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A vulnerable soil environment study in karst areas: a bibliometric analysis

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Karst landforms are widely distributed around the world, and karst rocky desertification has occurred on a large scale in many countries and regions, causing significant adverse impacts on local natural environments and societies. The improvement and rational use of karst soil is a key aspect of rocky desertification governance. Karst soil science studies are of great value in karst regions and are essential for controlling karst rocky desertification and ecological restoration. In order to understand the research hotspots and the development directions in the field of vulnerable karst soil environment, we undertook bibliometrics citation analysis on 1913 contributions to the literature written in the range from 2001 to 2019 based on the "Web of Science" core collection citation index database. Hopefully, this work will help to set up a scientific foundation for further studies. Using CiteSpace visualization software, we analyzed the distribution of disciplinary categories, reference co-citation clusters, and keyword clusters in the literature. The results show the basic characteristics and evolution of the literature related to karst pedology. We then recognized the main intellectual bases in the domain of karst soil science. This study also revealed the research hotspots and trends in this field. Through a bibliometrics citation analysis of research on karst vulnerable soil environment, the present study provides a quantitative and objective understanding of development directions that have emerged in this field over the past 19 years, offering a reference for future research.

KEYWORDS

vulnerable soil environment, soil research, karst area, mapping knowledge domain, citespace, bibliometric analysis

1 Introduction

Karst is a geological landscape with specific characteristics formed under certain geological, climatic, and hydrological conditions via the erosion and transformation of soluble rocks (mainly carbonate rocks) by surface water and groundwater; the landforms are produced by the combination of highly soluble rocks and fully developed secondary pores (Ford and Williams, 2007). Karst occupies approximately 12.53% of global land area and has developed on continents and islands and from tropical to boreal regions, however it is absent from Antarctica, Greenland, and Iceland (Ford and Williams, 2007). Karst landforms are mainly distributed in China, Southeast Asian countries (Vietnam, Thailand, and Indonesia), Mediterranean countries (France, Italy, and Slovenia), and North American countries (United States of America, Mexico, and Canada) (Yuan, 2001; Clements et al., 2006; Zhang M. et al., 2016). Better-known karst landforms have been found in the provinces of Guizhou, Guangxi, and Yunnan in China, northern Vietnam, the Dinaric Alps, the Italian and Austrian Alps, the French Central Highlands, the Russian Ural Mountains, southern Australia, Kentucky and Indiana in the United States, the Sierra de los Organos (western Cuba), and Brazil. Rocky desertification refers to the process of land degradation in tropical and subtropical humid and semi-humid climatic conditions and often occurs in areas where karst is extremely developed; these are areas where human activities interfere with the surface vegetation, causing severe soil erosion, large areas of exposed bedrock, severe decline in land productivity, and desert-like landscapes (Sauro, 1993; Williams, 1993; Yuan, 1997). Karst rocky desertification is a major type of land desertification and has occurred on a large scale in several countries and regions, including the Euro-Mediterranean (Yassoglou, 2000), the Balkan Dinaric region (Gams and Gabrovec, 1999), Southwest China (Yuan, 1997), Haiti (Williams, 2011), and Barbados (The Government of Barbados and Ministry of Physical Development, 2002), causing significant negative impacts on the local natural environment and socioeconomic conditions (Chen et al., 2011; Jiang et al., 2014).

The basic characteristics of karst soils are that they are difficult to form and are easily lost (Yan et al., 2019). Generally, the time required to form a 10 mm thick layer of soil from carbonate rock in karst zones is 10–40 times longer than that in non-karst zones at the same latitude. The global rate of dissolution of carbonate rocks ranges from a few millimeters per millennium to 300 mm per millennium (Yuan, 2001; Ford and Williams, 2007). This erosion is both the driving force behind soil formation and an important cause of soil loss. Erosion forms various karst landforms while enlarging pores and fissures, which provides drainage pathways for soil or other residues. However, this process makes it more difficult to preserve soil, resulting in a thinner soil layer and a smaller distribution area than that of non-carbonate rocks under the same conditions; the output is characterized by a soil composition that is rich in calcium and low in nutrients (Toran and White, 2005; Tang et al., 2019). The thin soil layer also shortens the filtration time of water and pollutants, which in turn reduces the self-cleaning of the karst (Miko et al., 2003; García et al., 2011). More seriously, the difficult-to-form karst soils are highly erodible, and severe erosion can occur in karst areas even for soils formed by other parent rocks that are typically classified as “normal erosion” types (Peng et al., 2013). This is typical of the self-destructive nature of karst systems; however it can be attenuated by the formation of vegetation that increase the forest canopy and the humus layer, reducing the contact surface between precipitation and surface runoff and the soil, reducing rainfall velocity and infiltration, reducing total soil erosion, increasing water transpiration, and creating animal habitats (Ruiz-Jaén and Aide, 2005; Zhang et al., 2011; Batori et al., 2014).

As rocky desertification intensifies, the loss of karst soil increases, and the ability to support plant growth is severely weakened, leading to the degradation of vegetation and the disruption of the basic structure of karst soils. Soil infertility, reduced water-holding capacity of soils, and frequent environmental stresses on plants result in the failure or eventual death of vegetation, which in turn increases the risk of karst rocky desertification and further collapse of karst ecosystems. These factors directly or indirectly contribute to serious challenges to the productivity and sustainability of karst soil resources (Smith et al., 2013; Pachauri et al., 2014). The essence of karst rocky desertification is fundamental changes in the material composition and physical, chemical, and productive properties of karst soils, resulting in the degradation of vegetation, environmental degradation, and the exposure of large areas of rock (Long et al., 2012). Land-use practices, human activities, and their degrees of disturbance also have significant impacts on changes in karst soils (Wang et al., 2004; Peng and Wang, 2012). Therefore, the improvement and rational use of karst soils, which can improve soil sustainability and productivity, is the key to the management of karst rocky desertification and is thus the focus of karst soil science research. In addition, because of the special binary hydrological structure and complex geological and geomorphological conditions, karst regions have a large number of soil types and the soil layers are shallow. With high rock exposure, the soil bodies are often separated into discrete patches and the soil properties also exhibit a high degree of spatial heterogeneity (Hobley et al., 2014; Liu et al., 2014). These factors pose challenges in karst soil science research. In conclusion, karst soil research will be very valuable for karst regions, and information from these studies is of great significance for karst rocky desertification control and ecological restoration.

