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基于文献计量的近 30 年国内外土壤微生物研究分析*

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摘 要: 为了解国内外土壤微生物的最新研究热点和发展趋势, 借助 Web of Science 中 SCI-EXPANDED 数据库, 利用 VOSviewer、CiteSpace 可视化分析软件等工具, 对 1990—2018 年间发表的关于土壤微生物研究文献的国家、研究机构、期刊来源、主要研究内容及关注热点进行计量分析。结果表明, 该领域的中国发文量呈快速增长趋势, 但总被引频次较低; 美国的发文量、总被引频次均位于首位。中国科学院是重要的研究机构, 其发文量、总被引频次均位于第一, 但篇均被引频次较低。主要的期刊来源有 *Applied and Environmental Microbiology*、*Soil Biology & Biochemistry* 等。国内关键词共现网络形成较晚, 但发展速度较快, 表现出同国外研究热点趋同的发展趋势。国内外研究热点主要集中于土壤微生物参与土壤有机质分解、碳氮养分循环、对污染土壤的微生物降解和修复作用、环境条件变化对土壤微生物群落结构多样性的影响、植物-微生物相互作用机理等。本文对了解土壤微生物研究领域的发展态势具有一定参考价值。

关键词: 土壤微生物; 文献计量学; Web of Science; 关键词共现网络; 数据可视化分析

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Bibliometric-based Analysis of Researches on Soil Microbes at Home and Abroad in the Past 30 Years

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Abstract: [Objective] Soil microbes are an indispensable active component of soil ecosystems. The research on soil microbes is closely linked to current international hotspot issues such as global change, agricultural production, soil environmental protection, etc. The research in soil microbiology is very fruitful, and of great significance for quantitative analysis of soil microbiology literature and data. The use of traditional literature analysis methods to handle large volumes of relevant literature and information and to track development of the research fields has come across a number of difficulties. This paper was oriented to find out latest research hotspots and development trends in the field of soil microorganisms at home and abroad. [Method] Bibliometric analysis of the soil microbial literature contained in the Science Citation Index Expanded (SCI-EXPANDED) database of 1990-2018 in the Web of Science was carried out by country, research institute, source journal,

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citation, main research content and hot spot of attention, with the aid of visual analysis software, like VOSviewer and CiteSpace. A diagram of cooperations between countries or between research institutions was drawn with the aid of VOSviewer, and keyword co-occurrence network atlases by time period and by country were with CiteSpace. 【Result】 Results show that in this research field, the number of documents in China is growing rapidly, but the total citation is still low; the USA ranks first in number of documents and total citation frequency. The Chinese Academy of Sciences, an important research institution in China, its on the top of the lists of number of documents and total citation frequency in the country, but is still quite low in per-paper citation frequency. The “Applied and Environmental Microbiology”, “Soil Biology & Biochemistry” are the main journal sources. Though the journal “Soil Science Society of America Journal” is quite low in influence and in volume of publications, it is high or in the forefront in total citation frequency. The keyword co-occurrence network in China formed quite late, but it develops rapidly, showing a trend of convergence with foreign researches in hotspot. The study object has evolved from a single species to a complex microflora, and the research direction has turned more attention to microbial community composition and diversity. Keywords in the soil microbiology research papers in China are increasing in number and in linkage, forming cross-cutting research hotspots. Soil microbiology researches both at home and abroad focus mainly on the following aspects: soil microbes participating in soil organic matter decomposition, carbon and nitrogen recycling as nutrient; biodegradation of heavy metal or organic pollutants matter and bioremediation of heavy metal or organic compound polluted soils; mechanisms of soil microbial communities responding to global environmental change in structure; and mechanisms of rhizosphere microbes, soil and plants interacting with each other. 【Conclusion】 Researchers all over the world in this field have made great progresses in the field of soil microbial community structure, function and diversity. Through co-occurrence analysis of keywords by time periods in China and abroad, this paper has brought to light hotspots and trend of the research on soil microbiology, which may be of some reference value for understanding the context of the overall researches in the field of soil microbe and provide certain theoretical guidance to researchers who have just begun their exploration in the field.

Key words: Soil microbes ; Bibliometrics ; Web of Science ; Keyword co-occurrence network; Data visualization analysis

2013 年 Jansson 和 Prosser^[1]提出“生物暗物质”的理念，将土壤微生物比作物理学中的暗物质。土壤微生物是土壤生态系统中不可缺少的活跃组成成分^[2]，是养分循环转化的驱动力^[3]，是评价土壤质量的潜在指标^[4]。土壤微生物研究与农业生产、全球变化、土壤环境保护与修复等当前国际上关注的热点问题密切联系。随着研究方法与技术的不断创新，土壤微生物学研究在微生物多样性、群落结构和功能上取得显著进展，土壤微生物多样性及其活性会直接或间接影响植物群落多样性和生产力^[5-6]。与土壤肥力改良、温室气体排放、有机污染降解、重金属污染修复、土传病害防治、土壤生物固氮等相关的土壤功能微生物的研究地位突出。土壤微生物作为生态系统中重要的分解者，其与环境的相互作用也受到了广泛关注。因此，土壤微生物学领域研究成果丰硕，对基于土壤微生物学文献数据进行计量分析具有一定价值。

