Bibliometric analysis of research trends and focuses of plant functional traits

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Abstract. Plant functional traits (PFTs) are a research focus in ecology, and an illustration of the research focuses and development of this field that can serve as a reference for future related research. Through the retrieval of relevant papers on PFTs published from 1998 to 2017 from the Web of Science and extracted literature information, this study applied a bibliometric analysis to analyze information on 1938 papers to reveal the research focuses, development patterns and potential problems of this field. The results show the following: research on PFTs has undergone three stages from 1998-2017: slow development (1998-2002), steady growth (2003-2009) and rapid development (2010-2017). The scholar with the largest number of published papers is Reich PB (56 papers) followed by Lavorel S (51 papers) and Garnier E (48 papers). The country with the most published papers is the United States (579 papers), followed by France (302 papers) and China (279 papers). The research institution with the largest number of published papers is the Chinese Academy of Sciences (161 papers), followed by the French National Institute for Agricultural Research (94 papers) and the University of Minnesota (87 papers). The Journal of Vegetation Science, Journal of Ecology and New Phytologist are the three journals with the most published papers. A keyword analysis shows that research focuses of this field include the trade-off between functional traits, the relationship between PFTs and community assembly, and the impact of PFTs on responses to global climate change.

1. Introduction
Plant functional traits (PFTs) are a series of plant traits that have a potentially significant impact on the planting, survival, growth, and death of plants, and these traits can individually or jointly indicate an ecosystem's response to environmental changes and have a great influence on ecosystem processes [1]. Research on PFTs, as one of the focuses of ecology, provides important approaches to revealing frontier ecological issues such as processes of community assembly, mechanisms of biodiversity maintenance, and ecosystem functions [2,3].

Research on PFTs has involved different levels of community organizations and spatial-temporal scales, covering individuals, communities and ecosystems and focusing on trade-offs among PFTs [4,5],...
spatial-temporal patterns of PFTs \cite{6,7}, trait-based plant coexistence mechanisms \cite{8,9}, relationships between PFTs and phylogeny \cite{10,11}, plant functional diversity \cite{12,13}, relationships between PFTs and ecosystem functions and services \cite{14,15}, and relationships between PFTs and disturbances \cite{16,17}. PFTs data have become important basic data for research in evolutionary biology, community and functional ecology, and biogeography. Although research on PFTs has developed rapidly with extensive research content, many research directions still require attention and focus. If the information provided in relevant papers can be comprehensively organized and statistically analyzed to reveal research trends, research focuses and gaps can be found, and the development of related research and reference information and inspiration for future research can be elucidated.

Bibliometrics is a quantitative analysis method based on mathematical statistics that is used to analyze the distribution structures, quantitative relationships, and change laws of various forms of information taken from literature to objectively and quantitatively reflect the overall layout, research focuses, and development trends of a field or discipline and to help researchers find new solutions. Therefore, bibliometrics is widely used in many research fields. Liu et al. \cite{18} carried out a quantitative analysis of the literature of biodiversity research and revealed the literature’s output and features of academic cooperation in this field, providing a new perspective for studying global biodiversity. Zhi et al. \cite{19} quantitatively analyzed relevant literature on the carbon cycle published from 1993 to 2013 via bibliometric analysis and evaluated development in that field. Romanelli et al. \cite{20} evaluated the results of scientific research on global ecological restoration published from 1997 to 2017, in turn revealing the status and gaps of ecological restoration research. In addition, bibliometrics is applied to fields related to ecology such as global climate change \cite{21}, global environmental evaluation \cite{22}, sustainable development \cite{23}, and global research in deforestation \cite{24}, providing important information for understanding the development and research focuses of related fields.

Some scholars have conducted detailed reviews of research progress in the field of PFTs, illustrating developments in that field \cite{25,26}. However, there is a lack of analysis and evaluation of the trends and focuses of PFTs research from the perspective of bibliometric analysis. In this paper, the Science Citation Index Expanded (SCI-E) database of the Web of Science (WoS) core collection database is used as a data source to retrieve relevant papers on PFTs published from 1998 to 2017, and bibliometric analysis is adopted to fields related to ecology such as global climate change \cite{21}, global environmental evaluation \cite{22}, sustainable development \cite{23}, and global research in deforestation \cite{24}, providing important information for understanding the development and research focuses of related fields.