Literature is the main indicator of the output of scientific research (Homrich et al., 2018). Scholars have conducted a great deal of research in the field of vulnerable karst soil environment and have published many scientific papers, including some high-impact review articles (Reichstein et al., 2002; Ying et al., 2002; Jiang et al., 2014). These reviews play an important role in the in-depth study of the specific direction of this field. However, it is also necessary to comprehensively understand the current research progress, research hotspots, and developments in karst soil science from a macro perspective. Thus, using bibliometric methods, we provided a statistical description and content analysis of research results related to karst soil science; we used CiteSpace to perform data mining, visualization, and metrological analysis of the literature, refine the knowledge base of the research field, show the current research status and popular trends, and grasp the latest progress and dynamics of the research. This work helps to define the research clusters and researchers with a stronger impact on the field by identifying the mature and emerging research topics online using bibliometrics tools. Bibliometric analysis revealed the interests and new topics in the field and pointed out the possible directions of future studies. Although the importance of researches on vulnerable karst soil environment has been increasingly emphasized, there is no bibliometric analysis popped up into our sight of searching. This work summarized the knowledge foundation and research frontiers in the field of vulnerable karst soil environment through bibliometric analysis on the literature in the “Web of Science” database. It clarified current research hotspots and future research directions and provided scientific foundation for further studies in this field.

2 Materials and methodology

2.1 Data collection

The data were obtained from the Web of Science (WOS) Core Collection: Science Citation Index Expanded (SCI-EXPANDED).

The search date was 20 May 2020. To retrieve documents related to karst pedology, the study used "Advanced Search" by setting the field tags as "TS (Topic)" and setting the timespan from 2001 to 2019. The query was created as follows: TS= ("karst" OR "karstification" OR "karstic" OR "epikarst") AND TS= ("soil" OR "soils" OR "soil environment" OR "pedology" OR "edaphology" OR "pedogenesis" OR "soil stoichiometry" OR "soil microbiology" OR "plant-soil interactions" OR "soil respiration strategies" OR "soil science" OR "plant nutrition" OR "degraded soil") NOT TS= ("pice*" OR "abies" OR "l karst" OR "spruce" OR "papyraceum" OR "ganoderma" OR "Haematoxylum" OR "Fomitopsis" OR "P. KARST" OR "ex-fr karst" OR "fr karst" OR "puteana" OR "Uwe Karst" OR "pine" OR "Inonotus" OR "Bjerkandera" OR "Postia caesia (Schrad. Fr.) P. Karst" OR "gloeophyllum-sepiarium-(WULF) Karst") (Shi et al., 2019). We restricted the results by setting the language as "English" and setting the document types as "Article" or "Review." The titles and abstracts of the retrieved documents were consulted to determine whether the documents were related to karst pedology and irrelevant documents were eliminated.

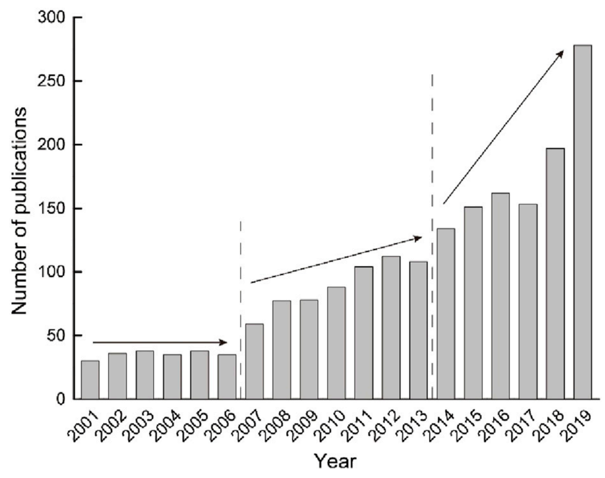

FIGURE 1
Annual variations in documents on karst pedology.

2.2 Methodology

Using systematic and precise bibliometric methods (Chen, 2004; Homrich et al., 2018), we quantified and characterized a large body of literature in the field of vulnerable karst soil environment in combination with visualization analysis, which provided a more precise and comprehensive analysis of this research topic. The visualization analysis software CiteSpace, a popular software for visualizing research data, has been utilized to analyze the frontiers of disciplinary research and trends in theme evolution and to evaluate the relationships between knowledge bases (Chen, 2004). Using the bibliometric and analytical features of WOS, we obtained data on the annual number of publications and the number of articles. We exported the data in a plain text format (.txt), and then imported into CiteSpace visualization software. Using CiteSpace, we analyzed the literature's discipline category distribution (Chen et al., 2010). We also used CiteSpace to check the strength of association or similarity between references and keywords by cluster analysis, which has a strong graphical presentation capability (Chen, 2006). In the knowledge maps generated by CiteSpace, the size of a node concentric circle represents the frequency, with a larger concentric circle indicating that the node appears more times, the color of the concentric circle represents the year, the lines between the node concentric circles show the co-occurrence frequency of the two nodes, with a thicker line indicating a higher co-occurrence frequency; the distance between node concentric circles also shows the co-occurrence frequency of the two nodes, with a closer distance indicating a higher co-occurrence frequency; if the outermost circle of a node is purple, the betweenness centrality of the node is greater than 0.1. By analyzing the clustering of references, we identified the knowledge base in the field of vulnerable karst soil environment, and identified hotspots and development directions in research in the field by keyword clustering. The visualization of keywords is a commonly used method in bibliometric analysis. By extracting the keyword frequency from massive literature, constructing a co-occurrence matrix, and visualizing high-frequency keywords, the research hotspots and progress of vulnerable karst soil environment, can be determined based on the visual knowledge map.

