]. Significant genotype frequency differences were also found between SSBs and extant plant populations, but the results were not consistent and more focused on the higher genetic diversity in extant plant populations [23]. The most active citer was a review that emphasized the various factors influencing the movements and fates of seeds in nature; SSB was found to be less studied but important in this review [24].

For the valuable references in cluster #0, one book had high centrality (0.09), *Nature Management by Grazing and Cutting*, was in this cluster [25], showing that SSB was connected to management treatments. The first book on SSB: *Ecology of Soil Seed Banks* [8], which also caused citation bursts (25.05), was also included in this cluster.

The second largest cluster (#1) included 227 references and the silhouette score was 0.669 (silhouette > 0.5). It was labeled as physical dormancy and the average year of publications was 2011,

which is the most recent cluster. The physical dormancy refers to the species with water-impermeable seed coats that prevent seeds from germination. Physical dormancy is suggested to play a defensive role against microbial attack, predation, and other harmful abiotic factors, and thus, in theory, extends seed longevity and persistence in the SSB [26–28]. However, a view was also expressed that seed dormancy was unconcerned with SSB persistence [29]. This contradiction was discussed in a publication which caused citation bursts (27.5) in this cluster, as researchers argued that it is a premature dismissal of an important relationship. This publication is a review of seed persistence [30]. The most active citer in this cluster was “Seed-bank dynamics of native and invasive *Impatiens* species during a five-year field experiment under various environmental conditions”, which was a research article [31]. This cluster was also involved in invasive species, and the knowledge in this cluster could serve research on invasive species, as successful invasive species often have long persistence in the SSB. Therefore, the longevity of SSB should also be considered when making eradication plans [31,32].

For the remaining valuable references in cluster #1, the book *Seeds: Ecology, Biogeography, and, Evolution of Dormancy and Germination 2nd edition* in this cluster received both high local citation counts (108) and high citation bursts (55.12), which is worthy of attention [33]. A publication in the cluster #1 with high centrality (0.09), using meta analyses, also studied the topic of cluster #0 (genetic variation), which concluded that a persistent SSB may mitigate random genetic drift but genetic diversity could hardly accumulate in the SSB, and the variation of genetic composition between the SSB and extant population may rather be the result of local selection instead of the accumulation of genetic diversity [13]. This publication is significant mainly because of its performing a systematic review and analysis for some general trends of genetic variation in SSB.

The third largest cluster (#2) included 179 references and the silhouette score was 0.662 (silhouette > 0.5). It was labeled as seed size and the average year of publications was 1996. Seed size, often combined with seed shape and seed mass, is commonly used as a seed trait. Researchers often associate these traits with the distribution and persistence of seeds in the soil. There are two valuable publications with this theme in this cluster, one had high centrality (0.09), entitled “Seed size and shape predict persistence in soil” and the other had high local citation counts (55) and high citation bursts (25.59) entitled “Seed size, shape and vertical distribution in the soil: indicators of seed longevity” [34,35]. Both publications provided improvements in the study method; the former proposed the use of the variance of the three main dimensions of seeds to quantify seed shape (shape = 0 indicates perfectly spherical, increasing with flatness and stretch) and the latter proposed a longevity index to quantify seed persistence (longevity index = 0 denotes strictly transient and longevity = 1 denotes strictly persistent). The most active citer in this cluster was “Riparian seed banks: structure, process and implications for riparian management” [36], which described the evolution of SSB research before 2001 and highlighted the riparian seed bank as a neglected area in SSB research. In this cluster, the research content of SSB moved towards diversification; its role in restoration, recovery, and conservation was recognized [36].

