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*Review*

# Study of Soil Nitrogen in Karst Rocky Desertification Areas: a Literature Review

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**Abstract**

Nitrogen, as a limited nutrient in Karst rocky desertification areas, is of great significance in terms of ecological restoration measures and social and economic development. Based on the China national knowledge infrastructure and the Web of Science Core Collection, the current literature on soil nitrogen in Karst rocky desertification areas was reviewed and organized, and CiteSpace, a reference analysis tool, was used to visually present and analyse this research. The countries, institutions, authors, keywords and research hotspots in this field were reviewed, and the current status and trends in the evolution of related research were summarized.

**Keywords**: soil nitrogen, Karst rocky desertification, CiteSpace

## Introduction

Rocky desertification refers to the process of land degradation resulting from disturbances and destruction caused by unreasonable human social and economic activities [1]. It has become a major global economic, social, ecological and environmental problem, threatening the sustainable development of human society [2].

Nitrogen is an important component of all living things and is the major nutrient limiting life on Earth. In 1840, Liebig J V put forward the theory of plant mineral nutrition. He believed that nitrogen is an essential element for plant growth. Laws established a laboratory in Lausanne to further demonstrate that the nitrogen used by plants mainly originates in the soil. Soil nitrogen supply capacity is also an important index for evaluating soil quality.

Land quality includes soil, water and biological properties related to human needs and environmental condition. With an increase in Karst rocky desertification, soil quality decreases along a power series, thus becoming the major factor limiting local economic, social development and restoration of vegetation [3]. With the current developments in research, increasing attention has also been given to soil nitrogen pollution in recent years. Soil nitrogen cycling may lead to increases in greenhouse gas emissions and water eutrophication and increase the health risks of local residents [4]. As a result, the soil nitrogen present in Karst rocky desertification areas has important impacts on land quality, ecological environment restoration and reconstruction, and human health. This review serves as an important reference for the control of rocky desertification, ecological restoration, and social and economic development of Karst areas.

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## Data and Methods

### Data

This study utilized the China national knowledge infrastructure as the research object for relevant Chinese literature. The search conditions for the first retrieval were set to [“topic = Karst" and "topic = nitrogen"], and ["topic = desertification" or "topic = soil" or "topic = land" or "topic = earth"] was set as the search conditions for the second retrieval using a time span of all years (as of December 31, 2021), and the document type was set to all types. Using these parameters, 247 studies were obtained.

This study also used the Web of Science Core Collection as the research object for relevant English literature. The search conditions were set to ["topic = Karst" and "topic = desertification" and "topic = soil" and "topic = nitrogen"] or ["topic = Karst" and "topic = desertification" and "topic = land" and "topic = nitrogen"] or ["topic = Karst" and "topic = desertification" and "topic = earth" and "topic = nitrogen"]; the time span was all years (as of December 31, 2021), and the document type was set to all types. Using these parameters, 77 studies were obtained.

### Methods

CiteSpace combines science development theory, science frontier theory, structural hole theory, burst detection technology, optimal information collection theory of science communication, and knowledge about discrete units and recombination theory to visualize the results of academic literature mining, yielding a ‘scientific knowledge map’. The map directly shows the location and size of each knowledge node in the knowledge structure network. By selecting different functions, it can analyse the regions, authors, hotspots and evolutions in the trends of academic literature.

This review used CiteSpace 6.1.R2 version to analyse the literature addressing the research on soil nitrogen in Karst rocky desertification areas, summarize the results of the current research, propose scientific issues that remain to be resolved, and finally discuss future research directions in the areas. In the ‘scientific knowledge map’, the coloured upper bar represents the time evolution from left to right, and the coloured node circle corresponds to the publication time. The node size represents the frequency of occurrence; the connection density between nodes represents the connection strength. A purple mark on the outer ring of nodes represents greater centrality, reflecting the importance of the literature. In burst analysis, the outer ring of some nodes is red, indicating emergence.

## Results

### Overview of Soil Nitrogen in Karst Rocky Desertification Areas

#### *Annual Distribution*

The publication of relevant literature is increasing, and the research is relatively novel. As shown in Fig. 1, the trends in the annual distribution can be roughly divided into three stages. The first stage was from 2003 to 2007, with relatively few Chinese and English studies. The total number of studies per year did not exceed 5, indicating that this stage was an embryonic one. Between the rapid but fluctuating growth over the period from 2008-2015, more than 10 articles were published per year. After 2016, the number of publications exceeded 20 each year, and publication peaked in 2021. Moreover, the trends in Chinese literature, English literature and total literature were essentially the same, but the number of the Chinese studies was significantly greater than the number of English studies.

In the 21$^{st}$ century, the research on Karst rocky desertification has been increasing gradually, and it is concentrated in China. This annual distribution is clearly consistent with the introduction of related policies by the Chinese government. In 2004-2005, the China State Forestry Administration carried out

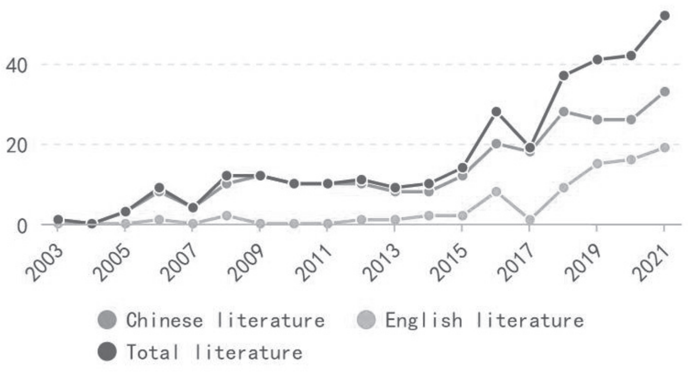


Fig. 1. Annual distribution of the literature.

the first monitoring studies of Karst areas. In 2007, the State Council of China approved the 'Outline of the National Plan for the Comprehensive Control of Rocky Desertification in Karst Areas' and decided to launch a three-year pilot project for the comprehensive control of rocky desertification in 100 counties in eight provinces, autonomous regions and municipalities directly governed by the central government, which was expanded to 200 counties in 2011. In 2016, the Ministry of Science and Technology of China launched the national key research and development programme 'Research on The Restoration and Protection of Typical Fragile Ecosystems', which supported four comprehensive technology projects for the treatment of rocky desertification areas that included Karst peak-cluster depressions, Karst plateaus, Karst faulted basins and Karst trough valley areas, which greatly promoted the development of research on Karst rocky desertification.

