Research Status and Trends of *Taxodium distichum*

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**Abstract.** In the context of intensified global climate change, *Taxodium distichum* has been attracting attention as an essential wetland plant. Through the literature visualization analysis software CiteSpace, the Spatial Distribution, Journal Distribution, Research Power, research status, and trends of *T. distichum*. The main conclusions are as follows. 1) The United States and China are the major countries for *T. distichum* research. The major institutions are Louisiana State University and the US Geological Survey. 2) The popular research areas mainly include growth, response, wetland, forest, climate change, adventitious root, and soil. 3) The research trends are soil and Florida (1992–98), survival (1999–2005), *T. distichum* (2006–12), salinity (2018–22), and sea-level rise (2020–22). These findings offer the current research status of *T. distichum* and could provide reference information for scholars in related fields to determine research directions and refine issues.

*Taxodium distichum* (Linn.) (*T. distichum*) Rich. is an ancient relict plant of *Taxodium* native to southeastern North America, from Maryland in the north, Florida in the south, and Texas in the west (Yin and Yu 2005). It was introduced to China in 1917 and cultivated for more than 100 years (Yu and Yin 2008). After years of cultivation experiments and large-scale popularization and application, this tree species has performed well in the cultivation areas of China, such as Nanjing (Yu 2008), Guangzhou (Xu et al. 2018), Chongqing (Jing et al. 2018), Shanghai (Xu et al. 2018). Notably, *T. distichum* was rated as an essential fast-growing and high-yield forest tree species by the China State Forestry Administration (Song and Song. 2018). The study analyzes the spatial distribution, journal distribution, research power, popular research areas, and comparative analysis of research trends using bibliometrics and literature visualization analysis software CiteSpace (Zhuoran et al. 2022). It aims to promote more comprehensive and in-depth research on *T. distichum* and provide reference information for scholars in related fields to determine research directions and refine issues.

**Materials and Methods**

Data source and processing. The Web of Science (WOS) Core Collection database was used as the international data source; 501 international papers were published from 1940 through mid-2022 by topic search using “TS = (Taxodium distichum) OR TS = (bald cypress)” Subsequently, “Article or Comment” was selected as the document type. The 501 English documents were first de-duplicated using CiteSpace 5.8.R1. The time window was set from Jan 1940 to Apr 2022, and the time zone to 1. Select other settings were chosen according to different research questions. The full list of publications may be obtained from the corresponding author. 

Research methods. The research methods used in this work are the bibliometric method and the mapping knowledge domains. Bibliometrics is a statistical method used to assess and quantify the growth trends of a particular topic and is widely used in scientific research in various disciplines (Guo et al. 2022; Mohammadpour et al. 2022). Therefore, this study mainly used the bibliometric method to consider the annual variations in publications of *T. distichum* research. The mapping knowledge domains can perform a visual analysis of a specific research field, which is realized by data mining, scientific measurement, information analysis, and drawing (Mohammadpour et al. 2022). CiteSpace is a visual
analysis software developed by Professor Chao- 
mei Chen from Drexel University, Philadelphia, PA, USA, based on the Java language and iteratively updated to version 5.8.R1. Many researchers use CiteSpace software to conduct mapping knowledge domain research and achieve good results (Ge et al. 2022; Guo et al. 2022). We used CiteSpace 5.8.R1 software to visualize the cooperative network, co-occurrence network, and cited cases, obtaining relevant mapping knowledge domains.

The literature resources from the WOS core collection were imported into CiteSpace software. Information such as publication year, author, institution, funding unit, and keywords of all articles were extracted. Authors and institutions were ranked according to word frequency, and major research forces were analyzed. The timeline and time zone graph of keyword clustering was obtained through the CiteSpace clustering function. Keywords that suddenly surged in a certain period were obtained through the CiteSpace clustering function. Information such as publication year, author, institution, funding unit, and keywords of all articles were extracted. Authors and institutions were ranked according to word frequency, and major research forces were analyzed. The timeline and time zone graph of keyword clustering was obtained through the CiteSpace clustering function. Keywords that suddenly surged in a certain period were obtained through the CiteSpace clustering function.