For the remaining valuable references in cluster #2, the book *The Soil seed banks of North West Europe: Methodology, Density and Longevity* is worthy of attention because it appeared in all three categories (citation counts = 116, citation bursts = 46.5, centrality = 0.1). The main part of the book is a large SSB database for north-west Europe [37], which was used in a reference with high centrality (0.12) entitled “Ecological correlates of seed persistence in soil in the north-west European flora” [38], in which the databases were evaluated to test some SSB hypotheses. Other publications in this cluster included an improvement in a seedling emergence method for assessing the size of the SSB (citation counts = 56) [39], a review of the constraints in grassland and heathland restoration (citation counts = 56) [40], a research article on regeneration perspectives under different land uses (citation counts = 61, citation bursts = 25.38) [41], and a research article about succession from grassland to forest, testing two proposed hypotheses about changes in secondary succession, which were not confirmed by previous studies (centrality = 0.1) [42].

The fourth largest cluster (#3) contained 136 references and the silhouette score was 0.72 (silhouette > 0.5). It was labeled as fen meadow restoration and the average year of publications was 2001. The label was well interpreted by the most active citer entitled “Prospects for fen meadow restoration on severely degraded fens” [43]. Most fens in Europe were degraded or disappeared due to agricultural intensification or abandonment [44,45]. There is often a lack of target species in the SSB of degraded fens and, instead, it is dominated by competitive and ruderal species, which are considered to act as biotic limitations for fen meadows restoration [43]. The restoration potential of SSB was questioned in this cluster.

As for the valuable references in cluster #3, the reference with the highest centrality (centrality = 0.2) is a research article in which the SSBs of ancient and recent forests were compared, and the SSB was reported to potentially enhance the negative effect of early succession because the SSBs of recent forests are mainly composed of competitive species [46].

The fifth largest cluster (#4) included 130 references and the silhouette score was 0.752 (silhouette > 0.5). It was labeled as seasonal dynamics and the average year of publications was 2008. The main topics in this cluster included temporal pattern (succession), often combined with spatial pattern (altitude, latitude), of the variation of SSB density and species richness [47]. The seasonal dynamics are treated as a temporal pattern in SSB research [48]. In most ecosystems, the SSB reaches the maximum after seed rain, and then decreases gradually [49]. The most active citer was “Can ecological engineering restore Mediterranean rangeland after intensive cultivation? A large-scale experiment in southern France” [50], which assessed the restoration process of degraded rangeland, being the main application both in clusters #3 and #4.

For the valuable references in cluster #4, this cluster had three valuable publications and they were all in the top 10 publications among the three categories. One is the book *The Ecology of Seeds*, published in 2005 (citation counts = 130, citation bursts = 55.67, and centrality = 0.14) [1], and the other two are review works based on former studies with the titles “A review of similarity between seed bank and standing vegetation across ecosystems” (citation counts = 100, citation bursts = 45.36, and centrality = 0.14) [11], and “Can the seed bank be used for ecological restoration? An overview of seed bank characteristics in European communities” (citation counts = 90, citation bursts = 40.45, and centrality = 0.09) [12]. In both publications, meta analyses were performed to determine the general trends in SSB characteristics among different community types. Both studies found a low floristic similarity between the SSBs and the standing vegetation.

The remaining clusters were relatively small in size or short in terms of the length of their duration compared with the five main clusters mentioned above. However, we outlined cluster #5, which was labelled as modelling black-grass, and mainly focused on designing weed models to quantify the effects of cropping systems on the weed lifecycle and thus managing weeds [51]. The first edition of the book *Seeds: Ecology, Biogeography, and, Evolution of Dormancy and Germination* was worthy of attention in this cluster (citation counts = 195, citation bursts = 82.45) [52]. Cluster #7 was labeled as light sensitivity. Light is a key environmental factor modulating seed germination. However, it is not a simple dichotomous factor; the light sensitivity of some species was found to be seasonal [53]. The duration of the main five clusters and the time position of the valuable references were also visualized (Figure 8). The selected valuable references were mainly distributed between 1997 and 2008, within clusters #2 and #4, indicating that the SSB research in recent years has been lacking attention.