*Country- and Institution-Based Distributions*

The distribution based on countries is illustrated in Fig. 2. Many countries have published related literature and the countries that formed the key nodes included China, Germany, Japan, Ireland, England, and Spain. The country with the largest number of publications was China, indicating it holds an important position in this field of research. The analysis of the layers of the node colour circles showed that the earliest countries to conduct research were China and the USA, and the most active countries publishing recent research were China, Germany, England and Ireland. Through node connection density analysis, it was found that China has close cooperation with other countries, with Japan, Panama and Sri Lanka having the closest cooperation.

The distribution by institutions is shown in Fig. 3. Guizhou Normal University, Guizhou University, Zunyi Normal University and the Chinese Academy of Sciences published the greatest volume of Chinese

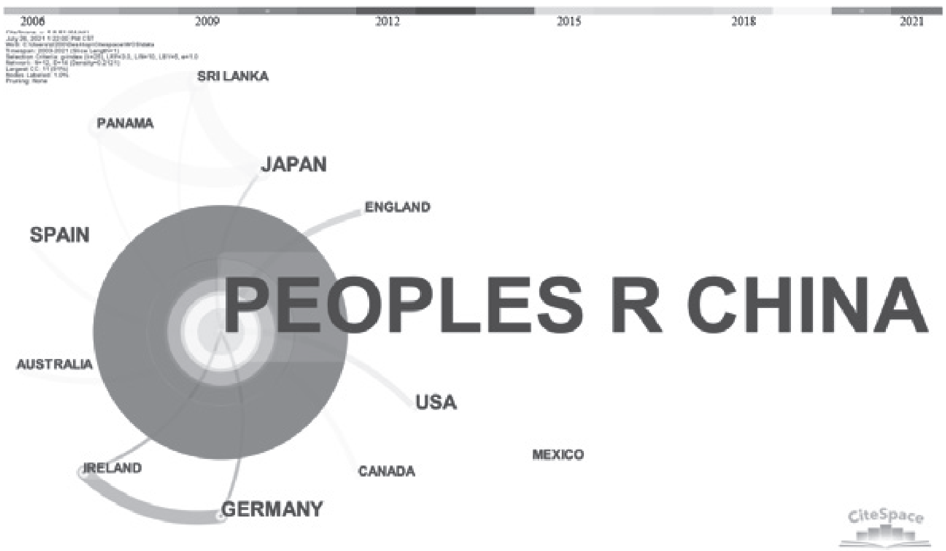


Fig. 2. Country-based distribution of the literature.

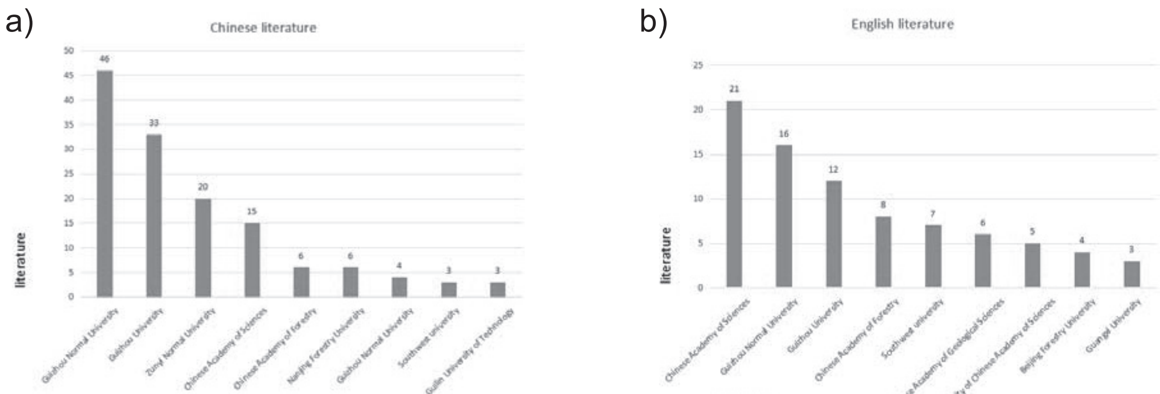


Fig. 3. Institution-based distribution of the literature: a) Institution-based distribution of Chinese literature; b) Institution-based distribution of English literature.

literature, accounting for more than 50% of the total literature. The Chinese Academy of Sciences, Guizhou Normal University and Guizhou University published the greatest volume of English literature, accounting for more than 70% of the total literature.

The Karst areas of South China, representative of East Asia, are the core areas for rocky desertification research [5-6]. The fragile Karst environment is burdened with overpopulation and disturbances caused by intense human activities, leading to severe rocky desertification in this region [7-10]. Therefore, the challenges associated with the rocky desertification of the Karst areas of South China are the most pronounced in the world, and there is clearly a need for developing more practical rocky desertification control measures. Chinese institutions showed the most extensive volume of research on the topic of soil nitrogen in Karst rocky desertification areas, and their research findings and advancements were the most prolific.