3 Results and discussion

3.1 Basic characteristics of the literature

3.1.1 Annual variations in publications

The annual number of publications reflects the theoretical development of a research field and the degree of attention that it receives, making it an important indicator of the evolution of the field (Mongeon and Paul-Hus, 2016). We retrieved 1913 research articles related to karst soil science published between 2001–2019. Of these, 212 were published between 2001–2006, accounting for 11.08% of the total volume of literature; 626 articles were published between 2007–2013, accounting for 32.72%, and 1,075 articles were published between 2014 and 2019, accounting for 56.19%. The aforementioned results indicate that karst soil studies has gone through three stages: initial accumulation, developmental, and rapid developmental (Figure 1). Before 2006, the research field received little attention and was in its initial stage; between 2007 and 2013, the theoretical foundation was basically formed, and a large amount of relevant research literature appeared, entering the development stage; and in 2014–2019, the field received a rapid increase in attention and entered the rapid developmental stage. This indicates that the research field of karst soil science has attracted widespread attention from researchers. It is expected that research on karst soils will continue to deepen and improve with the continuous development of related work.

3.1.2 Subject category distribution

The literature on karst soil research covers a number of disciplinary categories in the WOS. To understand the distribution of disciplines and strengths, we conducted a disciplinary category co-occurrence analysis to help us determine the development of research area disciplines (Xiang et al., 2017). We set the time span in CiteSpace from 2001 to 2019, selected the annual

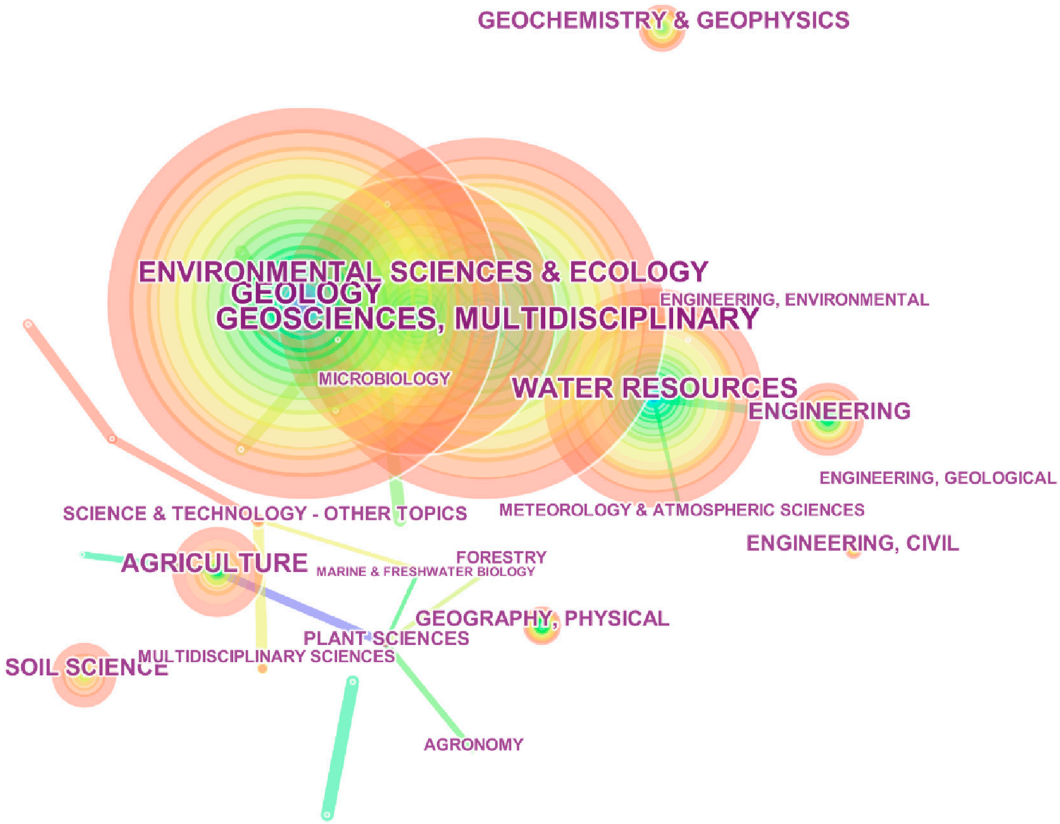

FIGURE 2
Top 20 co–occurring subject categories during 2001–2019.

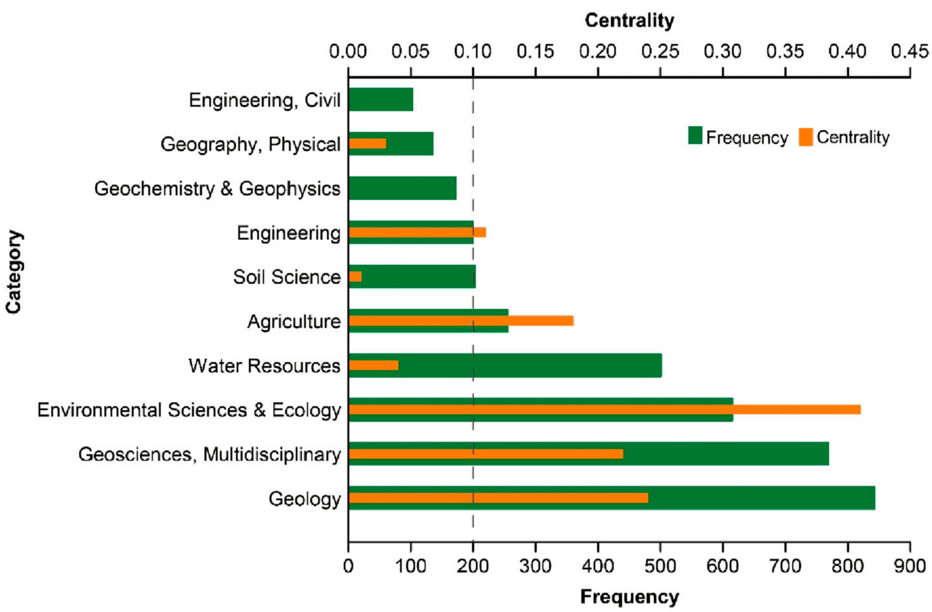

FIGURE 3
Top 10 most frequently appearing subjects with frequency and centrality.