Based on the above cluster analysis results of the reference co-citations, the major research areas of SSB can be summarized as follows: (1) ecological genetic variation of SSBs; (2) persistence and longevity of seeds in the soil, especially for invasive species; (3) relationship between seed traits and their distribution and persistence; (4) SSB roles in the restoration and management of degraded ecosystems; and (5) the temporal dynamics and spatial distribution pattern of SSB. According to the time sequence of the clusters (Figure 8), the evolution path of SSB research can also be concluded, SSB was considered less studied in cluster #0, research contents developed towards diversification in cluster #2, limitation in restoration was realized in cluster #3 and cluster #4, and in cluster #1, the application

of SSB research achievements in plant invasion has been gradually recognized at present. In addition, some debates in the genetic diversity of SSBs, the relationship between seed dormancy and seed persistence in the soil, the potential application of SSBs on restoration and the changes in SSBs during succession had also received much attention.

The SSB research methods can be also highlighted by valuable references. Some pioneering experiments and analysis methodologies were two of the most important driving forces for SSB research development, as were the method for improving seedling emergence and the two indexes designed for measuring seed traits.

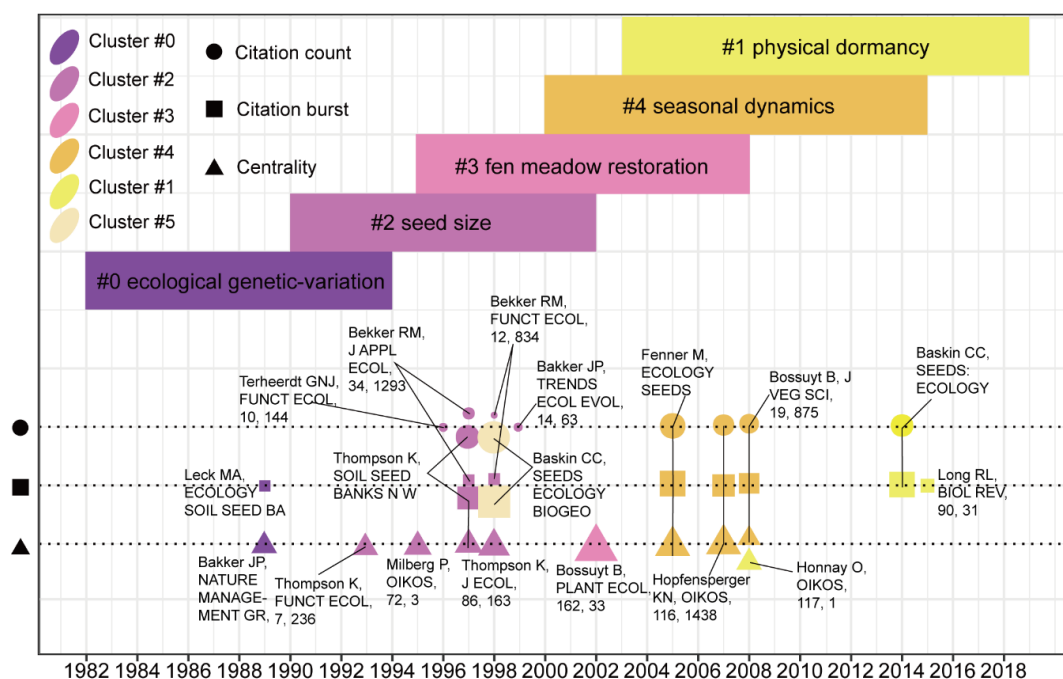


Figure 8. The duration of the five main clusters and the distribution of valuable SSB publications on the time line. The same references are linked; the sizes of the circles, squares and triangles, are proportional to the local citation counts, citation bursts, and centrality, respectively. Books are tagged in the form of “first author, abbreviation of book”. Journal articles are tagged in the form of “first author, abbreviation of journal, volume, starting page”.

