Knowledge Graph-Based Analysis of Frontier Trends in Plant Functional Traits and Environment Research: Postprint

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Abstract

Plant functional traits significantly influence ecosystem functions and can reflect plant responses to environmental changes, serving as a bridge linking plants and the environment. To systematically understand the international research progress on plant functional traits and environment, this study is based on Web of Science data sources, utilizing Web of Science database analysis tools and Thomson Data Analysis (TDA) for data cleaning and statistical analysis, and employing software such as Ucinet, Netdraw, and EXCEL for visual mapping. Data mining and quantitative analysis were conducted on relevant papers from 1992-2017, particularly those from the recent nine years (2009-2017) on plant functional traits and environment research, from the perspectives of annual publication trends, research topics, major contributing countries/institutions, comparative distribution of research strength, journal distribution patterns, and highly cited papers. The results show: (1) Over the past 26 years, the number of publications on plant functional traits and environment research has shown a sustained and steady growth trend, with an accelerated growth pattern particularly in the recent nine years; (2) In the recent nine years, research topics have primarily focused on functional indicators such as specific leaf area, leaf area (index), photosynthesis (performance), leaf thickness, leaf morphology, leaf nitrogen content, chlorophyll, chlorophyll fluorescence, specific root length, and environmental factors including light, temperature, water (water use efficiency, drought, etc.), fertilizer (primarily nitrogen and phosphorus), CO2, etc.; stoichiometry has been widely applied in this field; (3) During 2009-2017, developed countries such as Europe and the USA were the main research forces in this field. The USA leads the world in both publication quantity and literature quality. China ranks second in publication volume in this field, only after the USA, but has lower average citations per paper and H-index. The Chinese Academy of Sciences ranks first in publication volume with an absolute advantage, though

its literature quality needs further improvement; (4) Among the Top 10 journals by publication volume in this field, eight are in JCR Q1 category and two are in Q2 category. Among them, Plant and Soil and Plant Ecology rank first and second in publication volume, respectively; (5) The Top 10 highly cited papers were published in eight journals, with first authors from the USA, the Netherlands, Canada, Germany, and France.

Full Text

Frontier Trend Analysis of Plant Functional Traits and Environment Research Based on Knowledge Mapping

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Abstract

Plant functional traits significantly influence ecosystem functioning and reflect plant responses to environmental changes, serving as a critical bridge between plants and their environment. To systematically understand international research progress on plant functional traits and environment, this study conducted data mining and quantitative analysis of relevant papers from 1992 to 2017, with particular focus on the most recent nine years (2009-2017). Using the Web of Science (WoS) database as the data source, we employed WoS analytical tools and Thomson Data Analyzer (TDA) for data cleaning and statistical analysis, and utilized Ucinet, Netdraw, and Excel for visualization. We analyzed annual publication trends, research themes, leading countries/institutions, comparative distribution of research strength, journal distribution, and highly cited papers. The results revealed: (1) Over the past 26 years, publications on plant functional traits and environment have shown sustained growth, with accelerated expansion in the last nine years. (2) Research themes during 2009-2017 focused primarily on functional indicators such as specific leaf area, leaf area (index), photosynthesis (performance), leaf thickness, leaf morphology, leaf nitrogen content, chlorophyll, chlorophyll fluorescence, and specific root length, as well as environmental factors including light, temperature, water (water use efficiency, drought, etc.), fertilizer (mainly nitrogen and phosphorus), and CO . Stoichiometry has been widely applied in this field. (3) From 2009-2017, developed countries in Europe and North America dominated the research landscape. The United States led globally in both publication quantity and quality. China

ranked second in publication output but exhibited lower average citations per paper and H-index values. The Chinese Academy of Sciences ranked first in publication volume by a substantial margin, though its paper quality requires further improvement. (4) Among the top 10 journals by publication count, eight were in JCR Q1 category and two in Q2. *Plant and Soil* and *Plant Ecology* ranked first and second, respectively. (5) The top 10 highly cited papers were published in eight journals, with first authors from the United States, the Netherlands, Canada, Germany, and France.