### *Author- and Literature-Based Distribution*

The results from the citation frequency analysis of the Chinese literature are shown in Table 1. The paper 'Changes of soil quality in the process of Karst rocky desertification and evaluation of impact on ecological environment' published by Liu F. and Wang S.J. et al. in Acta Ecologica Sinica in 2005 was cited the greatest number of times, 278 times. Through a vegetation survey and soil sampling analysis in the Karst areas of central Guizhou, the paper discussed the soil quality changes and their impacts on the ecological environment during the process of rocky desertification [11].

The results from the high cocitation frequency analysis of the English literature are shown in Table 2 and Fig. 4. The paper 'Rocky desertification in Southwest China: Impacts, causes, and restoration' published by Jiang Z.C. et al. in Earth-Science Reviews in 2014 was co-cited the greatest number of times, 15 times, and its centricity was also the greatest. Based on decades of research on the Karst areas of Southwest China, Europe and other parts of the world, this paper reviewed the impacts, causes and recovery measures for rocky desertification [12]. It is worth noting that although the cocitation frequency of Zhang W's paper 'Changes in nitrogen and phosphorus limitation during secondary succession' published in Plant Soil in 2015 was low, it showed a higher centrality. The node was purple in the literature cocitation network. This article mainly studied how N limitation and P limitation change from the early to the late stages of secondary succession following farmland abandonment in the Karst ecosystems of Southwest China [13].

## Topics and Hotspots for Research in the Area of Soil Nitrogen in Karst Rocky Desertification Areas

The keyword co-occurrence analysis based on the Chinese literature using CiteSpace is shown in Table 3, and a total of 308 nodes and 712 connections were generated. As shown in Table 3, the frequency of literature found using the keywords Karst rocky desertification as the basis for literature retrieval was much higher than that of other keywords, up to 111 times. Karst, soil nutrients, soil physical and chemical properties, and Karst slope ranked second to fourth, with frequencies of 93, 50, 38 and 21, respectively.

For the frequency rankings of the top 20 keywords, Karst, Karst slope and Karst mountain were keywords indicating major study areas. Based on the institution-based analysis, author-based analysis and literature-based analysis, it can be concluded that Guizhou, as a core area of the Karst region in Southwest China, was a key area for soil nitrogen research related to Karst rocky desertification. In addition, calcareous soils and shallow Karst fissures were the main objects of this field of study, and soil physical and chemical properties, soil nutrients, soil environment, soil quality, land use, vegetation restoration and soil fertility were the main directions of study. The characteristics of soil and vegetation are important bases for the identification of rocky desertification in Karst areas. Along with the occurrence of rocky desertification, the soil and vegetation of these regions also change significantly,

Table 1. Chinese literature with high citation frequencies (top 5).

| The first author | Document title | Year | Citation frequency |
|---|---|---|---|
| Liu F. | Changes of soil quality in the process of Karst rocky desertification and evaluation of impact on ecological environment | 2005 | 278 |
| Sheng M.Y. | Plant diversity and soil physical-chemical properties in Karst rocky desertification ecosystem of Guizhou, China | 2015 | 208 |
| Sheng M.Y. | Response of soil physical-chemical properties to rocky desertification succession in South China Karst | 2013 | 155 |
| Yue Y.M. | Relationships between soil and environment in peak-cluster depression areas of Karst region based on canonical correspondence analysis | 2008 | 95 |
| Long J. | Relationships between soil and rocky desertification in typical Karst mountain area based on redundancy analysis | 2012 | 58 |

Table 2. English literature with high citation frequencies (top 5).

| The first author | Document title | Year | Citation frequency |
|---|---|---|---|
| Jiang Z.C. | Rocky desertification in Southwest China: Impacts, causes, and restoration | 2014 | 15 |
| Dail Q.H. | Runoff and erosion processes on bare slopes in the Karst rocky desertification area | 2017 | 10 |
| Xie L.W. | Evaluation of soil fertility in the succession of Karst rocky desertification using principal component analysis | 2015 | 7 |
| Yan X. | Multiscale anthropogenic driving forces of Karst rocky desertification in Southwest China | 2015 | 7 |
| Zhang W. | Changes in nitrogen and phosphorus limitation during secondary succession in a Karst region in Southwest China | 2015 | 6 |

Table 3. Keyword co-occurrence analysis of Chinese literature (top 20).

| Serial number | Keyword | Frequency | Serial number | Keyword | Frequency |
|---|---|---|---|---|---|
| 1 | Karst rocky desertification | 111 | 11 | Soil quality | 14 |
| 2 | Karst | 93 | 12 | Soil organic carbon | 13 |
| 3 | Soil nutrients | 50 | 13 | Shallow Karst fissure | 12 |
| 4 | Soil physical and chemical properties | 38 | 14 | Land use | 10 |
| 5 | Karst slopes | 21 | 15 | Biological crust | 9 |
| 6 | Aggregate | 20 | 16 | Vegetation restoration | 8 |
| 7 | Soil environment | 20 | 17 | Soil fertility | 8 |
| 8 | Calcareous soil | 19 | 18 | Variation characteristics | 4 |
| 9 | Soil microorganism | 19 | 19 | Karst mountain | 4 |
| 10 | Fruit production | 15 | 20 | Karst ecosystem | 4 |