Tableau 10.5 (Seattle, WA, USA) software was used to analyze the global data distribution by country or region.

Results

Research status

Time distribution. The number of publications before 1980 is too small, and the data for 2022 is incomplete. We only analyzed the time distribution of published volume from 1980 to 2021 (Fig. 1). The number of publications has increased significantly since 1990. There were 474 after 1990, accounting for 94.6% of all documents. The minimum annual publication volume is five, and the annual publication volume in 2018 reached a maximum of 28.

Spatial distribution. This work uses the country analysis function of CiteSpace to process data. According to each country’s papers published, a map analysis was carried out with Tableau software (Fig. 2). The map analysis shows the spatial distribution characteristics of the countries or regions where T. distichum is studied. It can be seen from the statistical results that the United States and China have the first (348) and second (54) highest number of publications, respectively. The eight countries after China are Japan (26), the United Kingdom (10), Serbia (9), Mexico (7), Australia (7), Egypt (6), Iran (5), and Canada (5).

Journal distribution. Table 1 provides the top 10 journals with the highest number of publications, which can help us grasp the journal distribution. The top 10 journals contained 103 publications, accounting for 20.6% of all the publications in the literature. In descending order, the top two journals with the highest publications were Wetlands and Forest Ecology & Management. The first citation year can be traced back to 1989 and 1986 and continues today. In descending order, the five journals with an impact factor greater than 3 were Environmental and Experimental Botany, Tree Physiology, Ecological Engineering, American Journal of Botany, and Forest Ecology and Management.

Research power analysis. We processed the data with CiteSpace software to obtain the distribution of coauthors (Table 2, Fig. 3) and cooperative institutions (Table 3, Fig. 4). The top 10 authors published 130 publications, accounting for 26.0% of all the publications in the literature (Table 2). Authors with more than 20 publications include Beth A. Middleton and William H. Conner. Authors with between 10 and 20 publications include Ken W. Krauss, S. R. Pezeshki, Kenneth W. McLeod, R. R. Sharitz, and David W. Stahle. Authors with eight or nine publications include J. P. Megonigal, Changxiao Li, and Yunlong Yin. Notably Changxiao Li, Beth A. Middleton, and Ken W. Krauss belong to the US Geological Survey, and Kenneth W. McLeod and R. R. Sharitz belong to the Savannah River Ecology Laboratory. Analysis of the network of international coauthors shows (Fig. 3) that one closely cooperating research team was in the field. The research team, with Beth A. Middleton as the core and comprising Ken W. Krauss, Bobby D. Keeland, and J. A. Allen, investigated the population genetic structure, litter decomposition, carbon storage, and regeneration potential of T. distichum. Four research institutes and six higher education institutions are among the top 10 T. distichum research institutions (Table 3). The research institutes include the US Geological Survey, Institute of Botany, Jiangsu Province and Chinese Academy of Sciences, Savannah River Ecology Laboratory, and Chinese Academy of Sciences. Higher education institutions include Louisiana State University, Clemson University, University of Florida, North Carolina State University, and Southwest University. China’s Institute of Botany, Jiangsu Province; the Chinese Academy of Sciences, Southwest University; and the Chinese Academy of Sciences rank among the top 10 international research institutions. The institution with the highest total citation frequency and average citation frequency per is Savannah River Ecology Laboratory. The analysis of the network of institutes shows close communication between major research institutions, such as the US Geological Survey, Louisiana State University, and Clemson University (Fig. 4).

Fig. 1. Annual variations of Taxodium distichum documentation.
Table 1. Top 10 journals based on the number of documents.