Keywords: plant functional traits; environment; bibliometrics; trend analysis

Introduction

Plant functional traits refer to any measurable morphological, physiological, or phenological characteristics at scales ranging from cells to whole organisms, including specific leaf area, leaf thickness, leaf dry matter weight, fine root number, specific root length, root tissue density, nitrogen and phosphorus content in roots and leaves, and canopy height. As core attributes of plants, these traits significantly influence ecosystem functioning and reflect vegetation responses to environmental changes, serving as a vital bridge between plants and their environment. Plant functional traits have been widely applied in evolutionary ecology, community ecology, biogeography, macroecology, and global change science.

The interaction between plants and their environment represents a central question in ecological research. The relationship between plant functional traits and environment results from filtering effects of climate, disturbance, and biological conditions. Plant traits adapt to environmental changes—for instance, leaf morphology, anatomical structure, and stomata exhibit adaptive responses to variations in light, temperature, and CO concentration. Plants in arid regions typically exhibit traits such as thick leaves, low specific leaf area, high water use efficiency, and long leaf lifespan to cope with water stress, whereas wetland plants show opposite characteristics. In forests, maximum stomatal conductance follows the pattern: trees > shrubs > herbs, deciduous > evergreen, and broadleaf > coniferous.

In recent years, large-scale and regional studies on plant functional traits have emerged. Wang et al. (2016) examined plant functional trait characteristics across a 3,700 km forest transect in eastern China, while Tian et al. (2016) investigated relationships between tree functional traits and latitudinal patterns. Roots, as organs for water and nutrient absorption, carry important information about environmental changes, with their trait characteristics providing crucial indicators for plant growth and distribution. Environmental factors such as water and nutrients significantly influence root traits. Some plant traits are closely linked to growth strategies and resource utilization capacity. Therefore, studying trait-environment relationships reveals plant adaptation strategies and

provides methods and basis for understanding ecosystem functions under current conditions and predicting future global change impacts.

Bibliometrics applies mathematical and statistical methods to describe, evaluate, and predict research trends based on quantitative characteristics of literature. This study utilizes the Science Citation Index Expanded (SCIE) database from the Institute for Scientific Information to reveal the evolution of plant functional traits and environment research, analyze frontier trends, and provide a new perspective for researchers and managers while offering references to advance domestic research in this field.

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1. Materials and Methods

We retrieved literature from the Web of Science Core Collection (SCIE) focusing on relationships between leaf traits and climate, root/leaf traits and soil, root/leaf traits and topography, and root traits and climate. After iterative test searches and consultation with domain experts, we finalized the retrieval strategy using advanced topic searches with Boolean operators (Table 1). The search was conducted in August 2018, covering 1992-2017 and limited to articles, discussions, and reviews, yielding 3,854 records. After content screening, 3,036 papers were selected for analysis. We used TDA for data cleaning and Ucinet, NetDraw, and Excel for visualization. Keywords (Author' s Keywords + Keywords Plus) and title phrases were used as subject terms. After cleaning to remove broad, redundant high-frequency terms and merging synonyms, we analyzed temporal changes in themes and hotspots, as well as characteristics of thematic networks and collaborating countries/institutions.

Table 1 Retrieval strategy for plant functional traits and environment research

Retrieval Type	Search Query
(1) Leaf traits and climate	TS=(("leaf thickness" OR "leaf lifespan" OR "specific leaf area" OR "leaf tissue density" OR "leaf carbon concentration" OR "leaf nitrogen concentration" OR "leaf phosphorus concentration" OR "leaf N:P" OR "leaf carbon content" OR "leaf nitrogen content" OR "leaf phosphorus content") AND (precipitation OR rainfall OR air temperature OR temperature OR evaporation OR solar radiation OR radiation OR insolation duration)) AND PY=(1992-2017)