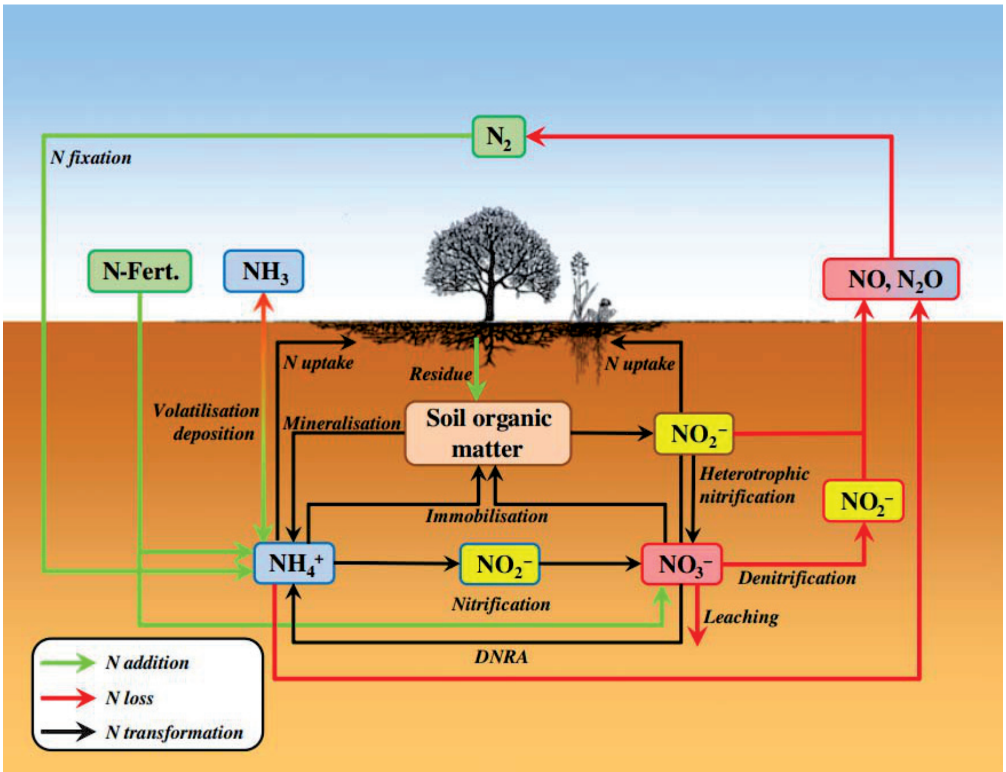


Fig. 4. The nitrogen cycle and its main processes [14].

Table 4. Keyword co-occurrence analysis of English literature (top 20).

| Serial number | Keyword | Frequency | Serial number | Keyword | Frequency |
|---|---|---|---|---|---|
| 1 | Karst rocky desertification | 28 | 11 | Matter | 7 |
| 2 | Nitrogen | 24 | 12 | Impact | 7 |
| 3 | Area | 23 | 13 | Biome | 6 |
| 4 | Karst | 13 | 14 | Plant | 6 |
| 5 | Land use | 10 | 15 | Pattern | 6 |
| 6 | Organic carbon | 10 | 16 | Microbial biome | 5 |
| 7 | Diversity | 9 | 17 | Dynamics | 5 |
| 8 | Carbon | 9 | 18 | Organic matter | 5 |
| 9 | Vegetation restoration | 9 | 19 | Erosion | 5 |
| 10 | China | 8 | 20 | Phosphorus | 5 |

which was also the focus of research on Karst rocky desertification. At the same time, soil nitrogen, as an environmental factor influencing Karst ecosystems, was related to aggregates, soil microorganisms, soil organic carbon and biological crusts. These were also important topics in the academic research.

The keyword co-occurrence analysis based on the English literature using CiteSpace is shown in Table 4, and a total of 203 nodes and 769 connections were generated. As shown in Table 4, the results were the same as those of the Chinese literature keyword co-occurrence analysis. Using Karst rocky desertification as the basis for literature retrieval achieved a frequency much higher than that of other keywords, up to 28 times. Nitrogen, area, Karst, and land use ranked second to fourth, and the frequencies were 24, 23, 13 and 10, respectively. Compared with the results of the keyword co-occurrence analysis in the Chinese literature, the repeated or highly similar keywords were Karst rocky desertification, land use, Karst, organic carbon, vegetation restoration, biome, microbial biome, organic matter and so on. This shows that these research directions have also received the attention of international academic circles.

For the frequency rankings of the top 20 keywords, area, Karst and China were keywords indicating the major study areas. These results showed that China was once again an important area for soil nitrogen research in Karst rocky desertification areas. In addition, several keywords revealed the main content of this field. The keyword ‘area’ was ranked No. 3 and can be used to represent the scope of influence of rocky desertification in Karst areas, and pattern was also a keyword indicating the evolution patterns of rocky desertification. Land use, as a comprehensive representation of human activities, has a profound impact on the forward and reverse succession processes of rocky desertification. Therefore, land use has also received much attention, ranking 5$^{th}$ in frequency. Vegetation restoration was still an important research area; however, compared with the Chinese literature, there were more keywords involving ecological and environmental elements. Nitrogen ranked second, and organic carbon, carbon, matter, biomass, plants, microbial biomass, organic matter and phosphorus occupied the 6$^{th}$, 8th, 11$^{th}$, 13$^{th}$, 14$^{th}$, 16$^{th}$, 18$^{th}$ and 20$^{th}$ places, respectively. Furthermore, the emergence of keywords such as impact and dynamics indicated that the international academic circles may have paid more attention to the microrelationships between ecological and environmental factors and the dynamic mechanisms of rocky desertification in the field of soil nitrogen research in Karst rocky desertification areas.

## Main Progress and Landmark Achievements

The research on soil nitrogen transport and transformation has a long history. Lohis first studied the law of nitrogen transport in 1913. Since then, researchers in various disciplines (such as soil, meteorology, geography, agriculture, water conservancy, environmental science) have carried out a great deal of research on the dynamics of nitrogen transport and transformation in soils from different perspectives and obtained a series results.