<table>
<thead>
<tr>
<th>Journal</th>
<th>No. of documents</th>
<th>Impact factor</th>
<th>First and last cited yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetlands</td>
<td>26</td>
<td>2.204</td>
<td>1989–2021</td>
</tr>
<tr>
<td>Journal of Coastal Research</td>
<td>7</td>
<td>0.854</td>
<td>1994–2018</td>
</tr>
<tr>
<td>Environmental and Experimental Botany</td>
<td>6</td>
<td>5.545</td>
<td>1998–2015</td>
</tr>
<tr>
<td>Tree Physiology</td>
<td>6</td>
<td>4.196</td>
<td>1986–2006</td>
</tr>
<tr>
<td>HortScience</td>
<td>6</td>
<td>1.455</td>
<td>1993–2018</td>
</tr>
<tr>
<td>American Midland Naturalist</td>
<td>6</td>
<td>0.735</td>
<td>1988–2002</td>
</tr>
</tbody>
</table>

Fig. 2. Country/region distribution map based on the number of publications. Tableau 10.5 (Tableau, Seattle, WA, USA) software was used to analyze the global data distribution by country or region. Different colors represent different countries/regions, and the number of publications in gray is 0.

**Popular research areas and trends**

**Keyword clustering analysis.** The keyword timeline cluster diagram drawn by CiteSpace can directly reflect the larger keyword clusters, which helps analyze the distribution of popular research areas (Fig. 5). Table 4 shows the information on the top 10 clusters. The largest labels for each cluster are shown in the keyword timeline cluster plot, and the top two for each cluster are shown in the tabular statistics.

Among them, Cluster 0 was labeled “survival” and “salt tolerance” focused on the research of *T. distichum* for salt stress and survival (Conner and Flynn 1989). Cluster 1 was labeled “matter” and “water quality” and focused on the research of *T. distichum* on metabolites and water quality (Lundberg et al. 2011; Middleton 2020a). Cluster 2 was labeled “elevated CO₂” and “photosynthesis” and focused on the effect of elevated CO₂ on photosynthesis in *T. distichum* (Pezeshki and Santos 1998; Vann and Megonigal 2002). Cluster 3 was labeled “taxodone” and “methide tumor inhibitor” and focused on the research on compounds isolated from *T. distichum* cone extract (Bajpai et al. 2015; Kupchan et al. 1969). Cluster 4 was labeled “impact” and “drought” and focused on the research on *T. distichum*’s response to drought stress (Stiller 2009). Cluster 5 was labeled “pollution” and “acid rain” and focused on the research effects of environmental pollution and acid rain on *T. distichum* (Knight et al. 2014; Kozlowski 2000). Cluster 6 was labeled “growth response” and “growth rate” and focused on the research on *T. distichum* growth response to moisture, salinity, soil, and other factors in the external environment (Lundberg et al. 2011; Thomas et al. 2015). Cluster 7, labeled “submergence” and “Three Gorges Reservoir,” focused on the effects of long-term periodic flooding on photosynthesis and growth (Wang et al. 2016). Cluster 8 was labeled “carbohydrates” and “saline flooding” and focused on the research on the physiological response to saline flooding and carbohydrates (Iwanaga et al. 2011; Wang et al. 2019). Cluster 9 was labeled “single nucleotide polymorphisms” and “caps” and focused on the research on *T. distichum* molecular mechanisms of genetic diversity and resistance (Duan et al. 2020; Tsunura et al. 1999).

**Keyword Timezone analysis.** The data were subjected to Timezone view analysis to obtain the evolution path of the keyword (Fig. 6). Analyze the keyword evolution path to obtain *T. distichum*’s development trend. *T. distichum*’s research can be traced back to 1940 or earlier, but high-frequency keywords were concentrated in 1991–2022. We divided the study period into three parts to explore the research topics more accurately. The first stage was from 1991 to 2000, mainly to study the effect of climate change on growth, the higher inundation threat caused by sea-level rise, and the response to flood stress (Ghanbary et al. 2012; Middleton 2009b; Zhai et al. 2018). Popular research areas include growth, climate change, forests, wetlands, roots, soils, gas exchange, sea-level rise, tolerance, and water. The second stage was from 2001 to 2010, mainly to study the response to salinity stress, the adventitious
roots under flooding stress, and the photosynthetic acclimation to high CO₂ (Guibin and Fuliang 2004; King et al. 2011). Popular research areas include salinity, rhizosphere, competition, atmospheric CO₂, adventitious roots, flood tolerance, forest wetlands, photosynthetic acclimation, and heartwood. The third phase is from 2011 to the present, mainly studying the community structure of *T. distichum* in wetland forests and the effects of hydrology and hurricanes on the forest structure and growth of *T. distichum* other species (Conner et al. 2014; Kimbrough et al. 2019). Research hotspots mainly include floodplain woodland, timber harvesting, nutrient dynamics, hurricanes, freshwater, light, ecosystem services, carbon isotope identification, coastal forests, and biomarkers.