Retrieval Type	Search Query
(2) Root/leaf traits and soil	TS=((“leaf thickness” OR “leaf lifespan” OR “specific leaf area” OR “leaf tissue density” OR “leaf carbon concentration” OR “leaf nitrogen concentration” OR “leaf phosphorus concentration” OR “leaf N:P” OR “leaf carbon content” OR “leaf nitrogen content” OR “leaf phosphorus content” OR “specific root length” OR “root tissue density” OR “fine root nitrogen concentration” OR “root nitrogen concentration” OR “root phosphorus concentration” OR “fine root carbon content” OR “root carbon content” OR “root nitrogen content” OR “root phosphorus content” OR “root N:P” OR (root “mechanical composition”) OR plant “ecological stoichiometry”) AND (soil nutrient OR soil organic matter OR soil nitrogen OR soil total nitrogen OR soil available nitrogen OR soil phosphorus OR total phosphorus OR soil available phosphorus OR soil carbon OR soil aggregate structure OR soil moisture OR soil bulk density)) NOT TS=(apple OR “white yam” OR rice OR maize OR barley OR soybean OR potato OR wheat) AND PY=(1992-2017)

Retrieval Type	Search Query
(3) Root/leaf traits and topography	TS=((“leaf thickness” OR “leaf lifespan” OR “specific leaf area” OR “leaf tissue density” OR “leaf carbon concentration” OR “leaf nitrogen concentration” OR “leaf phosphorus concentration” OR “leaf N:P” OR “leaf carbon content” OR “leaf nitrogen content” OR “leaf phosphorus content” OR “specific root length” OR “root tissue density” OR “fine root nitrogen concentration” OR “root nitrogen concentration” OR “root phosphorus concentration” OR “fine root carbon content” OR “root carbon content” OR “root nitrogen content” OR “root phosphorus content” OR “root N:P” OR (root “mechanical composition”) OR plant “ecological stoichiometry”) AND (terrain OR “terrain location” OR topography OR altitude OR altitude gradient OR elevation OR “elevation gradient” OR aspect OR slope OR latitude OR “slope position” OR “slope location”)) AND PY=(1992-2017)

Retrieval Type	Search Query
(4) Root traits and climate	TS=(("specific root length" OR "root tissue density" OR "fine root nitrogen concentration" OR "root nitrogen concentration" OR "root phosphorus concentration" OR "fine root carbon content" OR "root carbon content" OR "root nitrogen content" OR "root phosphorus content" OR "root N:P" OR root "mechanical composition" OR plant "ecological stoichiometry") AND (precipitation OR rainfall OR air temperature OR temperature OR evaporation OR solar radiation OR radiation OR insolation duration)) AND PY=(1992-2017)

2. Results

2.1 Temporal Characteristics of Publication Output

The annual distribution of publications reflects research progress over time and provides a quantitative basis for identifying research phases. From 1992-2017, we identified 3,036 SCI papers on plant functional traits and environment, averaging 116.8 articles annually. The data show a consistent growth trend in both absolute numbers and percentages over the 25-year period (Figure 1 [Figure 1: see original paper]). This increase indicates growing scholarly attention to plant functional traits and environment research. Based on publication patterns and research content, we divided the period into three phases: 1992-2000, 2001-2008, and 2009-2017. The most recent nine years (2009-2017) accounted for 1,728 publications (56.9% of the total), warranting focused analysis.

Figure 1 Number and proportions of SCI articles on plant functional traits and environment research during 1992-2017

2.2 Research Theme Analysis

We conducted social network analysis of keywords from 2009-2017 to examine mainstream academic groups and their connections across four research areas: leaf traits and climate, root/leaf traits and soil, root/leaf traits and topography, and root traits and climate (Figure 2 [Figure 2: see original paper]). In these networks, larger nodes and more connecting lines indicate higher centrality, while

thicker lines between two points represent stronger co-occurrence.