TABLE 1 Top 6 subject categories with the strongest frequency bursts.

Subject Categories	Strength	Begin	End	2001–2019
Engineering, Environmental	4.20	2005	2008	
Chemistry	4.38	2007	2013	
Meteorology & Atmospheric Sciences	6.23	2010	2013	
Multidisciplinary Sciences	6.23	2016	2017	
Science & Technology – Other Topics	5.07	2016	2019	
Microbiology	5.17	2017	2019	

co-occurrence frequency of the top 50% of the disciplines, and analyzed their developmental characteristics.

Betweenness centrality is the ratio of the shortest path that passes through a point in the network and connects the two nodes to the total number of shortest path lines between the two nodes. If centrality is >0.1, the node is a critical node in the network. Our results revealed the importance of disciplines related to karst soil science: (i) The largest node, and thus the most popular discipline category, was "geology" (Figure 2) with a frequency of 843, followed by "geosciences," "multidisciplinary" (769), "environmental sciences and ecology" (615), and "water resources" (501), indicating that the most popular disciplines in this field include earth sciences, environment, and ecology. (ii) Among the ten most frequent disciplinary categories, "environmental sciences and ecology" had the highest betweenness centrality, meaning that this category played an important pivotal role in karst soil research and was an important link between the different disciplines in the field, followed by "geology," "geosciences," "multidisciplinary, agriculture," and "engineering" (Figure 3). The five disciplines (environmental sciences and ecology, geology, geosciences, multidisciplinary, and agriculture) with betweenness centralities >0.1 played key mediating roles in the network structure of the research field.

CiteSpace can detect research subjects with high rates of change from a larger number of disciplinary categories based on the frequency of disciplinary co-occurrence over a given period of time; the detected high rate subjects are called emergent subjects. Emergent subjects reflect the increase in co-occurrence over a certain period of time; the greater the emergence, the faster the increase in frequency, indicating that it is a popular emerging subject in that time period. From Table 1, it can be seen that there are six highly emergent subjects. "Environmental engineering" was the earliest emergent subject in the field of karst soil studies and continued from the initial stage of the research field to the developmental stage. "Chemistry" and "meteorology and atmospheric sciences" were the two emergent subjects in the developmental stage and "chemistry" continued to receive constant interest throughout the developmental stage. The rapid developmental phase saw the emergence of three new popular subjects, "multidisciplinary sciences," "science and technology - other topics" and "microbiology," among which multidisciplinary sciences had a relatively short duration. "Science and technology - other topics" and "microbiology" were the most popular emergent subjects at the end of the study period.

3.2 Intellectual base recognition

3.2.1 References co-citation network

To understand representative literature clustering, we constructed a literature co-citation network containing 68,295 articles between 2001 and 2019; these 68,295 papers were the papers cited in the 1913 documents mentioned above. In the generated network, the modularity Q value reached 0.8449. It is generally accepted that a Q > 0.3 implies a significant clustering structure (Yang et al., 2019) and a Q > 0.5, indicates that the cluster is of high quality. Therefore, we conclude that the clustering effect is significant. However, the mean silhouette, with a value of 0.2328,

TABLE 2 Top 10 co–citation clusters based on frequency.

Cluster ID	Size	Silhouette	Mean cited year	Label (LLR)
0	115	0.763	2013	small karst catchment
1	112	0.845	2010	Czech Republic
2	104	0.76	2003	hydrological uncertainties
3	90	0.831	2011	hydrological control
4	81	0.938	2013	Southwest China
5	69	0.917	2012	rocky desertification control
6	61	0.948	2010	recharge processes
7	59	0.964	2010	diurnal hydrochemical variation
8	42	0.998	2003	underlying dolomite
9	40	0.909	2005	northern Yucatan

Note: LLR, extraction algorithm of cluster labels based on log–likelihood rate.

FIGURE 4
Cluster visualization based on the document co–citation network.

was relatively low because there were many small clusters. The 10 main clusters that we were interested in all had silhouettes greater than 0.5 and had significantly higher cluster values (Table 2).

As shown in Figure 4, there were 10 key co-cited clusters in the network that were labeled with index entries; the details of the 10 clusters are summarized in Table 2. Clustering at the initial stage of the karst soil study included: #2, marked as hydrological uncertainties; #8, underlying dolomite; and #9, northern Yucatan. Clustering at the developmental stages included #1, labeled as Czech Republic; #6, recharge processes; #7, diurnal hydrochemical variation; #3, hydrological control; #5, rocky desertification control; #0, small karst catchment; and #4, Southwest China.

Cluster #2 in the initial stage had 104 members and a silhouette value of 0.76. This cluster was labeled "hydrological uncertainties." By analyzing the literature cited in this cluster, we found that the cluster focused on the response of karst cave drip information to the surface environment (Ihlenfeld et al., 2003; Arbel et al., 2010; Bradley et al., 2010). The most cited paper in this cluster was "Hydrological uncertainties in the modeling of cave drip-water delta O-18 and the implications for stalagmite paleoclimate reconstructions." Cluster #8 had 42 members and a silhouette value of 0.998. This cluster was labeled "underlying dolomite" and focused on the elemental geochemical characteristics of the weathering profiles of karstic dolomite (Ji et al., 2004; Feng, 2010; Solleiro-Rebolledo et al., 2011). The most cited paper in this cluster was "Geochemistry of red residual underlying dolomites in karst terrains of the Yunnan-Guizhou Plateau I. Formation of the Pingba profile". Cluster #9 had 40 members and a silhouette value of 0.909. It was labeled "northern Yukata" and focused on the study of water seepage processes in the karst region (Arbel et al., 2010; Lange et al., 2010; Li et al., 2011). The most cited paper in this cluster was "Infiltration processes and flow rates in developed karst vadose zones using tracers in cave drips."