3.7. Emerging Research Trends

The time scale was narrowed to the most recent 10-year period (2010–2019) and citation bursts that emerged after 2017 were chosen to enhance the timeliness of the trends. A total of 12 references with citation bursts were obtained. After removing a reference that was more focused on off-site seed banks (ex-situ seed collection), 11 references with the strongest citation bursts in SSB researches after 2017 were obtained (Table 2). These 11 references were divided into four topics for further discussion. The four topics are: (1) hot data analysis tools and methods, (2) plant invasion, (3) restoration potential and restoration projects, and (4) seed traits and environment effects.

According to the references with most citation bursts in SSB after 2017, R language (strength = 15.94) is currently widely applied in SSB research. R is highly extensible free software that provides a wide variety of statistical and graphical techniques [54]. The linear mixed-effects model (LMM; strength = 9.21) and generalized linear mixed-effects model (GLMM; strength = 5.64) also showed an increasing trend in recent years. Both models allow the consideration of random effects [55,56], and evidence shows that researchers have more recently begun to consider random variation in space and time or among individuals [57]. For example, the variation in plots that were treated the same could be fitted as random effects in an SSB research. Both models can be run in the lme4 package for R, which appears popular due to the high strength of its citation bursts (strength = 9.21).

The SSB of invasive species is now gaining attention. Researchers paid the most attention to the management and restoration practices of impacts caused by invasive species (strength = 6.25) [58], followed by the role of the SSB in species invasiveness, the long-term impact of invasion on community dynamics (strength = 5.84) [2], and the reproductive traits of invasive species (strength = 3.30) [59]. The three publications almost cover the entire process of plant invasion: reproduction, dispersal, long-term effects, management, and restoration. The co-citation results also showed that the recent knowledge of SSB could serve studies of plant invasion. These strongly suggest that the achievements in SSB research can provide the knowledge base of plant invasion.

The restoration potential and restoration projects seem to be an old topic that covers all five clusters in the co-citation analysis, but this topic is still hot due to its application prospects. The role of the SSB in restoration varies in different publications and books, with its recovery potential being often questioned in empirical cases. As we discussed in the co-citation analysis, the SSBs of some ecosystems lacked target species for restoration, were dominated by SSB of ruderal species and had a low floristic similarity with the aboveground plant population. Thus, the SSB could be hardly applied in conservation or restoration projects under these circumstances. In a study published in 2015, Vandvik et al. stated these points could be explained by a systematic bias in the sampling of SSBs versus established plant communities; they found higher SSB diversity relative to the established plant community when considering the species–area relationship and sampling effort (strength = 5.17) [60]. The restoration of fen meadows is still worthy of attention. As discussed in the co-citation analysis, the SSB of degraded fen meadows was not suitable for establishing target community. However, the SSB can contribute to novel wetland vegetation assemblages under natural succession, and the established community may be more adaptive to climate change and contributive to ecosystem functions (strength = 4.04) [61].

Some easily observed seed traits, such as seed size, shape and mass, have been extensively studied, but little is known about other traits. Seed traits are important factors affecting seed dispersal, persistence, germination timing, and establishment [62], which are closely related to the dynamics of SSBs. Seed longevity (strength = 4.04) [63], and seed dormancy (strength = 5.88) [64] seem to have garnered more attention in recent years. To better understand how seed traits are associated with the SSB, databases must be developed and improved. For example, the database by Thompson et al. is a valuable reference in co-citation analysis [37]. Some environment effects are also hot topics often combined with seed traits, including the warming and high temperature environment effects due to climate change (strength = 5.84) [2] and fire (strength = 4.70) [65]. These effects act like filters to select species and their traits, further influencing the species composition of SSBs. For example, climate change and fire may affect the viability and longevity of seeds, dormancy release, the bet-hedging strategies of species, and the success of recruitment [66,67], which is important for predicting the future distribution and persistence of seeds in the soil.