**Keyword burst analysis.** A keyword burst describes the event when a keyword increases sharply in frequency (Huang et al. 2020). Table 5 lists the keywords with the strongest citation bursts in different periods and shows the research topics of *T. distichum* and their changes. Table 5 shows the first and last times for each keyword, reflecting the persistence of the keyword’s influence. In addition, the blue squares indicate the entire study period (1991–2022), whereas the red squares indicate the duration of citation bursts (Qi and Liu 2018).

According to the keyword burst analysis results, the research topics were soil and Florida from 1992 to 1998. The effects of soil moisture, salinity, and redox conditions on the growth and root system of *T. distichum* were studied (Pezeshki and DeLaune 1998). Florida became a hot spot for *T. distichum* research (Noel et al. 1995). The research topic from 1999 to 2005 was survival, focusing on the growth and survival of *T. distichum* in wetland and swamp cultivation (Conner and Flynn 1989). From 1999 to 2005, survival was the research topic, mainly studying the growth and survival of *T. distichum* in wetlands and marsh cultivation. From 2006 to 2012, the research topic was *T. distichum*. The research since 2018 is salinity, which mainly studies the effect of salinity on the growth and community structure of *T. distichum* (Kimbrough et al. 2019). The research topic for 2020 to date was sea-level rise. *T. distichum* is mainly distributed in swamps and floodplains along rivers. Climate change makes the sea level rise, threatening *T. distichum* with long-term flooding, and the flooding time and depth will gradually increase (Zhai et al. 2018). Therefore, the impact of sea-level rise on the growth and survival of *T. distichum* has become a research trend.

![Network of coauthors and the strongest collaborations among them international. CiteSpace 5.8.R1 software was used for author analysis. Big names indicate high frequency, and large nodes indicate strong connections with other authors. The top 20 authors are retained for clarity of the figure.](image-url)
Table 3. Top 10 institutions in China and internationally based on the number of documents.

<table>
<thead>
<tr>
<th>Institution (international)</th>
<th>Number of documents</th>
<th>Total citation frequency</th>
<th>Avg citation frequency per paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Louisiana State University</td>
<td>64</td>
<td>761</td>
<td>11.89</td>
</tr>
<tr>
<td>US Geological Survey</td>
<td>54</td>
<td>722</td>
<td>13.37</td>
</tr>
<tr>
<td>Clemson University</td>
<td>24</td>
<td>299</td>
<td>12.46</td>
</tr>
<tr>
<td>University of Georgia</td>
<td>20</td>
<td>185</td>
<td>9.25</td>
</tr>
<tr>
<td>University of Florida</td>
<td>16</td>
<td>200</td>
<td>12.50</td>
</tr>
<tr>
<td>North Carolina State University</td>
<td>15</td>
<td>97</td>
<td>6.47</td>
</tr>
<tr>
<td>Institute of Botany, Jiangsu Province, and the Chinese Academy of Sciences</td>
<td>10</td>
<td>91</td>
<td>9.1</td>
</tr>
<tr>
<td>Savannah River Ecology Laboratory</td>
<td>10</td>
<td>872</td>
<td>87.2</td>
</tr>
<tr>
<td>Southwest University</td>
<td>10</td>
<td>86</td>
<td>8.6</td>
</tr>
<tr>
<td>Chinese Academy of Sciences</td>
<td>10</td>
<td>104</td>
<td>10.4</td>
</tr>
</tbody>
</table>