文献计量学可以系统地分析某一研究领域的整

体发展情况，把握该领域的研究热点与趋势，为科研工作提供参考依据^[7]。已有大量学者运用文献计量学手段来分析相关研究领域的作者、机构、学科间的合作关系，了解研究领域的知识结构、热点趋势等。如使用文献计量学和社会网络分析评估了 1995—2015 年地下水修复文献，了解目前的发展趋势和未来研究方向^[8]。分析土壤污染修复的文章，确定主要污染物和最具前景的土壤修复技术^[9]。由于土壤微生物研究领域的文献数量庞大，传统的文献分析方法对于准确处理相关文献信息，追踪研究领域的发展动态难度较大，基于文献计量学的可视化软件能够对引文数据进行提取处理分析，形成可视化的网络图谱，缩短工作量且便于解读分析。可视化软件既可用于呈现不同作者、国家、机构间的合作关系，又可展现研究主题和领域的共现网络关系，还可进行文献共被引和耦合分析，揭示研究热点、研究趋势和研究前沿。因此，数据可视化软件 VOSviewer 和 CiteSpace 作为文献计量分析的重要

工具被不同国家不同领域的人员广泛使用,如分析国内外土壤科学发展不同时间段的研究热点和研究前沿^[10]。通过 VOSviewer 识别食品化学 40 年来的研究热点和最具影响力的研究主题^[11]。

国内有涉及土壤微生物的文献计量学研究,如利用 CiteSpace 工具构建土壤养分循环微生物机制不同时间段的关键词共现网络^[12],研究内容主要是微生物的土壤养分循环方面。Zheng 等^[13]借助 CiteSpace 共被引分析了氨氧化细菌、氨氧化古菌和厌氧氨氧化研究主题,国外的相关文章较少。本文基于文献计量学方法,从发文量、总被引频次、篇均被引频次评价指标分析土壤微生物研究领域的国家/地区、研究机构、期刊来源、高被引文章,构建了国家、研究机构间的合作关系。重点分析了国内外不同时间段的关键词共现网络谱图,揭示了不同时期土壤微生物领域的高频关键词或者中心度较高的关键词的变化情况,旨在为科研工作者提供数据参考。

1 材料与方法

1.1 数据来源

美国 Thomson Scientific (汤姆森科技信息集团) 基于 Web 开发的产品 Web of Science 是一个综合性、多学科、核心期刊引文索引数据库^[14]。本文利用 Web of Science 中科学引文索引扩展版数据库 (SCI-EXPANDED),在高级检索的检索框内输入 TS (主题) = ((soil*) AND ("microorganism*" OR "microb*" OR "bacteri*" OR "fung*" OR "actinomyce*" OR "algae" OR "archaeobacteria" OR "mycorrhiza*" OR "earthworm" OR "nematode*" OR "protoz*")),文献类型为 (ARTICLE OR REVIEW OR PROCEEDINGS PAPER),时间跨度为 1990 年 1 月 1 日至 2018 年 12 月 31 日,检索时间是 2019 年 6 月 5 日。由于检索结果数量较多,限定土壤生物学领域的期刊,使得土壤微生物领域筛选结果更加精确,共得到国外文献 25 306 篇,中国文献 3 452 篇。

1.2 分析方法

利用 Web of Science 的自带功能分析检索结果,按照国内和国外筛选检索结果,分别以 5 年为一个时间段保存为纯文本格式。将获取的文献信息导入 VOSviewer 软件进行可视化分析,主要涉及土壤微生物国内外发文量的变化趋势、主要的研究机构、