The soil nitrogen cycle refers to the process of nitrogen entering a soil ecosystem from different sources and then leaving the soil in different forms after a series of processes involving transport and transformation. As shown in Figure 4, the soil nitrogen cycle includes inputs, transformations, outputs and accumulation.

The dynamic trends in soil nitrogen transport and transformation are challenging issues that are of substantial interest to researchers. At present, some progress has been made on elucidating the soil nitrogen transport and transformation mechanisms.

### *Soil Nitrogen Input and Biological Fixation*

In Karst rocky desertification areas, the main sources of soil nitrogen inputs are as follows: atmospheric nitrogen deposition, fertilization, animal residues and litter, and biological nitrogen fixation.

The increase in atmospheric nitrogen deposition is one of the most important characteristics of global change, and it is an important index that reflects the changes in atmospheric environmental quality. Atmospheric nitrogen deposition has an important impact on global food production, the carbon and nitrogen cycles and environmental quality. In recent years, the trends in atmospheric nitrogen deposition (dry deposition and wet deposition) in China, which is a core area for the soil nitrogen research in Karst rocky desertification areas, has shown the following characteristics: (1) Nitrate nitrogen ($NO_3^-$) deposition has continued to increase, but the wet deposition of ammonia nitrogen ($NH_4^+$) has significantly decreased, with the result that the previously rapid growth in the national total nitrogen deposition has now reached a stable state; (2) With the increase in dry atmospheric deposition, the ratio of dry and wet deposition has changed gradually from wet deposition to both wet and dry deposition; (3) With the decrease in the $NH_4^+/NO_3^-$ ratio, the contribution of nitrate nitrogen ($NO_3^-$) deposition continued to increase, while the contribution of ammonia nitrogen ($NH_4^+$) deposition decreased. In recent years, the nitrogen deposition mode previously dominated by ammonia nitrogen ($NH_4^+$) deposition has gradually shifted to a new mode dominated by nitrate nitrogen ($NO_3^-$) and ammonia nitrogen ($NH_4^+$) deposition [15]. Furthermore, Zeng J. studied the wet atmospheric nitrogen deposition occurring in Karst rocky desertification areas and found that the concentrations of the major nitrogen forms ($NO_3^-$ and $NH_4^+$) present in wet atmospheric deposition were high in the winter and spring seasons but low in the summer and autumn season and had a negative natural logarithmic relationship with the rainfall. The wet nitrogen deposition concentration showed distinct vertical differences due to air flow and due to organic matter released by plant growth [16].

Soil erosion is severe in Karst rocky desertification areas, and it often causes underground soil fertility. A direct application of fertilizer is one of the most effective ways to increase soil nitrogen contents and increase plant yield. The long-term application of nitrogen fertilizers can improve the nitrogen content of soil microbial biomass and improve soil fertility, especially when combined with organic fertilizers, which yields nitrogen contents in the soil microbial biomass that are higher than those achieved with inorganic fertilizers alone [17]. In addition, nitrogen fertilizers can significantly increase nitrogen activities within the 0-40 cm soil layer, which is more conducive to total soil organic carbon and nitrogen accumulation and can improve productivity [18]. The nitrogen contents of soils treated with compost increase more than those of soils treated with conventional nitrogen fertilizers or green manure; additionally, the microbial species populations are more diverse and the soil microbial activities and enzyme activities are strengthened [19]. Different fertilization methods can affect the variations in the gene abundances of functional microorganisms related to nitrogen cycle processes such as nitrification, denitrification, nitrogen fixation and nitrate dissimilatory reduction in soils and thereby affect the soil nitrogen cycle [20].

Under the action of soil microorganisms and a limited number of soil organisms, the protein from animal residues can be broken down to produce nitrogen. However, due to the small contribution of animal residues to the soil nitrogen input, there are few related studies. Litter is a product of plant metabolism; in addition to returning nitrogen to the soil, it plays a role in creating a protective film over the soil that reduces the erosion of the soil due to surface runoff, thus reducing the loss of nitrogen from the surface soil. In Karst rocky desertification areas, litter is the main source of soil nitrogen [21]. The quantity of litter and nutrient content shows distinct differences for different land uses, different vegetation covers and different seasons [22-24]. The nitrogen content of litter that has been affected by atmospheric nitrogen deposition or fertilizer application for a long time is consistently higher than that of undisturbed litter [25]. Different slope directions also have significant effects on the nitrogen content of litter, and the total nitrogen reserves of litter are as follows: shady slope>sunny slope>semishady slope [26]. The N:P ratio is an important factor that restricts the decomposition and nutrient cycling of litter. Litters with lower P contents have higher N and lignin contents (higher N:P values) and lower decomposition rates, and a lower N:P value allows litters to be more easily decomposed [27].

Biological nitrogen fixation refers to the process by which nitrogen-fixing microorganisms convert nitrogen in the atmosphere into ammonia by autogenous nitrogen fixation, symbiotic nitrogen fixation and combined nitrogen fixation [28]. The microorganisms capable of biological nitrogen fixation and their corresponding nitrogen fixation systems are summarized in Table 5. Lithology has a significant influence on the abundance and community compositions of nitrogen-fixing microorganisms in Karst rocky desertification areas [29]. A study found that the abundance of nitrogen-fixing bacteria in limestone soils was higher than that in dolomite soils. Lithology affects the composition of soil microbial communities mainly by influencing the composition of existing vegetation [30-31]. The higher the evenness index is, the more stable the composition of the nitrogen-fixing microbial community [32], and the more similar the vegetation community structure is, the more similar the nitrogen-fixing microbial community [33]. In addition, soil physical and chemical properties, such as pH, total nitrogen, total carbon,

Table 5. Three groups of nitrogen-fixing microorganisms.