**Research status**

The United States and China are the major countries for *T. distichum* research. They have close cooperative relationships with most countries or scientific research institutions in the cooperative network. Research on *T. distichum* involves resistance to flooding, wetland forests, soils, population numbers, salinity, nutrient dynamics, litter decomposition and rhizosphere microorganisms (Middleton 2020b; Pezeshki and Santos 1998; Thomas et al. 2015). The most attention is the resistance to flooding. Knee root, adventitious root, aerenchyma, antioxidant system, and gas exchange were studied (Anderson and Pezeshki 2000; King et al. 2011). In addition, global warming has also become the focus of international attention. Sea-level rise and atmospheric CO2 enrichment caused by climate change will affect the growth and survival of *T. distichum* and photosynthesis (Middleton et al. 2021; Zhai et al. 2018).

There are two main teams of *T. distichum* research in China: the research team composed of Yunlong Yin, Chaoguang Yu, Jianhua Xu, et al.; and the research team composed of Fuliang Cao, Guibin Wang, Qiming Wang, et al. Major research institutions in China are the Institute of Botany, Jiangsu Province; the Chinese Academy of Sciences; Nanjing Forestry University; Southwest University; Hubei Afforestation of Forestry; and Jiangsu Academy of Forestry. The primary international team consists of Beth A. Middleton and S. R. Pezeshki et al. The major international research institutions are the US Geological Survey, Louisiana State University, Clemson University, University of Georgia, and University of Florida.

**Popular research areas**

*Abiotic stress.* For *T. distichum*, the most commonly encountered abiotic stress is flooding. Soil hyphoxia caused by flooding adversely affected net photosynthesis and plant height growth (Kladze et al. 1994). Soil hyphoxia resulted in low soil redox potential and inhibited root elongation. Low soil redox potentials resulted in a changed cellular structure in the cortex of *T. distichum*. Increased alcohol dehydrogenase activity indicates stimulation of alcoholic fermentation. Alcohol fermentation and anatomical changes contribute to the flood resistance of *T. distichum* (Pezeshki 1991). The concentrations of oxalic acid, tartaric acid, and malic acid in the roots of *T. distichum* were affected by flooding in winter. However, organic acid metabolism would be regulated to normal levels in spring. The root system’s stable organic acid metabolism helps resist flooding (He et al. 2021).

Iwanaga et al. (2015) found that periodically flooded *T. distichum* saplings showed no significant growth or changes in morphology and anatomy under water, such as bud elongation and adventitious root formation development. The physiological characteristics of suspended growth and metabolism allow it to survive a long period of complete flooding (at least 2 years). Megenigal and Day (1992) found that continuously flooded *T. distichum* would show morphological adaptation, including the production of water roots, development of intercellular air spaces, and distinctly different root-system morphologies. Periodically flooded *T. distichum* allocated more carbon to roots than continuously flooded *T. distichum* and developed deeper root systems. Continuously flooded *T. distichum* had low root-to-shoot ratios and shallow root systems. A relatively shallow rooting zone with ample water and nutrients allowed continuously flooded *T. distichum* to allocate relatively more biomass to leaves. Periodically flooded saplings had higher underground yields, whereas continuously flooded saplings had higher above-ground yields (Elian and Pezeshki 2002).

Flooding inhibited the absorption of N and P and increased the ratio of nonstructural carbohydrates to N or P. *T. distichum* is well adapted to submerging because it balances growth through the regulation of nonstructural carbohydrate synthesis and storage (Nyman and Lindau 2016; Wang et al. 2019). In general, C content showed leaves > branches > fine roots; the contents of N and P showed leaves > fine roots > branches. *T. distichum* can maintain normal growth needs by reasonably distributing nutrients among different organs to adapt to long-term periodic flooding (Ding et al. 2021).