重要期刊来源以及高被引文章分析。然后运用 CiteSpace 的关键词共现网络分析在不同发展阶段下的国内外土壤微生物的研究热点和变化趋势。

2 结果与讨论

2.1 主要国家土壤微生物领域发文量

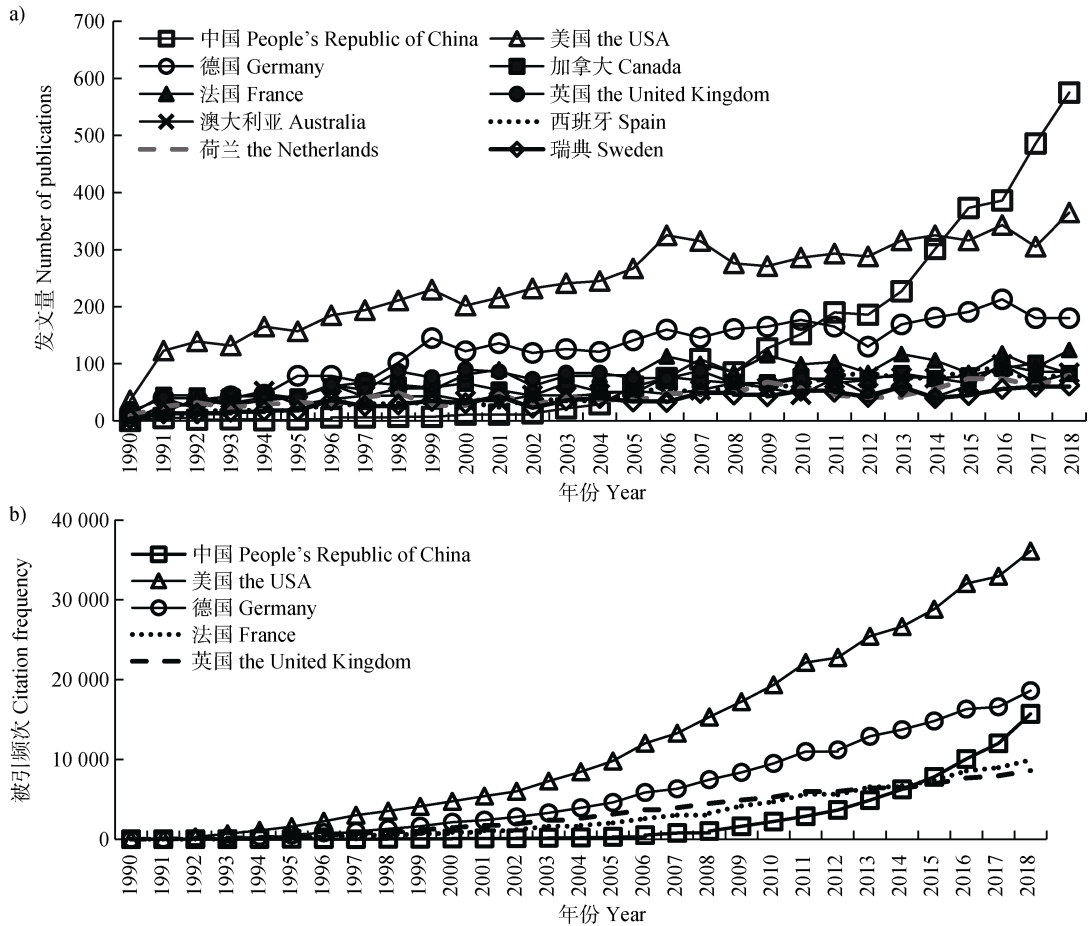
由图 1 可知,美国总发文量 6 999 篇,占世界总发文量 24.34%,呈现平稳增长的趋势;其论文的总被引频次共 362 514 次,年度被引总频次高于其他各国,论文的被引频次处于高水平。中国的发文量合计 3 452 篇,位于第二位;年度发文数量呈大幅增长,2015 年后发文数量超过美国,位于第一;其年度被引总频次也是不断上升,但相对较低,论文影响力有待提高。图 2 为各个主要国家间的合作关系,节点大小代表发文数量,网络中的连线表示国家间的合作关系,线宽代表合作强度。美国、德国同其他国家合作网络较为密集。中国和美国、德国、英国等存在合作关系。国家间合作是提高科研能力、实现创新性研究的重要手段。

2.2 重要研究机构土壤微生物领域发文

表 1 列举了发文量前 10 的研究机构,中国科学院的发文量和被引总频次均处于首位,发文量为位于第二位的法国农业科学研究所的 2.48 倍,图 3 揭示其年度发文数量快速增加,年度被引总频次也呈指数增长形势,但篇均被引频次较低。其他研究机构发文量无明显变化,处于平稳增减状态。重要研究机构间的合作关系如图 4,中国科学院与中国农业科学院、浙江大学、清华大学、美国农业部农业研究组织、哥廷根大学等研究机构存在合作,中国科学院处于合作网络图谱的中心位置,同国内研究机构的合作关系较为密切。

2.3 土壤微生物领域主要期刊来源

表 2 统计了国际土壤微生物相关研究主要的发文字刊。发文量最高的是期刊 *Soil Biology & Biochemistry*,占总发文量的 19.5%。期刊 *Applied and Environmental Microbiology* 发文量低于 *Soil Biology & Biochemistry* 的 50%,但是被引用总频次紧逼 *Soil Biology & Biochemistry*,篇均被引用频次位于首位。期刊 *New Phytologist*、*Global Change Biology*、*ISME Journal* 虽然发文数量较低,但是论文被引用频次



注：a) 为总发文章前 10 的国家的年度发文章量；b) 为总发文章前 5 的国家年度被引总频次变化趋势。Note: a) Top 10 countries in annual total number of publications; b) Variation of total citation frequency of the top 5 countries in total number of publications.