| Biological nitrogen fixation types | | Types of nitrogen-fixing microorganisms |
|---|---|---|
| Free living nitrogen fixation microorganisms | Photoautotrophic | Anabaena, Green sulphur bacteria |
| | Chemoautotrophic | Leptospirillum ferrooxidans |
| | Heterotrophic aerobic | Azotobacter |
| | Heterotrophic facultative anaerobic | Klebsiella |
| | Heterotrophic anaerobic | Clostridium, methanogens |
| Symbiotic nitrogen fixation microorganisms | Rhizobium-legume symbiosis, Rhizobium-parasponia symbiosis, Frankia-dicotyledon (nonlegume) symbiosis, Diazotrophic cyanobacteria-plant symbiosis | |
| Associative nitrogen fixation microorganisms | Azospirillum, Azolobacter, *Pseudomonas* spp | |

total potassium, ratio of carbon to nitrogen, available phosphorus, available potassium and available calcium, have significant effects on the community composition of nitrogen-fixing microorganisms [33-36].

### *Succession of Rocky Desertification and Soil Nitrogen*

Zhang D.Q. et al. (2006) studied the characteristics of soil nitrogen migration during the different stages of succession during rocky desertification in Guizhou, China, and found that total nitrogen, total acid-hydrolysable nitrogen, amino acid nitrogen and alkaline hydrolysable nitrogen decreased with the succession of rocky desertification from mild to extreme intensities [37]. Tang F.F. et al. (2016) found that with soil degradation during the succession of rocky desertification in Hunan, China, total nitrogen and available nitrogen also showed a rapid downwards trends [38]. Li D.D. et al. (2018), Su T. et al. (2019) obtained similar conclusions when they studied soil fertility during the process of rocky desertification succession in the Karst areas [39-40]. Li X.L. et al. (2011) found that rocky desertification not only reduced the content of total soil nitrogen but also reduced the seasonal variations in soil total nitrogen [41]. However, Li R. et al. (2016), Sheng M.Y. et al. (2018) and Wang L.J. et al. (2021) came to different conclusions. They found that the total nitrogen and hydrolysed nitrogen do not decrease with the increase in the degree of rocky desertification but show a trend towards first declining and then increasing [42-43]. In fact, due to the differences in temperature, altitude, land use and vegetation types, soil nitrogen distribution may be different [44].

### *Vegetation Restoration and Soil Nitrogen*

Liang Y.M. et al. (2016) studied the soil characteristics of different vegetation restoration modes in the Karst rocky desertification areas of China, and found that the contents of total soil nitrogen, available nitrogen and alkaline hydrolysable nitrogen changed in a consistent way and increased with the vegetative restoration from herbs to trees [45]. Hu N. et al. (2015) and Lan J.C. et al. (2020) further found that the contents of total nitrogen, light group nitrogen, alkaline hydrolysable nitrogen and mineral nitrogen in soil aggregates increased during the process of vegetative restoration, and the contents increased with decreasing aggregate sizes. Nitrogen is preferentially accumulated in small aggregates, which plays an important role in the accumulation of soil nitrogen [46-47]. Lv W.Q. et al. (2016), Liu X. et al. (2019), Guan H.L. et al. (2020) and Li D.J. et al. (2021) studied different vegetative restoration measures in Karst rocky desertification areas, and their results showed that some vegetative restoration patterns have more significant effects on the total nitrogen and available nitrogen contents of the soils than other patterns [48-51].

### *Land Use Patterns and Soil Nitrogen*

Li S. et al. (2013), Wang M.M. et al. (2018) and Zhu M.M. et al. (2021) studied the relationships between land use patterns and land quality in the Karst rocky desertification areas of Guizhou and Guangxi, and they found that land use patterns can cause changes in total soil nitrogen, available nitrogen and alkaline hydrolysable nitrogen contents; in terms of changes, woodland is the highest, and farmland is the lowest [52-55]. The nitrogen contents decreased with increasing soil depths [56]. Yang D.L. et al. (2018) further showed that, for different land use situations, there is a significant positive correlation between the total nitrogen and the P:K ratio and a significant negative correlation between the total nitrogen and the C:N and C:P ratios and showed that total nitrogen has an inhibitory effect on the C:N and C:P ratios [57]. Zhao C. et al. (2021) claimed that for different land use types, the environmental factors affecting the available nitrogen are essentially the same. Available soil nitrogen is positively correlated with the content of organic carbon components, enzyme activities, surface electrochemical properties and amorphous oxides but negatively correlated with the soil silt and free metal oxide contents. The organic carbon in soil particles, total organic carbon and the specific surface area of soils are the key factors that affect the available soil nitrogen, and the organic carbon content of soil particles correlated well with the available soil nitrogen [58].

*Biological Crusts and Soil Nitrogen*

Zheng Z.H. et al. (2021) studied the effects of biological crusts on the soil physical and chemical properties during different stages of Karst rocky desertification succession and found that biological crusts can effectively promote the accumulation of soil nitrogen and have the greatest impact on surface soils; at greater soil depths, their influence gradually decreases. In addition, different types of biological crusts have different effects on soil nitrogen accumulation, and the contents of total nitrogen and available nitrogen in the subsurface soils of moss and mixed crusts are higher than those of lichen and algal crusts [59].

*Microhabitat and Soil Nitrogen*

Liu F. et al. (2008), Liao H.K. et al. (2013), Liu L. et al. (2015), Yu Y.H. et al. (2018) and Liu Y.Y. et al. (2020) studied the distributions of total nitrogen, available nitrogen and alkaline hydrolysable nitrogen on soil surfaces, stone surfaces, stone ditches, stone caves, stone cracks, stone troughs and stone pits under different vegetation conditions, such as arbor forests, shrub areas and grasslands, and the results showed significant correlations [60-64].