2. Materials and Methods

2.1. Data retrieval
The WoS is the world’s largest, most authoritative and comprehensive academic information resource library covering most disciplines. In this study, the SCI-E database of the WoS core collection database is used as a data source to retrieve research papers on PFTs published between 1998 and 2017 with plant functional traits, plant functional trait, functional traits, functional trait, plant traits and plant trait used as keywords and with TS= (“plant functional trait*” OR “functional trait*” OR “plant trait*”) used as a query formula. After retrieval and screening, 1,938 papers were obtained, and a quantitative analysis was performed on publishing information (e.g., publication year, institution, author, journal, country and keywords).

2.2. Data analysis
Bibliometrix \cite{27} is a bibliometric analysis package based on the R language with powerful functions in scientific bibliometric analysis, citation network analysis and visualization. VOSviewer \cite{28} is a software program for building and visualizing bibliometric networks. The above two bibliometric analysis software programs have been widely used \cite{29}. After extracting information on 1,938 papers, the Bibliometrix package was used to perform a cluster analysis on author and country information and on cooperative relationships involved. VOSviewer was used to perform a cluster analysis on the information of main research institutions and keywords and to draw a cooperative relationship
network diagram among major research institutions and a cooccurrence network diagram of main keywords. Based on the keyword frequency and cooccurrence analysis of keywords, trends and focuses of PFTs research were examined. The ArcGIS v10.2 (ESRI, Inc., Redlands, CA) software was used to generate a distribution map of the number of papers published in countries around the world.

The impact factor and H index are important evaluation parameters of bibliometric analysis. The impact factor is an important indicator reflecting a journal’s influence, academic level and paper quality and an important reference indicator selecting journals to publish papers and for evaluating the academic level of scientific researchers [30]. The H index not only accurately measures the academic achievements of different authors in specific fields but also reflects the strengths of a country in a particular field [31,32]. Therefore, the higher the H index, the greater the degree of academic influence. In this paper, the impact factor and H index were used to reflect the academic influence of authors and countries. The impact factors of the journals were obtained by querying from the Journal Citation Report published by Clarivate Analytics in 2018, and H indexes were calculated using the Bibliometrix package.

3. Results and Discussion

3.1. Publication output

From annual changes in the 1,938 papers (Figure 1 and Table 1) it can be seen that the number of papers published annually on PFTs from 1998 to 2017 roughly involves 3 stages: a slow development period (1998-2002), steady growth period (2003-2009) and period of rapid development (2010-2017). During the slow development period, the number of published papers fluctuated slightly with an average of 15 papers published each year, and the number of authors publishing articles and H indexes remained almost unchanged. During the period of steady growth, the number of published papers increased steadily year by year; the number of authors publishing articles, the number of paper citations, and H indexes showed an upward trend. The period from 2010 has involved rapid development with a significant increase in the number of papers focusing on the subject increasing from 91 papers in 2010 to 275 papers in 2017. The number of authors publishing papers increased from 351 in 2010 to 1,375 in 2017, and the number of citations increased first and then decreased, increasing from 2,516 in 1998 to 7,311 in 2007 and then decreasing to 1,099 in 2017. The average number of citations per paper dropped from 179.71 in 1998 to 4.00 in 2017; this phenomenon can mainly be attributed to the fact that the number of citations is related to time, and it often takes a certain amount of time before the academic influence of research results can manifest.

![Figure 1. The number of periodical papers published annually from 1998-2017.](image-url)
Table 1. Characteristics of periodical papers published from 1998 to 2017