图 1 主要发文章国家的发文章量和被引频次的变化情况

Fig. 1 Publication and citation frequency of scientific papers relative to country

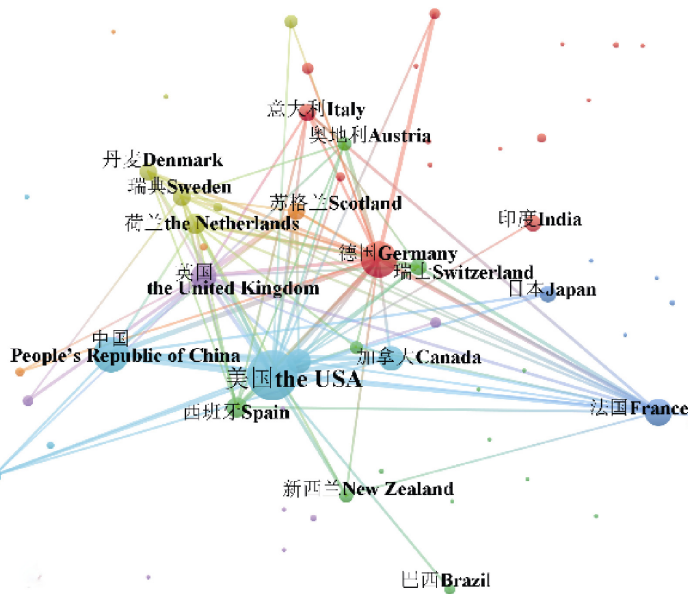


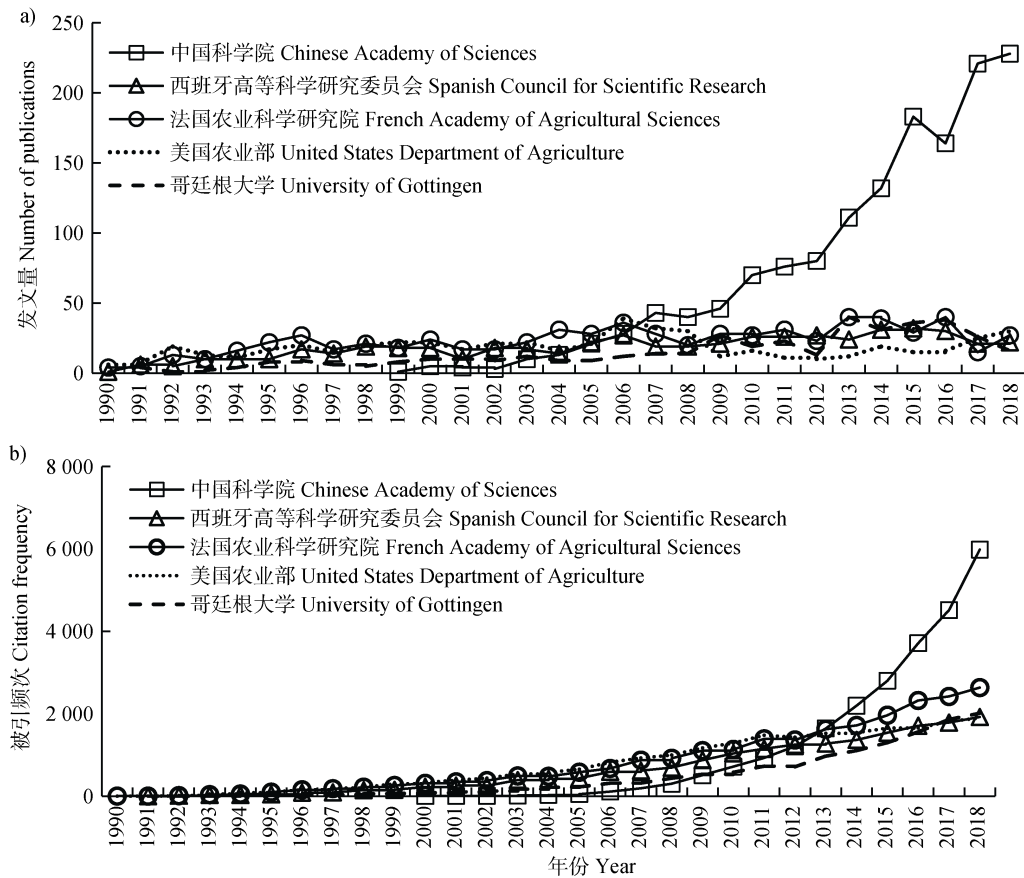
图 2 土壤微生物研究领域主要国家间的合作关系

Fig. 2 Cooperations between major countries in the field of soil microbiology

表 1 土壤微生物文献发表量前 10 名的研究机构

Table 1 The top 20 research institutions in literature contribution in the field of soil microorganisms