*Parent Rock and Soil Nitrogen*

Xiao S.Z. et al. (2020) studied the nutrient contents of soils that developed from limestone and dolomite in the Karst rocky desertification areas of Guizhou, and their results showed that the total nitrogen and alkaline hydrolysable nitrogen contents of the dolomite soils were higher than those of the dolomite soils. The total nitrogen contents of the limestone and dolomite soils were positively correlated with the alkaline hydrolysable nitrogen and organic carbon contents. The alkaline hydrolysable nitrogen and organic carbon contents were positively correlated with each other in the limestone soils and significantly positively correlated in the dolomite soils [65].

*Geographical Factors and Soil Nitrogen*

Yu Y.H. et al. (2018) studied the soils of a prickly ash forest at different elevations in the Karst rocky desertification areas of Guizhou, and their results demonstrated that the total nitrogen and available nitrogen contents of the soils at high and low elevations were significantly higher than those at mid-elevations [66]. Jin Z.L. et al. (2019) and Hu Q.J. et al. (2020) also conducted related studies and believed that the contents of total nitrogen and alkaline hydrolysable nitrogen in soils at different altitudes are significantly different [67-68]. Huang X. et al. (2017) and Jia H.J. et al. (2019) studied the geographical fluorescence factors of soil physical and chemical properties and found that the total nitrogen content of soils on shady slopes was higher than that of soils on sunny slopes in shrub and grassland ecosystems [69].

*Soil Nitrogen Migration and Transformation*

Nitrogen can be removed from the soil-plant system by various migration and transformation processes. Soil erosion is one of the most serious ecological problems in Karst rocky desertification areas, and it is one of the pathways for nitrogen migration. These areas develop unique surface characteristics and complex underground hydrological structures that change the mode of soil and water loss to mainly surface runoff erosion; underground leakage is also an important factor that cannot be ignored. Precipitation easily infiltrates, leaks from, dissolves, erodes and expands carbonate rock fissures and provides erosion-induced hydrodynamic pathways for the underground leakage of soils [70]. Zhu X.F. et al. (2017) discussed the main methods and mechanisms of nitrogen loss, and their results showed that deep percolation contributes the most to nitrogen loss, significantly more than surface runoff and soil flow do. 'Old water' may be the main medium for nitrogen transfer at the soil surface [71]. Peng X.D. et al. (2017) further confirmed that rainfall intensity is an important factor affecting the surface loss and underground leakage of nitrogen, and it has a significant effect on nitrogen migration [72].

In addition, the transformations of the various forms of nitrogen in the soil play an important role in migration. Nitrate ($NO_3^-$) can move with water from the upper soil profile to the deeper soil layers and finally into groundwater. Nitrate ($NO_3^-$) can also be reduced to nitrous oxide ($N_2O$) and molecular nitrogen ($N_2$) under anaerobic conditions, resulting in gaseous nitrogen loss. Ammonia nitrogen in soils can exist in the form of ammonium ions ($NH_4^+$) or ammonia ($NH_3$), and they can interconvert under certain conditions. When the partial pressure of ammonia in the soil or water is greater than the partial pressure of ammonia in the atmosphere above it, ammonia may volatilize. Liu X. (2016) et al. and Yang Y. et al. (2018) studied the transformations of soil nitrogen during the process of vegetative restoration in Karst rocky desertification areas and found that, with the positive succession of vegetation (brushgrass - thicket - secondary forest - primary forest), the nitrate nitrogen content, inorganic nitrogen content, net mineralization rate and net nitrification rate of soil nitrogen increased as a whole [73-74].

## Discussion

Based on the dynamic trends in soil nitrogen transport and transformation, establishing a numerical model is challenging, and it is an issue of substantial interest for researchers. In the early 1950s, Lapidus and Amundson proposed a simulation model similar to the convection-dispersion equation (CDE), which enabled the study of solute transport [75]. Since then, after nearly 60 years of development, solute transport theory and nitrogen transport model-related research have achieved many important advances. However, in Karst rocky desertification areas, the research on soil nitrogen has only been conducted via field and laboratory measurements and has not been conducted at the level of independent mechanistic models, nor have any rational organic ecosystem models for nitrogen cycle simulations been published. In addition, there is a lack of research on the dynamics of nitrogen transformation and transport and their impacts on the environment from the perspective of an overall system, which should be addressed in future studies.

The research on soil nitrogen in Karst rocky desertification areas is mainly concentrated in China, and this research has developed as a result of the Chinese government's rocky desertification control strategy for Karst areas. These studies have mainly focus on the relationships between soil nitrogen and the successions in rocky desertification, successions in vegetation, land use patterns, soil fertility and so on. The studies mostly address a single process or a single factor, ignoring the fact that the processes for soil nitrogen transport and transformation involve multiple processes and factors that are interrelated and that interact with one another. Therefore, it is necessary to adopt more system-wide analysis methods to achieve more comprehensive analyses.

Elser et al. (2000) were the first to clearly put forth the concept of ecological stoichiometry [76], and a large number of studies have been carried out since to verify the existence of constant ecological stoichiometric characteristics in different ecosystems [77], to determine ecosystem-restricted nutrients and to establish the relationship between the C:N:P ratio and the biological growth rate [78-79]. In Karst rocky desertification areas, this method is widely used to study the characteristics and driving forces for ecological stoichiometries, but the internal stability of an ecological stoichiometry is seldom considered [80]. In fact, the core concept applied in stoichiometric ecology is that of internal stoichiometric stability, and its strength is related to the ecological strategies and adaptabilities of species [81-82]. From the perspective of international research, this is an emerging field; the research results are scarce, and further research is needed.