Research on leaf traits and climate showed the most extensive keyword network. Core themes included specific leaf area, photosynthesis, CO , elevated CO , drought, climate change, and nitrogen. Hot topics encompassed leaf anatomy, structure, lifespan, thickness, morphology, leaf mass per area, chlorophyll, chlorophyll fluorescence, photosynthetic capacity, photoinhibition, photosynthetic pigments, stomatal conductance, stomatal density, dark respiration, and environmental factors affecting photosynthesis and respiration (light, temperature, water, fertilizer). Studies delved into physiological mechanisms such as photosystem II and temperature responses, while also developing toward modeling and stoichiometry.

Roots, as underground organs, are directly influenced by soil physicochemical properties while transporting mineral nutrients and water upward and receiving photosynthates from leaves. The adage "deep roots, lush leaves" reflects this relationship. Research on root/leaf traits and soil from 2009-2017 centered on specific leaf area, specific root length, photosynthesis, carbon, nitrogen, phosphorus, soil fertility, water (use efficiency), and drought. Plant functional traits and stoichiometry emerged as core themes, with stoichiometry branching into ecological stoichiometry and N-P stoichiometry.

Research on root/leaf traits and topography formed a network with specific leaf area and functional traits at the core, supported by secondary themes including climate change, leaf nitrogen, altitude, photosynthesis, gas exchange, temperature, nitrogen, phosphorus, and phenotypic plasticity.

Research on root traits and climate featured fewer keywords and weaker co-occurrence. Specific root length, temperature, nitrogen, phosphorus, and stoichiometry constituted the core direction, with stoichiometry further subdivided into ecological, N-P, and P stoichiometry. Root morphology, tissue density, and fine root characteristics received considerable attention, along with carbon allocation, nitrogen degradation, water use efficiency, and ectomycorrhizae.

Figure 2 Social network analysis of keywords on plant functional traits and environment research during 2009-2017

2.3.1 Distribution of Research Strength by Country

Publication output serves as a key metric for evaluating national research capacity. Table 2 shows the top 10 countries during 2009-2017. Except for China and Brazil, all are developed nations, with seven publishing 100 papers. The United States, as the world' s leading scientific power, topped the list with 421 publications. China ranked second with 380 papers, followed by Australia, Germany, Brazil, France, and Spain (all 100 papers). Notably, China surpassed the U.S. in 2015, 2016, and 2017, indicating rapid development despite a late start and growing national emphasis on this research area.

Table 2 Annual change in the number of papers published by the top 10 countries on plant functional traits and environment research during 2009-2017

2.3.3 Comparison of Research Strength

Publication count, citation frequency, and H-index are crucial metrics for evaluating research quality, reflecting both quantitative attention and qualitative impact. Figure 3 [Figure 3: see original paper] plots publication quantity (x-axis) against average citations per paper (y-axis), with point size representing H-index. Using mean values as the center, we established a coordinate system for research strength evaluation: Quadrant 1 (high quantity, high quality), Quadrant 2 (low quantity, high quality), Quadrant 3 (low quantity, low quality), and Quadrant 4 (high quantity, low quality).

At the national level (Figure 3a), only the U.S. occupied Quadrant 1, demonstrating both high productivity and impact. Australia, France, the Netherlands, Canada, and the United Kingdom fell in Quadrant 2, with below-average output but above-average quality. Germany, Spain, and Brazil were in Quadrant 3, requiring improvement in both quantity and quality. China was in Quadrant 4, ranking second in output but with low average citations, suggesting its high H-index derives primarily from publication volume.

At the institutional level (Figure 3b), the Chinese Academy of Sciences (CAS) was in Quadrant 4, with 249 publications far exceeding other institutions but requiring quality improvement. The University of California System (UCS) was in Quadrant 1, surpassing the mean in both quantity and quality. The French National Center for Scientific Research (CNRS), Commonwealth Scientific and Industrial Research Organisation (CSIRO), French National Institute for Agricultural Research (INRA), Spanish National Research Council (CSIC), and University of Minnesota System (UMN) were in Quadrant 2, with UMN showing the highest average citations. The State University System of Florida (SUSF), Wageningen University & Research (WUR), and United States Department of Agriculture (USDA) were in Quadrant 3, occupying peripheral positions.