| Publication year | Author | Average number of authors | Number of references | Number of citations per paper | H index |
|------------------|--------|---------------------------|----------------------|-------------------------------|---------|
| 1998             | 45     | 3.21                      | 2,516                | 179.71                        | 13      |
| 1999             | 48     | 2.82                      | 2,440                | 143.53                        | 16      |
| 2000             | 37     | 3.36                      | 894                  | 81.27                         | 10      |
| 2001             | 43     | 3.07                      | 3,005                | 214.64                        | 14      |
| 2002             | 62     | 3.65                      | 2,602                | 153.06                        | 16      |
| 2003             | 113    | 3.23                      | 5,682                | 162.34                        | 26      |
| 2004             | 170    | 5.67                      | 6,831                | 227.7                         | 24      |
| 2005             | 202    | 3.96                      | 3,018                | 59.18                         | 30      |
| 2006             | 155    | 3.23                      | 5,493                | 114.44                        | 31      |
| 2007             | 256    | 3.46                      | 7,311                | 98.8                          | 45      |
| 2008             | 322    | 4.6                       | 6,386                | 91.23                         | 34      |
| 2009             | 276    | 3.68                      | 6,390                | 85.2                          | 39      |
| 2010             | 351    | 3.86                      | 5,920                | 65.05                         | 40      |
| 2011             | 588    | 5.07                      | 5,399                | 46.54                         | 38      |
| 2012             | 537    | 3.95                      | 4,257                | 31.3                          | 37      |
| 2013             | 736    | 4.28                      | 5,011                | 29.13                         | 37      |
| 2014             | 873    | 4.55                      | 4,362                | 22.72                         | 33      |
| 2015             | 1,189  | 5.04                      | 3,978                | 16.86                         | 30      |
| 2016             | 1,158  | 4.39                      | 2,342                | 8.87                          | 21      |
| 2017             | 1,375  | 5                         | 1,099                | 4                             | 13      |

3.2. Author analysis

In total, 5,410 authors published 1,938 papers with an average of 2.79 authors per paper. Overall, 94 authors have published more than 10 papers, accounting for 1.74% of the total, and 3,893 authors have published only one paper, accounting for 71.96% of the total number of authors. Table 2 shows the top 10 authors by the number of papers published. According to this table, the author with the largest number of published papers is Reich PB (56 papers) followed by Lavorel S (51 papers) and Garnier E (48 papers). The author with the highest H index is Lavorel S (36 papers), indicating that this author has a strong influence on the field of research on PFTs, followed by Reich PB (35 papers) and Garnier E (33 papers). The author with the most cited papers is Garnier E (48 papers), whose papers have been cited 4,289 times, and each paper has been cited 89.35 times on average; Garnier E is followed by Reich PB (56 papers) and Cornelissen JHC (40 papers), whose papers have been cited 3,374 and 3,067 times, respectively, with each paper cited 60.25 and 76.68 times on average, respectively.

The cooperation network diagram for the top 50 authors by the number of published papers (Figure 2) shows 4 kinds of clustering results among the authors, of which the most representative cooperation network is the blue clustering network, covering most of the authors, with close cooperative relationships forged between members. In the red clustering network, Lavorel S and Garnier E are core members, who have published more papers than other authors and who have developed extensive cooperation with other members. The purple and green clustering networks represent only one author, who has exhibited less cooperation with other authors and often carried out related research independently. Generally, the authors have forged close cooperative relationships.
Table 2 The top 10 most productive authors of 1998-2017

| Ranking | Author          | Number of papers | % of 1,938 | H index | Number of citations |
|---------|-----------------|------------------|------------|---------|---------------------|
| 1       | Reich PB        | 56               | 2.89       | 35      | 3,374               |
| 2       | Lavorel S       | 51               | 2.63       | 36      | 2,751               |
| 3       | Garnier E       | 48               | 2.48       | 33      | 4,289               |
| 4       | Poorter L       | 47               | 2.43       | 32      | 1,468               |
| 5       | Diaz S          | 41               | 2.12       | 27      | 2,651               |
| 6       | Cornelissen JHC | 40               | 2.06       | 29      | 3,067               |
| 7       | Wright IJ       | 38               | 1.96       | 28      | 2,778               |
| 8       | De Bello F      | 37               | 1.91       | 17      | 564                 |
| 9       | Kattge J        | 30               | 1.55       | 28      | 349                 |
| 10      | Violle C        | 30               | 1.55       | 19      | 1,001               |

Figure 2. Cooperation network of the top 50 most productive authors of 1998-2017.

Note: The size of nodes indicates the number of articles published, the thickness of connections between nodes indicates the degree of cooperation between authors, and the color of different nodes indicates different clustering results.