Stable isotope technology has many functions, such as its use as tracers and indicators and for integration [83]. The determination of the nitrogen isotope abundance and nitrogen isotope tracers of each ecosystem component can provide explanations for quantifying the rate of nitrogen transformation processes, the sources and pathways for nitrogen and the mechanisms of nitrogen occurrence. For example, the 15N natural abundance method can be used to reflect and predict the characteristics and preferences of plants in terms of their use of soil nitrogen, and the 15N cross labelling technique can be used to study soil nitrogen conversion rates, gaseous nitrogen losses, and nitrogen distributions within ecosystems [84-89]. These findings can enhance our understanding of the nitrogen cycle at the ecosystem scale and improve our nitrogen management capabilities. At present, stable isotope technology is still in its incipient stages in the field of soil nitrogen research in Karst rocky desertification areas, and it is mainly used to study the isotopic compositions of soils or the migrations and transformations of water pollutants. An updated version of the nitrogen stable isotope technology may play a revolutionary role in this field and warrants further investigations.

Hartmann A. et al. (2021) used GIS continent-scale models to quantify the risks of biodegradable pollutants contaminating groundwaters in the Karst regions of Europe, North Africa, and the Middle East. The results showed that, at a time when agricultural productivity continues to increase, pollutant inputs can pose widespread risks to the amount of groundwater available [90]. Cui C. et al. (2016) studied Florida's aquifer system exhibits spatially variable hydrogeological characteristics with GIS, and found that these characteristics contribute to groundwater vulnerability to nitrogen contamination [91]. Chen J.A. et al. (2020) further demonstrated that agricultural activities are the main sources of lake nitrogen pollution in Karst rocky desertification areas [92]. This is essentially due to an imbalance in the soil nitrogen management approaches. On the one hand, due to the low soil fertility of Karst rocky desertification areas, a large amount of nitrogen fertilizer is applied. On the other hand, the nitrogen in the soil is not biologically effective and is not effectively utilized by plants but enters the groundwaters and surface waters. In addition, water is an important carrier of nitrogen, thereby contributing to nitrogen loss, so it is necessary to study water-nitrogen management overall to improve nitrogen use efficiency, limit soil nitrogen losses and achieve water efficiency during irrigation.

The soil nitrogen cycle may lead to increased greenhouse gas emissions and water eutrophication [93]. Nitrous oxide ($N_2O$) is an important greenhouse gas. It is estimated that 70%-90% of the nitrous oxide ($N_2O$) in the atmosphere originates in soils, either produced during the denitrification of nitrate nitrogen ($NO_3^-$) in soils or formed by nitrification via soil microorganisms [94]. The carbon content of Karst areas is 1014 t, accounting for 99.55% of the global sum [95]. In Karst areas, with the increases in their rocky desertification levels, the areas gradually lose their function as sinks for carbon [96], and the accumulation of carbon dioxide ($CO_2$) in soils can strengthen the denitrification process [97], inhibit nitrification [98], and promote the nitrogen cycle [99-100], which in turn affects the production and consumption of nitrous oxide ($N_2O$). During this process, soil respiration is enhanced [101-102], and the increased nitrous oxide ($N_2O$) released from soils can adversely affect plant growth [103]. At present, relevant research is scarce, and more research is needed.

To cope with global climate change, countries all over the world are actively promoting the 'carbon neutrality' strategy in industries, agricultural sectors, etc. The concepts of neutralization and carbon lifecycle management are also of significance for nitrogen management in Karst rocky desertification areas. The idea of 'nitrogen neutrality' may provide a new way of thinking in this field.

## Conclusions

In this review, 247 studies published in Chinese and 77 studies published in English addressing soil nitrogen in Karst rocky desertification areas were analysed by using CiteSpace software. The main conclusions are as follows: (1) the number of studies and number of publications in this field are increasing; (2) China is leading the research efforts with the greatest number of studies and publications in this field; (3) in terms of soil nitrogen input, the total atmospheric nitrogen deposition has tended to be stable, and nitrate nitrogen deposition continues to increase. Different fertilization methods can affect the degrees of migration and transformation of nitrogen in soils, thereby affecting the soil nitrogen cycle. Litter is a major source of soil nitrogen, and there are significant differences in the quantities of litterfall and nutrient contents among the different land use scenarios, vegetative successions, seasonal changes and geographical factors; (4) lithology has a significant effect on the abundance and community compositions of nitrogen-fixing microorganisms in Karst rocky desertification areas, and the soil microbial community composition is mainly influenced by the composition of the existing vegetation, which is affected by lithology; (5) soil nitrogen responds in distinct ways to the different stages of succession during rocky desertification and vegetative restoration and for different land uses, biological crusts, niches, parent rock compositions and geographical factors; (6) in Karst rocky desertification areas, the soil and water losses, mainly caused by erosion due to surface runoff and by underground leakage, are the main pathways for nitrogen loss, among which underground leakage contributes the most and is significantly related to rainfall intensity; and (7) the forms of soil nitrogen and their conversion processes in Karst rocky desertification areas show distinct heterogeneity.

This literature review summarizes several key scientific issues and future directions. These are (1) to establish a numerical model for soil nitrogen transport and transformation in Karst rocky desertification areas; (2) to study the process of soil nitrogen migration and transformation in Karst rocky desertification areas by means of multifactor comprehensive analyses; (3) to further explore the potential of the concept of ecological stoichiometry for soil nitrogen studies of Karst rocky desertification areas; (4) to explore the potentially revolutionary role of stable isotope technology in this research field and conduct further investigations; (5) to strengthen nitrogen management, integrate water and nitrogen management, reduce nitrogen losses and save water during irrigation; (6) to study the nitrous oxide produced during the process of soil nitrogen transport and transformation to comprehensively evaluate its impact on the ecological environment and human activities; and (7) to develop the concept of 'nitrogen neutrality' and study the overall life cycle management of soil nitrogen in Karst rocky desertification areas.

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## Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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