研究机构	发文量	被引总频次	篇均被引频次
Research institute	Number of articles	Total citation frequency	Citation frequency per paper
中国科学院 Chinese Academy of Sciences	1 477	35 126	23.78
法国农业科学研究院 French Academy of Agricultural Sciences	596	27 191	45.62
西班牙高等科学研究委员会 Spanish Council for Advanced Scientific Research	488	21 828	44.73
美国农业部 United States Department of Agriculture	468	24 385	52.10
哥廷根大学 University of Gottingen	386	17 015	44.08
瑞典农业大学 Swedish University of Agricultural Sciences	376	21 057	56.00
哥本哈根大学 University of Copenhagen	373	14 161	37.97
加拿大农业与农产食品部 Agriculture and Agri-Food Canada	358	11 383	31.80
加州大学戴维斯分校 University of California, Davis	332	18 103	54.53
瑞典隆德大学 Lund University	302	18 338	60.72



注：a) 为总发文量前 5 的研究机构的年度发文量变化；b) 为总发文量前 5 的研究机构的年度被引总频次变化趋势。Note: a) Change in annual publication of the top 5 research institutions in total number of publications; b) Change in total citation frequency of the top 5 research institutions in total number of publications.

图 3 主要研究机构的发文量和被引频次的年度变化情况

Fig. 3 Annual changes in publication and citation frequency relative to research institution

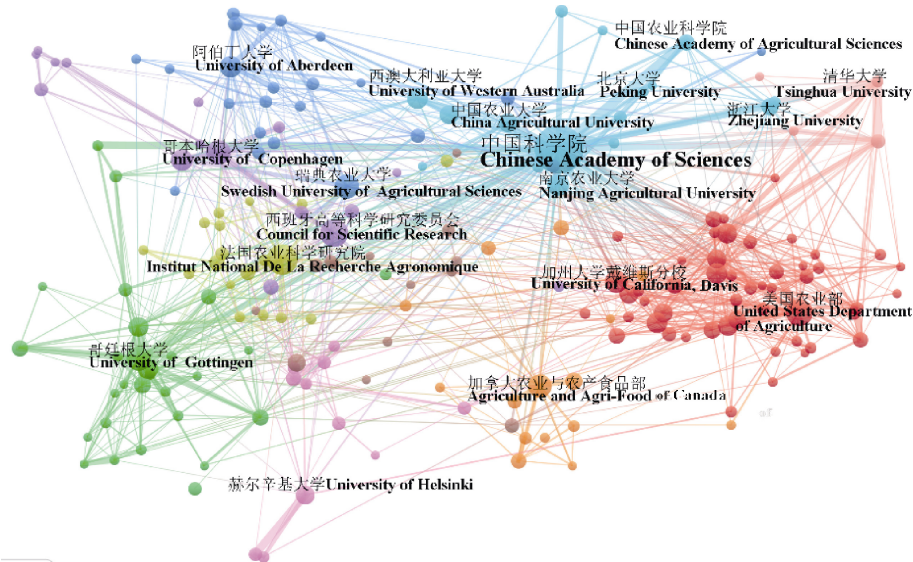


图 4 土壤微生物研究领域重要研究机构间的合作关系

Fig. 4 Cooperations between important research institutions in the field of soil microbiology

表 2 土壤微生物文献发文总量前 20 名的期刊

Table 2 Top 20 journals in literature contribution in the field of soil microorganisms

来源出版物 Journals	2018 年影响因子 Impact factor	发文量 Number of articles	被引用总频次 Total citation frequencies	篇均被引用频次 Citation frequency per paper
<i>Soil Biology & Biochemistry</i>	5.290	5 608	256 056	45.66
<i>Plant and Soil</i>	3.259	2 621	102 777	39.21
<i>Applied and Environmental Microbiology</i>	4.077	2 617	201 705	77.07
<i>Applied Soil Ecology</i>	3.445	2 318	60 092	25.92
<i>Biology and Fertility of Soils</i>	4.829	2 066	69 943	33.85
<i>FEMS Microbiology Ecology</i>	4.098	1 454	61 467	42.27
<i>Frontiers in Microbiology</i>	4.259	1 076	13 752	12.78
<i>Microbial Ecology</i>	3.611	953	34 223	35.91
<i>Applied Microbiology and Biotechnology</i>	3.67	953	32 266	33.86
<i>Soil Science Society of America Journal</i>	1.997	939	46 456	49.47
<i>New Phytologist</i>	7.299	855	63 639	74.43
<i>European Journal of Soil Biology</i>	2.244	852	16 880	19.81
<i>Environmental Microbiology</i>	5.147	826	46 157	55.88
<i>Mycorrhiza</i>	3.114	742	23 665	31.89
<i>FEMS Microbiology Letters</i>	1.994	581	18 674	32.14
<i>Global Change Biology</i>	8.88	561	34 615	61.70
<i>Journal of Applied Microbiology</i>	2.683	543	14 418	26.55
<i>European Journal of Soil Science</i>	2.818	451	18 487	40.99
<i>ISME Journal</i>	9.493	432	29 900	69.21
<i>Journal of Microbiological Methods</i>	1.803	427	17 280	40.47