3.3. Country analysis

In total, 98 countries are involved in the study of PFTs, and the countries outputting the most papers are located in North America, Oceania and Europe (Figure 3). Overall, 39 countries have published more than 10 papers and 31 countries have only published one paper. Among the top 10 countries by number of published papers (Table 3), the United States has the largest number of papers, reaching 579 and accounting for 29.88% of all published papers; the United States is followed by France (302 papers) and China (279 papers); in terms of number of citations, the United States ranks first (18,942 times) followed by France (12,046 times) and Australia (9,318 times). China is third in number of papers published but represents only 3,088 citations, a far lower value than that of the United States.

The network of cooperation among the top 30 countries with the most published papers (Figure 4) shows that the United States maintains close cooperation with Australia and China while France maintains close cooperation with Australia and Germany. The cluster analysis results presented in Figure 4 show that developed countries such as European countries and the United States are dominant in the study of PFTs. Three kinds of clustering results for countries are found. The red cooperation...
network with the United States at its core covers most countries in North America, Asia, Oceania, South America, Africa, and the Pacific. The green cooperation network covers 5 countries in Europe as is of a relatively small scale. The blue cooperation network covers Mexico and Bolivia, which maintain close cooperation with each other but less cooperation with other countries.

| Ranking | Country / territory | Number of papers | % of 1,938 | Number of citations |
|---------|---------------------|-----------------|------------|--------------------|
| 1       | The USA             | 579             | 29.88      | 18,942             |
| 2       | France              | 302             | 15.58      | 12,046             |
| 3       | China               | 279             | 14.40      | 3,088              |
| 4       | Germany             | 249             | 12.85      | 4,386              |
| 5       | Australia           | 231             | 11.92      | 9,318              |
| 6       | Spain               | 188             | 9.70       | 3,109              |
| 7       | The UK              | 188             | 9.70       | 3,744              |
| 8       | The Netherlands     | 170             | 8.77       | 7,560              |
| 9       | Canada              | 153             | 7.90       | 4,694              |
| 10      | Brazil              | 117             | 6.04       | 895                |

Figure 3. The distribution of countries publishing periodical papers from 1998-2017.

Figure 4. Cooperation networks of the studied periodical papers of the top 30 countries for 1998-2017.
3.4. Institution analysis

The 1,938 papers are affiliated with 1,476 institutions, among which 207 institutions have published more than 10 papers. Among the top 10 institutions cited in the papers (Table 4) are 2 institutions each in France and the United States and one each in China, Australia, the Netherlands, Germany, and Argentina. The Chinese Academy of Sciences has published the most papers with a total of 161 (8.31%) followed by the French National Institute for Agricultural Research (94 papers) and the University of Minnesota (87 papers). In terms of the number of citations of papers published by various research institutions (Table 4), Macquarie University (16,010 times) ranks first followed by the University of Minnesota (13,843 times) and the French National Centre for Scientific Research (10,510 times).

The diagram of cooperation between major institutions (Figure 5) shows that the institution exhibiting the most extensive cooperation with other research institutions is the University of Minnesota followed by Macquarie University and the French National Center for Scientific Research. The thickness of connections between institutions indicates that the University of Minnesota and Macquarie University maintain the closest collaboration. The results of the cluster analysis reveal five kinds of clustering results for cooperative relationships between major institutions. The red cooperation network covers the most research institutions, with a total of 16; the research institution with the most published papers in this network is the Chinese Academy of Sciences; and institutions sustaining the most extensive cooperation with other research institutions are the French National Center for Scientific Research and the Free University of Amsterdam.

Table 4 The top 10 most productive institutions of 1998-2017

| Rank | Organization                                      | Country         | Number of papers | % of 1,938 | Number of citations |
|------|---------------------------------------------------|-----------------|------------------|------------|-------------------|
| 1    | Chinese Academy of Sciences                       | China           | 161              | 8.31       | 2,691             |
| 2    | National Institute of Agricultural Research       | France          | 94               | 4.85       | 4,167             |
| 3    | University of Minnesota                           | The USA         | 87               | 4.49       | 13,843            |
| 4    | French National Center for Scientific Research    | France          | 81               | 4.18       | 10,510            |
| 5    | Macquarie University                              | Australia       | 81               | 4.18       | 16,010            |
| 6    | Spanish National Research Council                 | Spain           | 71               | 3.66       | 2,905             |
| 7    | Wageningen University                             | Nederland       | 58               | 2.99       | 6,933             |
| 8    | Smithsonian Tropical Research Institute           | USA             | 56               | 2.89       | 3,625             |
| 9    | Max Planck Institute for Biogeochemistry          | Germany         | 55               | 2.84       | 4,421             |
| 10   | National University of Cordoba                    | Argentina       | 54               | 2.79       | 10,434            |
3.5. Journal analysis