Although these trends were divided into four topics, connections existed between some of them. A keyword co-occurrence network was constructed to extract more information. “Soil seed bank” was the main keyword with the highest frequency (633) and centrality (1.30), two main branches linked with “soil seed bank” were identified by the path of nodes with high centrality (Figure 9). In branch #1, “vegetation” (centrality = 0.81), “restoration” (centrality = 0.68), “grassland” (centrality = 0.52) and “fire” (centrality = 0.38) were the key components. Fire was indirectly linked with “plant invasion”, related with the fact that a high biomass of invasive plants potentially increasing the fuel load of fires and fires are likely to leave more open spaces to be colonized by invasive species. “Climate change” was also linked with “fire”, related to high temperatures likely to increase the risk of fire. “Restoration” was indirectly linked with “fire” because prescribed fire or low-frequency fire was evidenced to be beneficial for restoration [68]. “Restoration” was linked to “soil seed bank” through vegetation. In branch #2, “germination” (centrality = 1.08), “seed longevity” (centrality = 0.81), “temperature” (centrality = 0.78) “viability” (centrality = 0.76), “emergence” (centrality = 0.44), “tillage” (centrality = 0.4), “crop rotation” (centrality = 0.37), “persistence” (centrality = 0.34), “system” (centrality = 0.33) and “management” (centrality = 0.3) were the key components. The keywords “tillage”, “crop rotation”, “weed seed”,

“weed control”, “biological control”, “invasion”, “weed” and “cropping system” indicated that this was a branch of weed seed banks. For example, Jernigan et al. compared the weed seed bank of four cropping systems that varied in cropping intensity and tillage [69]. These management practices could affect the longevity, persistence, viability, and germination of weed seeds [70].

By comparing the two methods that we used to explore the trends—one was reference-based (reference citation bursts) and the other was keyword-based (keywords co-occurrence)—similarities and differences can be found. The findings of the two methods were similar; the trends in terms of invasive species, restoration, seed longevity, climate change, and fire were found using both methods. However, in present study, the reference-based method can find cross-disciplinary references, while the keyword-based method can easily obtain more details about the trends and the connections between them, for example, weed control was not reflected in the reference-based method.

Table 2. References with the strongest citation bursts in SSB research after 2017.

Title	Year	Strength	Range (2010–2019)
R: A Language and Environment for Statistical Computing [54]	2016	15.94	
Fitting Linear Mixed-Effects Models using lme4 [55]	2015	9.21	
Impacts of invasive Australian acacias: Implications for management and restoration [58]	2011	6.25	
The evolution of seed dormancy: Environmental cues, evolutionary hubs, and diversification of the seed plants [64]	2014	5.88	
Soil seed banks in plant invasions: Promoting species invasiveness and long-term impact on plant community dynamics [2]	2012	5.84	
A general and simple method for obtaining R^2 from generalized linear mixed-effects models [56]	2013	5.64	
Seed banks are biodiversity reservoirs: Species–area relationships above versus below ground [60]	2016	5.17	
The Influence of Time on the Soil Seed Bank and Vegetation across a Landscape-Scale Wetland Restoration Project [61]	2012	5.14	
Fire in Mediterranean Ecosystems: Ecology, Evolution and Management [65]	2012	4.70	
Edaphic factors influence the longevity of seeds in the soil [63]	2012	4.04	
Reproductive biology of Australian acacias: Important mediator of invasiveness? [59]	2011	3.30	

Year, the published year; Strength, the intensity of the bursts; Range, the duration time of the bursts as the red bar.