高, 文章影响力较大。期刊 *Soil Science Society of America Journal* 期刊影响因子较低, 发文量不高, 但论文的被引总频次高, 篇均被引频次位于前列。在关注影响因子较高期刊的同时, 科研人员对综合影响力高的期刊上的论文也应加以关注, 全面地了解土壤微生物领域的发文动态。

2.4 土壤微生物领域高被引文章

通过对高被引文章的追踪分析, 了解该文章对后面研究的影响程度, 进而掌握关于土壤微生物研究的重点与热点。从表 3 中的第一作者国家分析来看, 美国 7 篇, 占半数以上, 证明其在土壤微生物

研究领域的较高国际影响力。2000 年后发表的高被引论文有 5 篇, 其中被引总频次第一的就是 Schloss 和 Handelsman^[15]在 2005 年发表的关于用软件 DOTUR 对测得的基因序列划分独立操作单元 (OTU), 估算生物丰富度和多样性指数。期刊 *Applied and Environmental Microbiology* 上的高被引文章有 6 篇, 高质量论文较多。其中有 6 篇高被引文章是关于分子生物学技术, 如聚合酶链式反应 (PCR)、末端限制性片段长度多态性 (T-RFLP) 分析技术、磷脂脂肪酸 (PLFA)、焦磷酸测序应用到土壤微生物学研究中, 推动了土壤微生物学的发展。由

表 3 土壤微生物研究领域被引总次数前 10 名的文章

Table 3 Top 10 highly cited articles in the field of soil microorganism

标题 Title	第一作者 The first authors	第一作者国家 Country of the first author	文章类型 Type of the article	发表期刊 Journal	出版年 Year of Publication	被引总频次 Total citation frequency	年均被引频次 Annual mean citation frequencys
Introducing DOTUR, a computer program for defining operational taxonomic units and estimating species richness	Schloss P D	美国 USA	研究论文 Article	<i>Applied and Environmental Microbiology</i>	2005	1 900	132.1
DNA recovery from soils of diverse composition	Zhou J Z	美国 USA	研究论文 Article	<i>Applied and Environmental Microbiology</i>	1996	1 869	99.17
Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils	Six J	美国 USA	综述 Review	<i>Plant and Soil</i>	2002	1 666	104.5
Development of a Dual-Index Sequencing Strategy and Curation Pipeline for Analyzing Amplicon Sequence Data on the MiSeq Illumina Sequencing Platform	Kozich J J	美国 USA	研究论文 Article	<i>Applied and Environmental Microbiology</i>	2013	1 614	235.57
Characterization of microbial diversity by determining terminal restriction fragment length polymorphisms of genes encoding 16S rRNA	Liu W T	美国 USA	研究论文 Article	<i>Applied and Environmental Microbiology</i>	1997	1 535	73.3

续表

标题 Title	第一作者 The first authors	第一作者国家 Country of the first author	文章类型 Type of the article	发表期刊 Journal	出版年 Year of Publication	被引总频次 Total citation frequency	年均被引频次 Annual mean citation frequencys
The ammonia monooxygenase structural gene amoA as a functional marker: Molecular fine-scale analysis of natural ammonia-oxidizing populations	Rotthauwe J H	德国 Germany	研究论文 Article	<i>Applied and Environmental Microbiology</i>	1997	1 503	71.17
Pyrosequencing-Based Assessment of Soil pH as a Predictor of Soil Bacterial Community Structure at the Continental Scale	Lauber C L	美国 USA	研究论文 Article	<i>Applied and Environmental Microbiology</i>	2009	1 430	137.64
Organic acids in the rhizosphere -a critical review	Jones D L	威尔士 Wales	综述 Review	<i>Plant and Soil</i>	1998	1 378	70.77
Biochar effects on soil biota-A review	Lehmann J	美国 USA	综述 Review	<i>Soil Biology & Biochemistry</i>	2011	1 371	171.89
The use of phospholipid fatty acid analysis to estimate bacterial and fungal biomass in soil	Frostegard A	瑞典 Sweden	研究论文 Article	<i>Biology and Fertility of Soils</i>	1996	1 332	62.13

图 5 可知, Kozich 等^[16]的论文于 2013 发表后, 其年度被引总频次呈快速增长, 论文影响力大, 可见新一代测序技术对土壤微生物学的发展有重要影响。