Cluster #1 in the developmental stage had 112 members and a silhouette value of 0.845. It was labeled "the Czech Republic" and focused on the response of karst cave CO_2 concentration and soil CO_2 concentration to seasonal changes (Cuezva et al., 2011; Noronha et al., 2015; Lang et al., 2017). The most cited paper in this cluster was "Radiocarbon evidence for decomposition of aged organic matter in the vadose zone as the main source of speleothem carbon" Cluster #6 had 61 members and a silhouette value of 0.948. This cluster was mainly concerned with the evaluation methods of karst groundwater recharge, the spatial and temporal distribution patterns of groundwater recharge, and the processes and mechanisms of groundwater recharge (Allocca et al., 2015; Fiorillo et al., 2015; Hartmann et al., 2015). The most cited study in this cluster was "A large-scale simulation model to assess karstic groundwater recharge over Europe and the Mediterranean." Cluster #7 had 59 members and a silhouette value of 0.964. This cluster was labeled "diurnal hydrochemical variation" and mainly dealt with changes in CO_2 concentrations in karst soils, karst springs, and soil water hydrochemistry and their relationship to karst action (Cao et al., 2012; Liu et al., 2015; Yang et al., 2015). The most cited study in this cluster was "Diurnal hydrochemical variations in a karst spring and two ponds, Maolan Karst Experimental Site, China: Biological pump effects." Cluster #3 had 90 members and a silhouette value of 0.831. It was labeled "hydrological control" and was mainly concerned with the geochemical characterization of stable isotopes in karst cave systems and their environmental significance (Riechelmann et al., 2012; Belli et al., 2013; Markowska et al., 2016). The most cited study in this cluster was "The magnesium isotope record of cave carbonate archives." In addition, cluster #3, entitled "Infiltration processes and flow rates in developed karst vadose zones using tracers in cave drips," had a betweenness centrality of 0.15 and played a pivotal role in the clustered network structure, effectively linking the clustering structure of the developmental stage to that of the initial stage (Arbel et al., 2010).

Cluster #5 had 69 members and a silhouette value of 0.917. It was labeled "rocky desertification control" and focused on the causes of karst rocky desertification and the governance of rocky desertification (Cerdà et al., 2016; Shoba and Ramakrishnan, 2016; Zhang J. Y. et al., 2016). The most cited study in this cluster was "The challenge and future of rocky desertification control in karst areas in Southwest China." Cluster #0 had 115 members and a silhouette value of 0.763. It was labeled "small karst catchment." This cluster focused on the saturated hydraulic conductivity of soil profiles in karst regions and the vertical distribution of Ks (Fu et al., 2015a; Fu et al., 2015b; Yang J. et al., 2016). The most cited study in this cluster was "Vertical distribution of soil saturated hydraulic conductivity and its influencing factors in a small karst catchment in Southwest China." Cluster #4 had 81 members and a silhouette value of 0.938. It was labeled "Southwest China" and was mainly concerned with the response of soil organic carbon and soil total nitrogen content dynamics to the return of forest to grass in the karst region of Southwest China (Wen et al., 2016; Wen et al., 2017; Yang L. et al., 2016; Li D. et al., 2017). The most cited study in this cluster was "Rapid recuperation of soil nitrogen following agricultural abandonment in a karst area in Southwest China."

3.2.2 Landmark references

Note that if two (or more) papers are simultaneously cited by one or more subsequent papers, the two papers constitute a co-citation relationship. Based on the literature co-citation analysis, the key literature in the relevant field can be easily identified. Based on co-citation network analysis, Table 3 summarizes the top ten highly cited studies in the field of karst soil science research. It is important to note that the references listed are not based on the most frequently cited literature in WOS, but on the most cited document among the 68,295 references obtained in the present study. Jiang et al. (2014), with 95 citations, was the most frequently cited study. This study provides a thorough review of rocky desertification studies in the southwestern karst area of China primarily focusing on the following three aspects: (a) environmental, social, and economic impacts; (b) causes of rocky desertification; and (c) rocky desertification control and ecosystem restoration (Jiang et al., 2014).

References with citation bursts reflect the growth in the frequency of citations to the literature over a given period; the greater the prominence, the faster the growth in the frequency of citations (Yang et al., 2019). As shown in Table 3, three of the 10 most frequently cited studies exhibited references with citation bursts. Ford and Williams (2007), a leading literature on karst studies that has served as an essential reference in the field, had a burst value of 13.96 (Ford and Williams, 2007).

Spötl et al. (2005) reported a burst value of 13.33. This article illustrates the role of changing air flow on the hydrochemistry of drip water based on a unique data set of the stable C isotopes of water caves and soil air in conjunction with standard water chemistry. The study revealed the annual variation in cave environments that deposit speleothems (Spötl et al., 2005). Williams (2008) reported a burst value of 5.76. The goal of this

TABLE 3 Top 10 cited references based on frequency.

Citation Counts	Bursts	Author	Title	Source	Year	Cluster ID
95		Jiang, Z.C. et al	Rocky desertification in Southwest China: Impacts, causes, and restoration	Earth–Science Reviews	2014	4
59	13.96	Ford, D.C. et al	Karst hydrogeology and geomorphology	Karst Hydrogeology and Geomorphology. 2nd Edition, Wiley	2007	6
55		Peng, T. et al	Effects of land use, land cover and rainfall regimes on the surface runoff and soil loss on karst slopes in southwest China	Catena	2012	6
47		Hartmann, A. et al	Karst water resources in a changing world: Review of hydrological modeling approaches	Reviews of Geophysics	2014	4
33		Zhang, W. et al	Changes in nitrogen and phosphorus limitation during secondary succession in a karst region in southwest China	Plant and Soil	2015	4
32	13.33	Spotl, C. et al	Cave air control on dripwater geochemistry, Obir Caves (Austria): Implications for speleothem deposition in dynamically ventilated caves	Geochimica et Cosmochimica Acta	2005	6
32	5.76	Williams, P.W. et al	The role of the epikarst in karst and cave hydrogeology: a review	International Journal of Speleology	2008	7
32		Chen, H S. et al	Spatial distribution of rock fragments on steep hillslopes in karst region of northwest Guangxi, China	Catena	2011	6
31		Frisia, S. et al	Carbon mass–balance modelling and carbon isotope exchange processes in dynamic caves	Geochimica et Cosmochimica Acta	2011	4
31		Gutierrez, F. et al	A review on natural and human–induced geohazards and impacts in karst	Earth–Science Reviews	2014	4

study was to provide a detailed review of the role of epikarsts in karst and cave hydrogeology from the following two aspects: (a) the form and function of the epikarst, and (b) storage, mixing, and transmission in the epikarst. The study emphasized the considerable importance of the epikarst aquifers in karst hydrogeology (Williams, 2008).