The 1,938 papers studied are published in 259 different journals, of which 44 journals include more than 10 published papers, and 114 include one published paper. As seen from Table 5, the top 10 journals by number of published papers have published a total of 770 papers, accounting for 39.73% of the total number of papers published in all journals. The journal with the largest number of published papers is the Journal of Vegetation Science with a total of 122 published papers, accounting for 6.30% of the total number of papers; this journal is followed by the Journal of Ecology and New Phytologist with 114 and 100 papers, respectively, accounting for 5.88% and 5.16% of the total number of papers, respectively. In terms of journal impact factors, the journal with the largest impact factor is New Phytologist, with a factor of 7.433 followed by Functional Ecology and Journal of Ecology with impact factors of 5.491 and 5.17, respectively.

Table 5. The top 10 most productive journals in PFTs research from 1998-2017.

| Ranking | Source journal            | 2017 impact factor | Number of papers | % of 1,938 |
|---------|---------------------------|--------------------|------------------|------------|
| 1       | Journal of Vegetation Science | 2.658              | 122              | 6.30       |
| 2       | Journal of Ecology        | 5.172              | 114              | 5.88       |
| 3       | New Phytologist           | 7.433              | 100              | 5.16       |
| 4       | Functional Ecology        | 5.491              | 87               | 4.49       |
| 5       | Oecologia                 | 3.127              | 70               | 3.61       |
| 6       | Ecology                   | 4.617              | 66               | 3.41       |
| 7       | Annals of Botany          | 3.646              | 57               | 2.94       |
| 8       | PLoS One                  | 2.766              | 57               | 2.94       |
| 9       | Plant Ecology             | 1.759              | 55               | 2.84       |
| 10      | Plant and Soil            | 3.306              | 42               | 2.17       |
3.6. Keyword analysis
The 10 most frequently used keywords are PFTs, specific leaf area, functional diversity, plant traits, wood density, photosynthesis, community assembly, plant functional types, leaf traits, and climate change. A cluster analysis and keyword cooccurrence network diagram for keywords occurring more than 20 times (Figure 6) show that connections between PFTs and specific leaf area, functional diversity, and community assembly are the most pronounced, indicating that the cooccurrence frequency of these groups of keywords is the highest and that the correlations between them are the strongest, meaning that most studies focus on these topics. Keywords such as climate change, disturbance, and biodiversity also occupy important positions in the cooccurrence network. Five kinds of clustering networks are shown in Figure 6, among which the red clustering network with PFTs at its core covers the most keywords, and the clustering results reveal research conducted on the correlations between PFTs and biodiversity, disturbance, global change, and ecosystem functions and services.

The green clustering network involves the study of the responses of plants to global climate change based on functional traits. The blue clustering network covers studies of the trade-offs between different functional traits. Keywords covered in the yellow clustering network mainly focus on the important functional traits of plants. It is apparent that this clustering network mainly involves research on the distribution patterns of important functional traits and plant survival strategies. Research covered in the purple clustering network mainly focuses on the relationship between PFTs and the environment and on the role this plays in community assembly.

To better understand changes in research focuses, the top 15 keywords in terms of their frequency of use in the slow development period (1998-2002), steady growth period (2003-2009), and rapid development period (2010-2017) (Table 6) were obtained. As seen from Table 6, specific leaf area, plant functional types, and photosynthesis are the most common keywords of the field throughout the development process. Specific leaf area, disturbance and plant functional types are the most frequently used keywords in the slow development period, when research focused on the responses of functional traits to various disturbances, internal relationships between functional traits, and relationships between functional traits and climate (e.g., the study of the trade-off between different functional traits [33,34], the responses of functional traits to disturbances [35,36]. The research content of the steady growth period becomes increasingly comprehensive, and exploration of the correlation between biodiversity and ecosystems through functional traits becomes a research focus [37,38]. Research of the rapid development period focuses on community assembly [39,40] and climate change [41,42].