Figure 3 Comparison of scientific research strength among major countries and institutions

Note: CAS—Chinese Academy of Sciences (University); UCS—University of California System; INRA—French National Institute for Agricultural Research; CSIC—Spanish National Research Council; CNRS—French National Center for Scientific Research; USDA—United States Department of Agriculture; WUR—Wageningen University & Research; SUSF—State University System of Florida; CSIRO—Commonwealth Scientific and Industrial Research Organisation; UMN—University of Minnesota System. (a) Countries; (b) Institutions.

2.4 Leading Journals in the Field

Analyzing source publications reveals distribution patterns and helps identify core information sources. Table 4 shows the top 10 journals published 400 articles collectively. *Plant and Soil* led with 63 articles (15.8% of the top 10 total), followed by *Plant Ecology* with 49 articles. *Plant and Soil* focuses on plant biology, soil science, and plant-soil interactions, while *Plant Ecology* publishes research, reviews, and commentaries on plant science.

The top 10 journals were high-quality: eight were JCR Q1 and two were Q2. Seven had 2017 impact factors 3, with *Global Change Biology* exceeding 8. By country of publisher, the 10 journals belonged to three nations: the United States (7), the Netherlands (2), and the United Kingdom (1).

Table 4 Top 10 journals on plant functional traits and environment research and their impacts

Journal	Articles	Impact Factor (2017)	Country	JCR Category
Plant and Soil	63	Netherlands	Q1	
Plant Ecology	49	Netherlands	Q1	
PLOS ONE	-	United States	Q1	
Journal of Ecology	-	United Kingdom	Q1	
Tree Physiology	-	United States	Q1	
Functional Ecology	-	United States	Q2	
Journal of Vegetation Science	-	United States	Q1	
New Phytologist	-	United States	Q1	
Global Change Biology	>8	United States	Q1	
Oecologia	-	United States	Q1	

2.5 Highly Cited Papers

Citation frequency reflects a paper' s influence on subsequent research. Analyzing highly cited papers assesses research strength and explores hotspots and trends. Table 5 lists the top 10 highly cited papers from 2009-2017. All first authors were from developed countries (U.S.: 5; Netherlands: 2; Canada, Germany, and France: 1 each). These papers were published in eight journals, with *New Phytologist* and *Journal of Ecology* each publishing two. Five papers were published in 2009, three in 2010, and one each in 2011 and 2012. The most cited paper was "Causes and consequences of variation in leaf mass per area (LMA): a meta-analysis" by Poorter, H. (Netherlands) in *New Phytologist* (2009), with 803 citations.

Table 5 Top 10 highly cited papers on plant functional traits and environment research in Web of Science (2009-2017)

Title	First Author	Country	Source	Citation
Causes and consequences of variation in leaf mass per area (LMA): a meta-analysis	Poorter, H	Netherlands	*New Phytologist*	803
Community assembly and shifts in plant trait distributions across an environmental gradient in coastal California	Cornwell, WK	Canada	*Ecological Monographs*	-
A global study of relationships between leaf traits, climate and soil measures of nutrient fertility	Ordonez, JC	Netherlands	*Global Ecology and Biogeography*	-

Title	First Author	Country	Source	Citation
Differential responses to changes in growth temperature between trees from different functional groups and biomes: a review and synthesis of data	Way, DA	USA	*Tree Physiology*	-
Resource stoichiometry elucidates the structure and function of arbuscular mycorrhizas across scales	Johnson, NC	USA	*New Phytologist*	-
Ecoenzymatic stoichiometry of microbial organic nutrient acquisition in soil and sediment	Sinsabaugh, RL	USA	*Nature*	-

Title	First Author	Country	Source	Citation
Quantifying photosynthetic capacity and its relationship to leaf nitrogen content for global-scale terrestrial biosphere models	Kattge, J	Germany	*Global Change Biology*	-
Intraspecific functional variability: extent, structure and sources of variation	Albert, CH	France	*Journal of Ecology*	-
Inferring community assembly mechanisms from functional diversity patterns: the importance of multiple assembly processes	Spasojevic, MJ	USA	*Journal of Ecology*	-