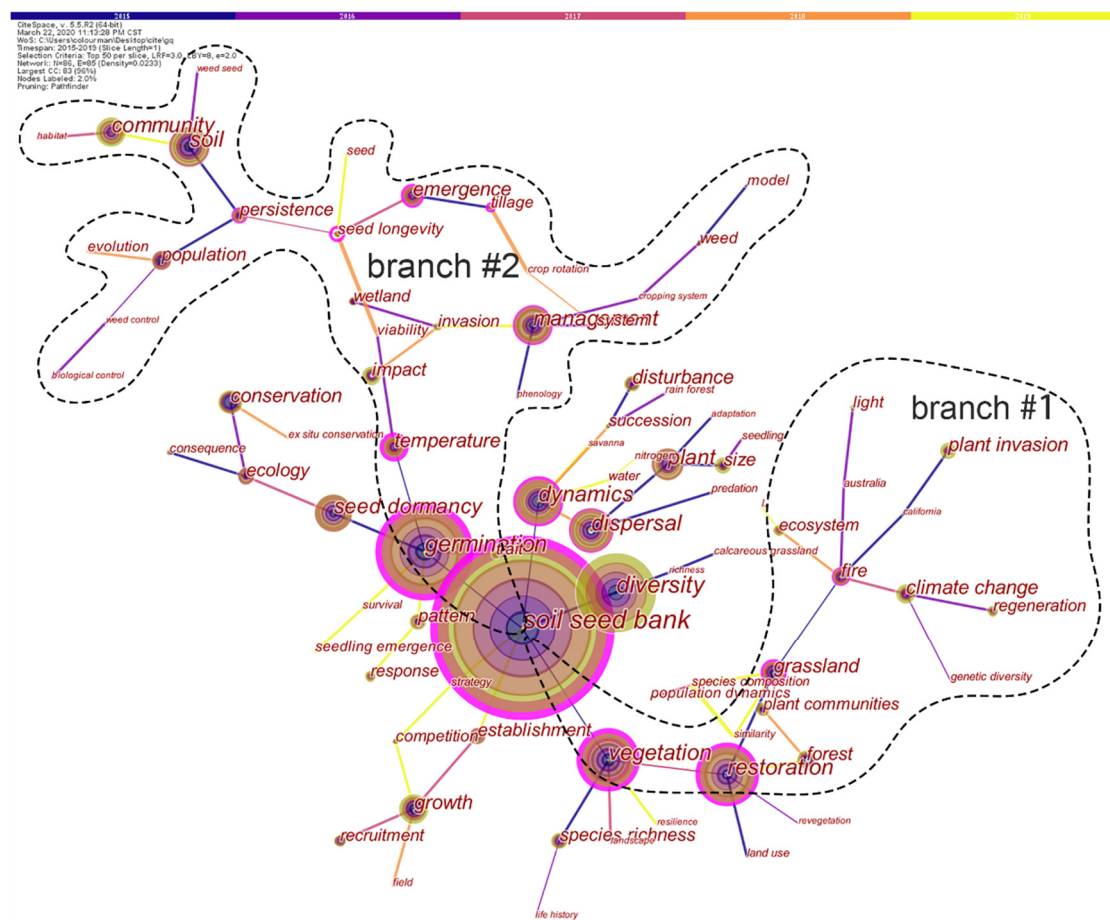


Figure 9. The network of keyword co-occurrence for SSB research.

4. Conclusions

The results obtained in the current study from the bibliometric analysis showed that the research progress on SSB can be roughly divided into four periods: beginning (1918–1977), slow growth (1978–1990), rapid growth (1991–2006), and stable growth (2007–2019). SSB research is an interdisciplinary field mainly involving ecology, environmental science, and plant science. Close cooperation mainly occurred among European countries that had more influential effects. The USA, Australia, the U.K., Germany, and China were the most active countries and the Chinese Academy of Sciences was the most active institution. However, the author collaboration network on SSB research was loose, showing that more collaboration is needed in the future. Five major research areas in SSB research are identified as follows: ecological genetic variation (genetic diversity), physical dormancy (seed persistence), seed size (seed trait), fen meadow restoration (restoration and management), and seasonal dynamics (spatial and temporal variation). The evolution of SSB research was mainly driven by new methods, opposing views and application needs. At present, invasive species, weed control, restoration potential and restoration projects, seed traits (especially seed longevity and dormancy), and SSB responses to environmental effects (especially climate change and fire) are newly emerging trends. We found that R language is a rather popular tool and the use of mixed-effect models is increasing in SSB research. Overall, we explored the characteristics of SSB research through an objective method. Future research trends are suggested, which may provide a useful guide. Based on the information obtained by this study, researchers may find relevant countries, institutions, and authors for communication and cooperation.

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