2.5 国外近 30 年不同时期的高频关键词

将 1990—2018 年国外发表的土壤微生物的论文分为 3 个时间段: 1990—2000 年、2001—2010 年、2011—2018 年。利用 CiteSpace 构建不同时期关键词共现网络图谱, 分析图谱结果。图 6 中节点的年轮结构表示的是该文献被引用的历史, 节点的半径越大说明该节点的总被引频次越高, 有紫色外圈的节点是具有高中介中心性的节点, 这些节点的中心度不小于 0.1。1990—2000 年中“细菌 Bacteria”和“微生物生物量 Microbial biomass”的出现频次较高, “微生物生物量”的中心度为 0.3, 是关键词网络中的重要连接点。“氮 Nitrogen”、“氮矿化 N mineralization”、“硝化过程 Nitrification”、“反硝化过程 Denitrification”“分解 Decomposition”、“有机

质 Organic matter”、“碳 Carbon”形成聚类, 反映土壤微生物研究主要是土壤碳氮养分转化和有机质降解过程^[17-18]。“生长 Growth”、“植物 Plant”、“小麦 Wheat”、“生物防治 Biocontrol”、“根际 Rhizosphere”相关联, 表明关注土壤微生物对植物的防病促生作用的研究^[19-20]。1990—2000 年对于特定土壤微生物纯菌株的研究是本阶段的特色, 如与固氮过程相关的根瘤菌, 以及参与植物根部氮磷吸收的丛枝菌根真菌、囊泡丛枝菌根等^[21-23]。随着 PCR 等分子生物学技术应用到土壤微生物研究中, 对于根际微生物过程的研究不断细化深入, 其包含的重要关键词数量增多。2001—2010 年关键词网络更加密集, 高中介中心度、高频词的节点明显增多, 不同研究热点间形成较多交叉。“微生物生物量”出现频次不断增加, 同时“微生物群落 Microbial community”和“多样性 Diversity”增长为主要的关键词, 关键词“微生物群落”、“PCR”、“基因 Gene”、“DGGE”、

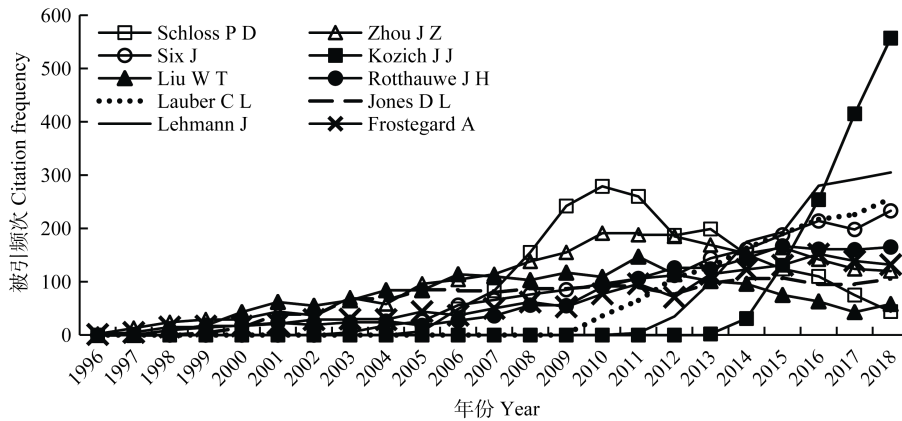
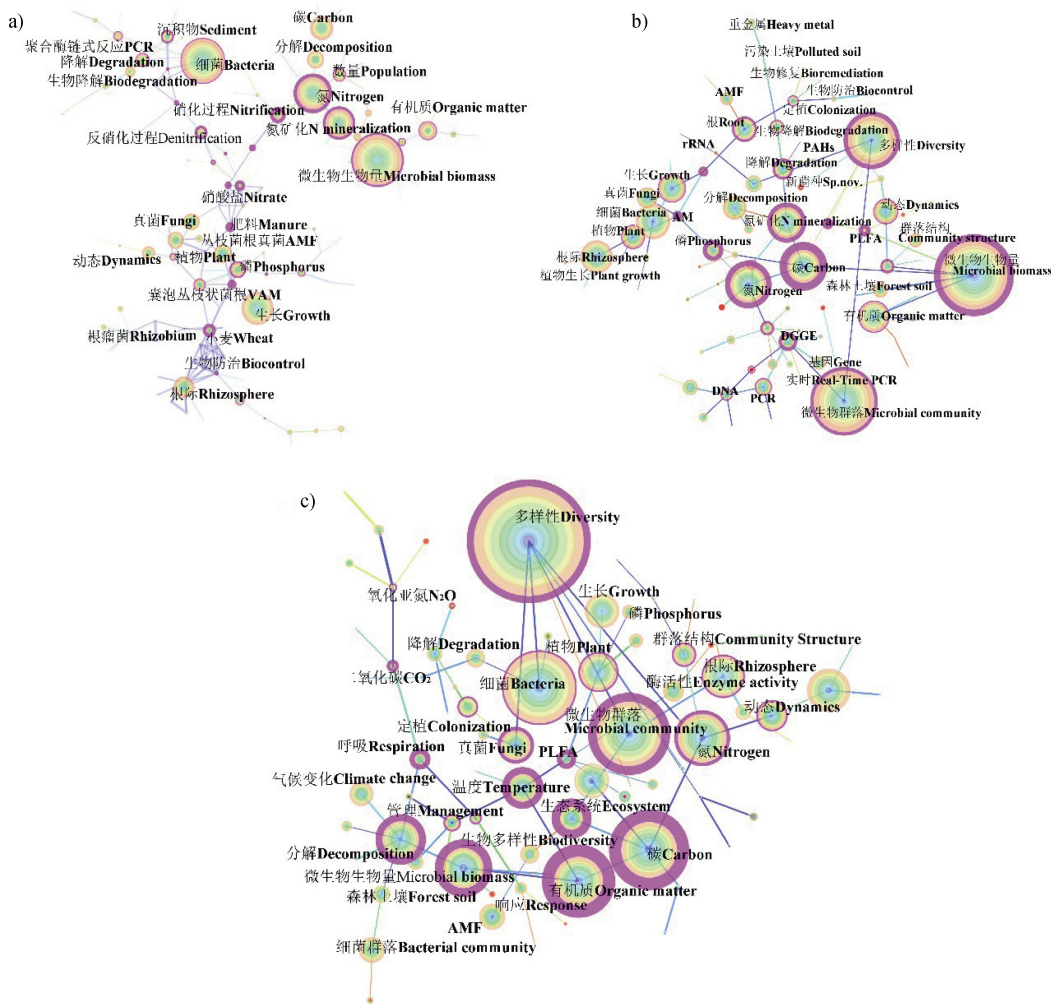