3.3 Research hotspots and development directions

3.3.1 Keyword clustering analysis

Keywords are the essence of a paper and are indicative of research hotspots within a subject area (Liu et al., 2011). Therefore, the keyword cluster metric can be used to summarize the research hotspots in the literature. The keyword-clustering map, created using CiteSpace, provides a good reflection of the correlation between keywords. The keyword cluster analysis of the literature produced seven clusters in the knowledge map (Figure 5). The modularity Q of the keyword clustering mapping was 0.3566, indicating a significant clustering structure; additionally, the mean silhouette was 0.5716, indicating reasonable clustering, and all clusters had silhouette values greater than 0.5, indicating a high quality of cluster grouping (Table 4).

The largest cluster (#0) had 125 members and a silhouette value of 0.728. It was labeled “karst ecosystem” and focused on the effects of rainfall on the karst groundwater system, the effects of tropical storms on forest litter within a karst region, the response of tree root growth to limestone bedrock, and the dissolution of karst features (Adame et al., 2013; Estrada-Medina et al., 2013; Yang et al., 2013). The second largest cluster (#1) had 97 members and a silhouette value of 0.684. It was labeled “soil erosion” and was mainly concerned with hydrological and soil erosion models for karst systems (Li et al., 2011; Coustau et al., 2012; López-Vicente et al., 2013). The third largest cluster (#2) had 95 members and a silhouette value of 0.706. It was labeled “subtropical stormwater infiltration basin” and focused on the effects of temperature and CO_2 content on cave ventilation (Sánchez-Cañete et al., 2013) and the effects of hydroclimatic conditions and soil moisture variations on nitrogen fate and transport in a humid, subtropical climate (Schwarz et al., 2011; O’Reilly et al., 2012). The fourth largest cluster (#3) had 92 members and a silhouette value of 0.724. It was labeled ‘Southwest China’ and focused on the responses of stalagmite stable isotope data and calcite fabrics to significant climate variability (Baker et al., 2013; Belli et al., 2013; Hori et al., 2013). The fifth largest cluster (#4) had 68 members and a silhouette value of 0.698. It was labeled “carbonate island” and was mainly concerned with the geochemistry of meteoric diagenesis in karst landscapes (Whitaker and Smart, 2007a; b; Cabadas-Báez et al., 2010). The sixth largest cluster (#5) had 55 members and a silhouette value of 0.778. It was labeled “Southwest China” and focused on the principal processes underlying the geochemical evolution of groundwater in carboniferous carbonate aquifers in a karst ecosystem in Southwest China (Han et al., 2009; Li et al., 2010; Yang et al., 2010). The seventh largest cluster (#6) had 36 members and a silhouette value of 0.826. It was labeled “karst cave sample” and

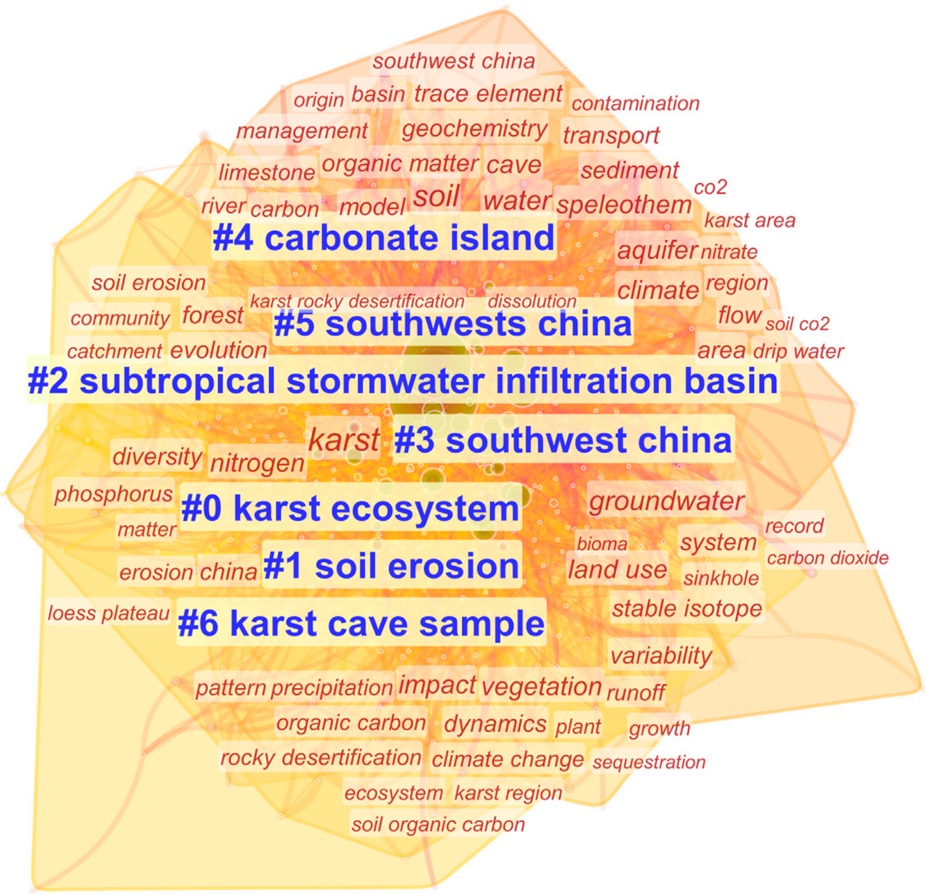

FIGURE 5
Keyword–clustering knowledge map of documents.

TABLE 4 Top 10 keyword clusters based on frequency.