Martin and Francke (2015) proved that *T. distichum’s* knee roots function as pneumatophores. When roots were submerged, the roots’ internal air O2 concentration was much higher than when the knee roots were above water. Kernell and Gerald (1990) found that the knee roots of *T. distichum* increased with the depth of water, but Middleton (2020a) and Martin and Francke (2015) found that this was not always the case. Knee roots respond to the interaction of flood environment, climate, temperature, and precipitation. Fukuj (1992) even found that the knee root’s formation decreased with increasing flooding depth. The xylem anatomy of knee roots resembled that of the xylem in the submerged portions of stems of deeply flooded trees. Flooding stimulates ethylene production in stem skin and root tips of knee roots. Ethylene and auxin interact in *T. distichum’s* response to flooding. The story of *T. distichum’s* knee root is more complicated than we know.

*T. distichum* cultivated in coastal areas face salt stress. The average annual soil salinity could reach a high level in the coastal swamp of the Mississippi River Deltaic Plain. In areas frequently invaded by saltwater, the
cumulative tree mortality rate was up to 85% (Hoeppner et al. 2008). The inhibition of photosynthesis by salt submergence reduced the biomass of leaves and stems but did not affect the biomass of roots. The contents of Na⁺ and K⁺ in seedlings increased with the salt concentration (Iwanaga et al. 2011). T. distichum saplings submerged in saltwater showed no morphological changes during the flooding treatment. However, leaf injury and shoot dieback were observed in drained saplings submerged in saltwater (Iwanaga et al. 2009).

Lei and Middleton (2018) investigating seed banks in the Mississippi River Alluvial Valley and the northern Gulf of Mexico, found that repeated droughts reduced the regenerative capacity of T. distichum seeds. Drought can also lead to a 20% to 60% decline in T. distichum growth (Powell et al. 2016). However, stress-affected biomass allocation increased xylem strength and reduced vulnerability to xylem cavitation, and the effect of drought was more evident than salinity (Stiller 2009). In addition, T. distichum showed an obvious morphological mechanism of increasing the specific mass of leaves under drought stress (Nash and Graves 1993). Domene et al. (2021) found that drought, flooding, and flooding plus salinity reduced K (root) and root aquaporin activity in Pinus taeda, whereas K (root) of the flood-tolerant T. distichum did not decline under flooding.

Aquaporins provide new insights into physiological responses to drought, flooding, and salinity. Elcan and Pezeshki (2002) demonstrated that earlier flooding did not increase subsequent susceptibility to drought by comparing gas exchange rates and growth responses between post-control drought and post-flood drought Cunninghamia alba seedlings. Photosynthesis. The external (leaf zone) pCO₂ rises from 40 to 80 Pa, and the leaf photosynthesis of T. distichum rises significantly. Increased carboxylation of rubisco by continuous light offset the photosynthetic response to high CO₂. However, the strong acclimation of Rubisco’s carboxylation ability was not always accompanied by carbohydrate accumulation. Light and CO₂ cooperatively regulate the balance of carbon and nitrogen sources and sinks in plants (Neufeld 1983; Osborne and Beerling 2003). When T. distichum experiences periodic flooding in the hydro-fluctuation zone of the Three Gorges Reservoir, its photosynthesis decreases significantly. Both moderate and deep flooding can reduce the chlorophyll content in the leaves of T. distichum and significantly reduce photosynthesis (Wang et al. 2016). In addition, the net assessment rate and relative growth rate of T. distichum are always positive during flooding (Nash and Graves 1993). Flooded, the net photosynthetic rate was significantly higher in aerated unrestricted roots than in aerated root restricted and in anaerobic root unrestricted than in anaerobic root restricted plants (Pezeshki and Santos 1998). Net photosynthesis declined from 7.6 umol·m⁻²·s⁻¹ to 0.9 umol·m⁻²·s⁻¹ when salinity increased from 0 to 140 mol·m⁻³ NaCl. The concentrations of Na, K, Ca, and Mg ions in leaves increased significantly with flood salinity. Despite the parallel reduction in stomatal conductance and net photosynthesis, the leaf’s internal CO₂ concentrations remained relatively constant. Salt stress leads to excessive accumulation of some ions in leaf tissues of T. distichum, accompanied by diffusion limitation due to stomatal closure, which leads to decreased photosynthesis (Pezeshki et al. 1988). Other studies indicate that when salinity floods increase in coastal areas, the degree of impact on photosynthesis is related to its flood tolerance (Kenneth et al. 1999).