Title	First Author	Country	Source	Citation
Soil warming, carbon-nitrogen interactions, and forest carbon budgets	Melillo, JM	USA	*Proceedings of the National Academy of Sciences of the USA*	-

3. Conclusions and Discussion

Overall, international research on plant functional traits and environment has grown steadily, with accelerated expansion in recent years. Our findings reveal several key patterns:

(1) Research Leadership: Developed countries in Europe and North America dominate this field. The U.S. leads absolutely in both publication quantity and quality. China ranks second in output, but its citation impact requires improvement. France, Australia, Spain, Germany, Brazil, the Netherlands, and the United Kingdom are also major contributors. At the institutional level, the Chinese Academy of Sciences far exceeds others in publication volume but needs quality enhancement. The University of California System excels in both quantity and quality. Among the top 10 institutions, four are American and two are French, with the remaining four being the Chinese Academy of Sciences, Spanish National Research Council, Wageningen University & Research, and Commonwealth Scientific and Industrial Research Organisation.

(2) Research Directions: The four main research directions show varying maturity. Studies on leaf traits and climate, and root/leaf traits and soil, have substantial literature and well-developed frameworks, representing hot topics with strong development momentum. Leaf trait-climate research features extensive themes forming dense networks, with core topics including specific leaf area, photosynthesis, CO , elevated CO , drought, climate change, nitrogen, phosphorus, soil fertility, and water use efficiency. However, most leaf-climate studies focus on conventional morphological traits at the individual level, with spatial mismatches between trait and functional data at ecosystem, regional, or global scales. Future research should systematically investigate leaf functional traits across scales (individual-population-community-ecosystem) and develop quantitative relationships among leaf traits, climate, and ecosystem functions. Existing networks like the Chinese Ecosystem Research Network, ChinaFLUX, and the Chinese Forest Biodiversity Monitoring Network provide valuable platforms for such research, and quantitative models are beginning to be applied in

multi-scale trait studies.

(3) Root Trait Research: Beyond leaves, roots represent important functional traits sensitive to environmental change. However, literature on root traits and climate remains limited and narrowly focused, with specific root length as the core topic, followed by (eco)stoichiometry, phosphorus, and nitrogen. Recent increases in root-climate research likely reflect advances in root observation techniques. As the organ directly sensing water and nutrients, roots provide critical feedback to aboveground functional traits. Research on root-soil interactions, particularly mycorrhizae, has become a hotspot. Studies demonstrate that mycorrhizal distribution, morphology, and types significantly influence plant trait responses to environmental conditions, while environmental factors also affect mycorrhizae. Advances in techniques for in situ root observation, root morphology, and physiological ecology are enriching this field.

(4) Publication Landscape: The top 10 journals by publication count (400 articles total) belong to three developed countries (U.S.: 7; Netherlands: 2; UK: 1), with eight in JCR Q1. All top 10 highly cited papers originated from developed countries (U.S.: 5; Netherlands: 2; Canada, France, and Germany: 1 each), published across eight journals, primarily in 2009-2010.

Challenges and Recommendations for China:

Despite progress, China faces several challenges: (1) Compared to the U.S., Europe, Australia, and Japan, China shows gaps in research quality despite high output, with low average citation rates. This may relate to later start, fewer international collaborations, and institutional evaluation policies. Chinese scholars should focus on publishing high-impact papers to achieve qualitative leaps beyond quantitative accumulation. (2) The Chinese Academy of Sciences demonstrates clear advantages in publication volume but needs to improve citation impact. Enhanced international collaboration, particularly with high-level institutions, is crucial for elevating research quality.

Therefore, China should closely monitor international developments, understand gaps with leading nations and institutions, identify research hotspots, and track trends to enhance its research capacity and influence in this field.

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Note: Figure translations are in progress. See original paper for figures.