Cluster ID	Size	Silhouette	Mean cited year	Label (LLR)
0	125	0.728	2011	karst ecosystem
1	97	0.684	2011	soil erosion
2	95	0.706	2008	subtropical stormwater infiltration basin
3	92	0.724	2008	Southwest China
4	68	0.698	2007	carbonate island
5	55	0.778	2010	Southwest China
6	36	0.826	2011	karst cave sample

was mainly concerned with the taxonomic status of the novel actinobacterial strain isolated from a soil sample collected from a karst cave (Fang et al., 2017a; b; Li Q. Q. et al., 2017).

3.3.2 Keyword bursts analysis

Keywords with bursts refer to keywords that increase sharply in frequency (Huang et al., 2020). Table 5 lists the keywords with high emergence at different times and presents the research themes and their variations in the field of karst soil studies. Table 5 shows the time when each keyword first appeared and its duration, which reflects the longevity of the impact of a keyword in the research field. In addition, it should be noted that the table indicates the entire study period (2001–2019) in blue and the duration of the reference burst in red (Qiu and Liu, 2018). Moreover, to more accurately explore the research theme of karst soil science and grasp its development patterns from 2001 to 2019, we divided the research process into three stages based on the annual distribution of the number of articles published: the initial stage (2001–2006), the development stage (2007–2013), and the rapid development stage (2014–2019).

TABLE 5 Keywords with the strongest bursts in different periods.

Period	Keywords	Strength	Begin	End	2001–2019
2001–2006	sinkhole	2.42	2001	2003	
	groundwater	2.16	2001	2002	
	cave	2.51	2001	2002	
2007–2013	paleoclimate	2.21	2007	2008	
	groundwater	2.10	2007	2008	
	model	2.53	2007	2009	
	biodiversity	2.57	2007	2008	
	16s ribosomal rna	2.92	2008	2009	
	bacteria	3.60	2009	2010	
	pollution	2.20	2009	2011	
	fractionation	2.43	2011	2013	
	respiration	2.54	2011	2013	
2014–2019	dilution	2.04	2014	2015	
	oxygen	3.26	2014	2015	
	vulnerability	3.04	2014	2016	
	origin	1.96	2014	2015	
	terrestrial	2.45	2014	2015	
	litter	2.04	2014	2015	
	zone	3.67	2014	2015	
	karst aquifer	4.70	2015	2016	
	abundance	2.43	2015	2016	
	fluxes	2.60	2015	2017	
	ecology	2.84	2015	2016	
	surface water	2.84	2015	2016	
	groundwater recharge	4.24	2015	2016	
	fractionation	2.87	2015	2017	
	rate	2.37	2016	2017	
	accumulation	3.75	2016	2017	
	Guizhou Province	2.70	2016	2019	
	yield	2.37	2016	2017	
	carbon dioxide	3.06	2016	2017	
	land	2.56	2016	2017	
	stock	2.92	2016	2019	
	mechanism	2.47	2016	2019	
	GIS	3.06	2016	2017	
	Southwest China	2.17	2016	2017	
	rainforest	2.37	2016	2017	
	karst cave	2.55	2017	2019	
	slope	2.41	2017	2019	
	decomposition	2.66	2017	2019	
	tolerance	3.04	2017	2019	
	karst region	3.00	2017	2019	

Three bursts of keywords appeared in the initial stage (2001–2006), indicating a low number of research topics. The bursts of the keywords “cave,” “sinkhole,” and “groundwater” indicating that the focus on karst studies was on groundwater in karst cave systems.

The development stage (2007–2013) had more keyword bursts than the initial stage, with nine bursts, indicating an increase in research topics. The burst of the keyword “paleoclimate” indicated that paleoclimate studies based on mineralogical characterization of karst basin profile sediments and carbon and oxygen stable isotope determination of karst cave stalagmites were research hotspots during this period. The burst of the keyword “groundwater” indicated that karst groundwater research remained a research hotspot. “Groundwater” was often combined with the keyword “pollution”, which also burst, to make the specific research topic of karst groundwater pollution research. The bursts of the “16S ribosomal RNA” and “bacteria” indicated that the structure and function of bacterial communities in karst caves based on 16S rRNA high-throughput sequencing technology was a research hotspot. The burst of the keyword “model” indicated that simulation studies using mathematical models, such as hydrology models, soil erosion models, and rainfall-runoff models in karst regions entered into the research studies. The burst keyword “biodiversity” indicates that biodiversity research was a focus of karst area research. The emergence of “fractionation” indicates that karst research began to consider isotope fractionation during the decomposition of soil organic matter and rare earth element fractionation during the weathering of dolomite. The burst of the keyword “respiration” indicates that soil respiration became an important issue in research on karst pedology.