Breeding. Taxodium has outstanding water logging tolerance and has significant ecological and economic value in wetland forestry production. The selection and breeding of excellent varieties are of great significance for the development and utilization of Taxodium. Taxodium includes three species: Taxodium distichum (T. distichum), Taxodium mucronatum (T. mucronatum), and Taxodium ascendens (T. ascendens). Since 1973, interspecific hybridization of Taxodium and breeding of fast-growing alkaloid tolerant varieties have been carried out at the Institute of Botany, Jiangsu Province, and the Chinese Academy of Sciences (Yu and Yin 2008). The first batch of T. distichum (♂)×T. mucronatum (♀) produced five excellent hybrids plant. Three fast-growing and alkaloid-resistant clones were obtained through the cutting propagation test, named ‘Zhongshanshan 301’, ‘Zhongshanshan 302’, and ‘Zhongshanshan 401’, respectively (Chen et al. 2006). After that, the excellent clones cultivated by T. mucronatum (♂)×T. distichum (♀) was named ‘Zhongshanshan 405’, ‘Zhongshanshan 406’, ‘Zhongshanshan 407’, ‘Zhongshanshan 502’, ‘Zhongshanshan

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Fig. 5. Timeline map of keyword clustering. The plus signs represent nodes in different years, and the size of nodes represents the frequency of keywords. Different colored lines represent different clusters.

Table 4. High-frequency keyword clustering.

<table>
<thead>
<tr>
<th>Cluster ID</th>
<th>Size</th>
<th>Silhouette</th>
<th>Mean cited yr</th>
<th>Label (LLR)¹³</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>61</td>
<td>0.752</td>
<td>2005</td>
<td>survival (9.54), salt tolerance (8.19)</td>
</tr>
<tr>
<td>1</td>
<td>57</td>
<td>0.695</td>
<td>2006</td>
<td>matter (7.9), water tolerance (4.38)</td>
</tr>
<tr>
<td>2</td>
<td>56</td>
<td>0.754</td>
<td>2005</td>
<td>elevated CO₂ (22.26), photosynthesis (9.52)</td>
</tr>
<tr>
<td>3</td>
<td>54</td>
<td>0.934</td>
<td>2007</td>
<td>taxodone (10.33), methide tumor inhibitor (10.33)</td>
</tr>
<tr>
<td>4</td>
<td>53</td>
<td>0.827</td>
<td>2003</td>
<td>impact (13.23), drought (8.96)</td>
</tr>
<tr>
<td>5</td>
<td>42</td>
<td>0.87</td>
<td>2007</td>
<td>pollution (4.83), acid rain (4.83)</td>
</tr>
<tr>
<td>6</td>
<td>41</td>
<td>0.818</td>
<td>1997</td>
<td>growth response (5.73), growth rate (4.67)</td>
</tr>
<tr>
<td>7</td>
<td>30</td>
<td>0.927</td>
<td>1998</td>
<td>submergence (9.24), Three Gorges Reservoir (7.59)</td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td>0.821</td>
<td>2008</td>
<td>carbohydrates (6.72), saline flooding (6.72)</td>
</tr>
<tr>
<td>9</td>
<td>29</td>
<td>0.937</td>
<td>2002</td>
<td>single nucleotide polymorphisms (7.35), caps ¹ (7.35)</td>
</tr>
</tbody>
</table>

¹ LLR = Log-likelihood rate.
³ caps = cleaved amplified polymorphic sequences.
Soil 3.64 1992 1998
Sea-level rise 3.50 2020 2022
Survival 4.23 2018 2022
Taxodium distichum 3.83 2006 2012
Survival 3.52 1999 2005

Table 5. Keywords with the strongest frequency bursts. The red squares represent the years in which keywords had citation bursts; the blue squares represent the years in which keywords did not.