| Table 6. The 15 most frequently used keywords in the three periods running from 1998 to 2017. |
|-----------------------------------------------|---------------------------------------------------------------|
| Period                                      | Frequency keywords                                                                 |
| Slow development period (1998-2002)          | specific leaf area (13 times), disturbance (9 times), plant functional types (9 times), photosynthesis (6 times), nitrogen (5 times), functional groups (4 times), sclerophyll (3 times), grazing (3 times), herbivory (3 times), seed size (3 times), leaf traits (3 times), shade tolerance (3 times), allocation (3 times), climate (3 times), comparative ecology (3 times) |
| Steady growth period (2003-2009)             | plant functional traits (68 times), specific leaf area (54 times), plant functional types (26 times), functional groups (25 times), photosynthesis (21 times), plant traits (19 times), wood density (19 times), shade tolerance (16 times), biodiversity (14 times), leaf traits (14 times), functional diversity (12 times), seed mass (12 times), leaf size (12 times), grazing (12 times), stomatal conductance (11 times) plant functional traits (483 times), specific leaf area (158 times), functional diversity (112 times), plant traits (79 times), community assembly (74 times), wood density (65 times), climate change (58 times), photosynthesis (55 times), leaf traits (54 times), environmental filtering (49 times), phenotypic plasticity (40 times), competition (40 times), plant functional types (38 times), seed mass (36 times), biodiversity (35 times) |
| Rapid development period (2010-2017)         |
Figure 6. The cooccurrence network of main keywords from the articles.

Note: The size of a node indicates the frequency of keyword use; a connection between two nodes indicates a cooccurring relationship between two keywords; the thickness of a connection between two nodes indicates the cooccurrence frequency of two groups of keywords; different node colors indicate different clustering results.

4. Conclusions and Recommendations

Over the past two decades, research on PFTs have become increasingly extensive and global. Since 2010, this field has developed rapidly with a continuously increasing number of papers and continuous development expected into the future. The authors with the most published papers are Reich PB, Lavorel S, and Garnier E, and papers published by Garnier E are widely cited. The United States is the country making the greatest contribution to research on PFTs, and its research results have greatly promoted development in this field. As a representative of developing countries, China ranks third in the number of published papers, but there remains a gap in academic influence between China and other developed countries in Europe and the United States. Institutions with the largest number of published papers are the Chinese Academy of Sciences, the French National Institute for Agricultural Research and the University of Minnesota. An analysis of cooperation among major countries, institutions and authors shows that cooperation and exchanges among countries, institutions and researchers are not close enough, and a global cooperation network has not yet been formed. The top 10 journals by number of published papers account for 39.73% of all papers published in this field. The journals with the most published papers are Journal of Vegetation Science, Journal of Ecology, and New Phytologist.

The study of PFTs involves many areas of ecology such as biodiversity, community assembly, ecosystem functions and services, and global change, and it has become an effective means through which ecologists explore various emerging ecological issues. At present, the research in this field mainly focus on the spatial-temporal patterns and internal relations of functional traits, the rules of changes along environmental gradients, relationships of the coexistence mechanisms of community species and dynamic community changes, impacts on ecosystem functions, and responses to various types of disturbances. These research results provide an important theoretical basis for exploring evolving ecological issues.
Although research on PFTs is developing rapidly, some issues are still worth exploring. First, more research has been conducted on the functional traits of ground surfaces than on those of underground areas. For example, research on leaf traits is much more prominent than the research on root traits, even though root traits are important for the study of plant responses to climate change and the circulation of ecosystem nutrients. Thus, more attention should be paid to underground plant parts in the future. In addition, international cooperation is mostly carried out in developed countries such as Europe and the United States, while developing countries such as China and Brazil started researching this field later. Hence, international cooperation here still needs to be improved. Although China has published a relatively large number of papers in this field, its citation rate shows much room for improvement. In addition to the existing database of global plant traits, the establishment of regional characteristic plant trait databases such as the karst region database of plant traits, the Qinghai-Tibet Plateau database of plant traits, and the dry-hot valley database of plant traits will be of great significance in further promoting research on PFTs. Finally, more efforts should be made to use theoretical research on PFTs to guide biodiversity conservation and vegetation management. For example, biodiversity protection strategies, ecological protection redlines and vegetation restoration measures can be formulated based on the responses of PFTs to environmental changes and the related impacts on ecosystem functions.

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