The rapid development stage (2014–2019) had 30 keyword bursts, indicating that the research topic showed an explosive increase and included more in-depth research. The emergence of the keywords “dilution” and “groundwater recharge” indicates that karst research began to look at the variations in hydrochemistry in karst dynamic systems by the dilution effect and the movement characteristics of karst groundwater. Furthermore, the burst of “fluxes” and “karst aquifer” indicates that research during this period focused on the assessment of groundwater fluxes in karst aquifers. The keyword “oxygen” suggested that the hydrogen and oxygen isotopic characteristics of karst groundwater systems were also a research focus. The keywords above indicate hydrology and hydrogeology were major topics in karst regions. The keyword “origin,” which burst during this period, represents a new research focus on the origin of karst rock desertification. The keywords “vulnerability” and “ecology” were related to the research on assessing the vulnerability of karst ecosystems. The keyword “terrestrial” suggests that research on karst terrestrial ecosystems was popular. The burst of the keyword “abundance” indicated that studies related to soil microbial abundance, species abundance, and plant species abundance emerged as active topics. The emergence of the keyword “litter” showed that the stoichiometric characteristics of plants, litter, and soils in karst forest ecosystems were the focus of studies. In addition, the keyword “decomposition” indicates that litter decomposition studies were also a research focus. The keyword “land” indicated that studies focusing on land use and land cover change were popular. The emergence of the keyword “carbon dioxide” suggested that studies related to soil CO_2 concentration, karst cave CO_2 concentration, surface CO_2 fluxes, soil CO_2 emissions, and the karst carbon cycle were the focus of research. Furthermore, the keyword “stock” indicated that the soil carbon stock was a research focus. The keyword “rate” was related to research on carbon sequestration rates, soil erosion rates, litter decomposition rates, denudation rates, and bedrock exposure rates. The burst of the keyword “yield” was used for studies on the characteristics of runoff and sediment yield in karst areas. The keyword “accumulation” indicated that the research focused on the element accumulation characteristics of plants and the accumulation of heavy metals in soil. The burst of the keyword “mechanism” was related to the study of the formation mechanism of karst rocky desertification. The keyword “tolerance” indicated that soil loss tolerance and plant drought tolerance were the research focuses. The bursts of the keywords “surface water” and “slope” were related to the study of surface runoff and soil loss on karst slopes. The keyword “rainforest” indicated that the biodiversity in tropical karst seasonal rainforests was a research focus. The bursts of the keywords “karst cave” and “oxygen” indicated that climatic interpretations of speleothem delta O-18 were the focus of research. The keyword “fractionation” indicated that the following two aspects were still research focuses: (a) isotope fractionation during the decomposition of soil organic matter; and (b) rare earth element fractionation during dolomite weathering The emergence of the keyword “GIS” suggested that studies in karst regions were increasingly using geographical information systems (GIS) technology. The bursts of the keywords “zone,” “Guizhou Province,” and “Southwest China” indicated that Southwest China, especially Guizhou Province, was a hotspot of karst pedology research.

3.3.3 Future challenges

As the keywords with the strongest bursts, “stock,” “mechanism,” “karst cave,” “slope,” “decomposition,” “tolerance,” “Guizhou Province,” and “karst region” were still research hotspots in the domain of karst pedology in 2019 (Table 5). The bursts of these keywords indicate that research post-2019 may focus on the following areas: (a) soil carbon stock, (b) the formation mechanisms of karst rocky desertification, (c) the climatic interpretations of stable isotopes in karst caves, (d) studies of surface runoff and soil loss on karst slopes, (e) litter decomposition studies, and (f) soil loss tolerance and plant drought tolerance. They also indicate that Guizhou Province, China, will be a popular karst region for karst pedology research.

As the disciplines with the strongest frequency bursts, “science and technology–other topics” and “microbiology” were still emerging subjects in the field of karst pedology in 2019 (Table 1). It is worth mentioning that soil microbial communities drive many biogeochemical processes and play a critical role in maintaining terrestrial ecosystem functions and stability. Moreover, shifts in soil microbial communities can sensitively mirror environmental changes. Xue et al. (2020) found that land use intensity can alter bacterial diversity and bacterial interactions in karst soils. In addition, amendments to karst soils have been reported to alter the soil microbial community structure and improve the soil nutrient status (Zhou et al., 2019a; Zhou et al., 2019b, Zhou et al., 2019c). Therefore, we speculate that molecular ecology research on soil microorganisms is of great significance for the restoration of degraded karst soils. Currently, there is a paucity of reports on the effects of ecological restoration measures on soil microbial community composition and metagenomics in degraded karst soils. It is imperative to increase the amounts of field experiments and long-term observational studies, as well as to provide more scientific basis, in order to elucidate the mechanisms by which restoration measures influence the structure and function of soil microbial communities in the vulnerable karst environment.

Generally, the research field of karst pedology is developing and maturing and interdisciplinary research has had a profound impact. Additionally, the application of fundamental knowledge and new methods has been emphasized. However, the characteristics of the landforms vary in different karst regions. The geographical differences in research subjects has led to a lack of cooperation between different research powers (Shi et al., 2019). Cooperation between different research powers should be strengthened to promote further research in this domain. To provide a scientific basis for the sustainable development of karst regions, future studies should focus on the formation mechanisms and restoration measures of karst regions.

Besides, this research was performed by a systematic quantitative analysis of literature in the field of karst soil studies. To form a comprehensive understanding of the research field, we utilized CiteSpace to analyze the current research situation and trends from macro to micro and from whole to local. The visualization of large amounts of literature data through CiteSpace allows for an in-depth analysis of the potential knowledge context of literature and an exploration of hidden patterns among data (Chen, 2006). However, owing to the limitations of the information extraction and analysis algorithms, there was a small unavoidable bias in the CiteSpace results (Yang et al., 2019; Huang et al., 2020). In addition, we used literature from the WOS Core Collection as the subject of our study, and although the literature in this database was representative and critical, WOS does not provide all relevant literature and particularly omits literature from non-English speaking countries. In contrast to other databases, however, the WOS core collection is an extensive research database. The results of this study are based on an analysis of objective data that are virtually unaffected by subjective experience, thus providing stability and objectivity to the results of the study. Therefore, the results of this study are convincing and can represent hotspots and development directions in vulnerable karst soil environment.

4 Conclusion

The research domain concerning vulnerable karst soil environment has undergone stable, growth, and rapid growth phases from 2001 to 2019, encompassing disciplines such as geology, environmental sciences, and water resources. Environmental sciences have served as a pivotal bridge among these fields. Initial focal points were centered on environmental engineering. However, contemporary trends are increasingly oriented towards science and technology as well as microbiology. Significant intellectual foundations include hydrological processes, dolomite studies, rocky desertification control, and specific karst regions like Southwest China. Principal research hotspots involve karst ecosystems, soil erosion dynamics, and carbonate rock formations. Research topics have evolved from sinkholes and groundwater issues to paleoclimate studies, biodiversity assessments, pollution concerns, culminating in advanced subjects such as the vulnerability of karst regions, karst aquifers, and GIS applications. Over the span of 19 years, research themes have diversified significantly while deepening in complexity and garnering heightened attention.

Author contributions

TY: Data curation, Methodology, Software, Writing–original draft. JX: Conceptualization, Supervision, Writing–review and editing.

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Conflict of interest

Author JX was employed by Co-Innovation Center for Sustainable Forestry in Southern China.

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Publisher's note

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