图 5 高被引论文的年度被引总频次变化情况

Fig. 5 Change in annual total citation frequency of the highly- cited papers



注: AMF: 丛枝菌根真菌; VAM: 囊泡丛枝状菌根; PAHs: 多环芳烃; rRNA: 核糖体 RNA; AM: 丛枝菌根; PLFA: 磷脂脂肪酸; DGGE: 变性梯度凝胶电泳; DNA: 脱氧核糖核酸; PCR: 聚合酶链式反应。下同。Note: AMF: Arbuscular mycorrhizal fungi; VAM: Vesicular-arbuscular mycorrhiza; PAHs: Polycyclic aromatic hydrocarbons; rRNA: Ribosomal RNA; AM: Arbuscular mycorrhiza; PLFA: Phospholipid fatty acid; DGGE: Denatured gradient gel electrophoresis; DNA: DeoxyriboNucleic acid; PCR: Polymerase chain reaction. The same below.

图 6 国外学者发表的土壤微生物研究领域文献的关键词共现网络图谱

Fig. 6 Keyword co-occurring network atlas of the literature contributed by foreign researchers in the field of soil microorganism

作用^[39-40]。“AMF”、“定殖 Colonization”、“根际”和“磷”相连接,表明研究更加关注菌根真菌与植物的相互作用方式^[41]以及菌根真菌提高植物吸收磷的作用机制^[42]。“生物修复”、“降解 Degradation”、“重金属”、“污染土壤”聚集在一起且出现频次不断提高,污染土壤及其生物降解修复机制成为研究热点。图 7 b)中“草原 Grassland”、“呼吸 Respiration”、“气候变化 Climate change”、“CO₂ 升高 Elevated CO₂”、“微生物生物量”相互连接,探究气候变化对土壤微生物多样性和结构功能的影响^[43-44],说明土壤微生物对全球环境变化的响应机制是该时期的一个研究主题。

3 结 论

本文基于文献计量学的可视化方法分析了 1990—2018 年的土壤微生物研究领域的文献数据,发现国际土壤微生物领域的总发文量呈增加趋势,各国间合作密切。中国的年发文量在 2010 年后大幅增加,但论文被引频次低于美国和德国。美国在土壤微生物学领域具有很大的国际影响力,引领该领域的研究发展方向。中国科学院的发文量和总被引频次均居于首位,且与国内外重要研究机构的合作不断加强。此外, *Applied and Environmental Microbiology*、*Soil Biology & Biochemistry*、*ISME Journal* 等均是土壤微生物领域的重要期刊。由关键词网络分析可知,国际上土壤微生物研究在土壤养分循环、全球环境变化和污染土壤修复等方面取得重大进展。中国土壤微生物学的研究网络形成稍晚,但发展迅速,研究内容逐渐与国际研究方向保持一致。其中土壤微生物的群落组成、多样性和功能的时空演变规律、驱动机制是土壤微生物学的主要研究方向之一。同时应加强土壤养分转化的微生物驱动机制,地上植物与地下微生物相互作用的研究,有助于提升土壤肥力,提高养分利用率,更好地服务于农业生产;加强土壤微生物与全球变化的研究,深入研究温室气体产生和氧化的微生物机理及其对全球变化的响应;土壤微生物-植物的联合修复技术是土壤污染修复领域的重要途径;增强对关键微生物类群的研究,微生物类群间的正反馈作用机制,定量研究微生物功能群的作用。

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