<table>
<thead>
<tr>
<th>Keywords</th>
<th>Strength</th>
<th>Begin</th>
<th>End</th>
<th>1991–2022</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>3.64</td>
<td>1992</td>
<td>1998</td>
<td></td>
</tr>
<tr>
<td>Survival</td>
<td>3.52</td>
<td>1999</td>
<td>2005</td>
<td></td>
</tr>
<tr>
<td>Taxodium distichum</td>
<td>3.83</td>
<td>2006</td>
<td>2012</td>
<td></td>
</tr>
<tr>
<td>Survival</td>
<td>4.23</td>
<td>2018</td>
<td>2022</td>
<td></td>
</tr>
<tr>
<td>Sea-level rise</td>
<td>3.50</td>
<td>2020</td>
<td>2022</td>
<td></td>
</tr>
</tbody>
</table>

Studies of hurricane, earthquake, isotope, trace elements, and paleoclimate. Middleton (2009a) and Ramsey et al. (2009) found that after Hurricane Katrina hit the Gulf Coast of Mississippi and Louisiana, mixed T. distichum forests were less affected. The damage of T. distichum in the mixed forest was largely limited to foliage loss and can rapidly recover. Compared with T. distichum, Acer rubrum, Liquidambar styraciflua, Quercus lyrata, and Quercus nigra suffered more damage, indicating that T. distichum had good wind resistance. Stahle et al. (1992) studied the growth response of T. distichum in Reelfoot Lake, TN, to the great New Madrid earthquake of 1811–12. These responses include a significant surge in radial growth during the decade following the earthquakes and a permanent reduction in wood density beginning in 1812. Anderson et al. (2005) performed isotopic studies of T. ascendens and T. distichum from various locations in South Florida. They found that T. ascendens isotopic time series positively correlated with the total amount of annual precipitation. In contrast, the T. distichum data had two records dependent on the level of saltwater stress. They then proposed a conceptual model based on changes in carbon assimilation and isotopic fractionation to explain the isotopic records from both sites. Galicki et al. (2008) investigated the migration capacity of trace elements in T. distichum using cores from century-old trees from a wetland in Humphreys County, MS. Clear evidence of P and Mn translocation to the sapwood and K, Mg, and Na to the heartwood. Ca and Zn were found with higher average concentrations in the sapwood, although evidence of translocation to the sapwood was equivocal. Delong et al. (2021) found that the late Pleistocene T. distichum stumps were 18 m below the sea surface of Gulf Shores, AL. They performed geophysical properties along with micropaleo and stratigraphical analysis of the stump. They hypothesize that rapid sea-level rise occurring ~60 or ~40 ka ago provided opportunities for local floodplain aggradation to bury the swamp, thus preserving the stumps.

Fig. 6. Timezone view of Taxodium distichum research keywords. Large keywords indicate high frequency, and the plus signs represent the node of the keyword. Different colors represent different time zones.
Research trends

The difference in high-frequency keywords in different periods shows that the research focus on *Taxodium distichum* has changed over the years. Before 2000, many articles studied wetland afforestation, water tolerance, and soil and gas exchange. Since 2000, the research content has become richer, with a significant increase in articles on salt stress, atmospheric CO₂, photosynthetic adaptation, wood harvesting, nutrient dynamics, and chemical extracts. The research has shifted from focusing on *T. distichum* itself in the early days to combining it with international concerns such as climate change and sea-level rise. Research has shifted from focusing only on basic research related to *T. distichum* to integrating with international concerns such as climate change and sea-level rise.

Conclusions

*T. distichum* has received extensive attention. This article analyzes the research status and trends for *T. distichum* from the perspective of literature measurement. The following conclusions can be drawn based on the focus of research in different periods.

1. The number of publications on *T. distichum* have shown a growing trend, and research power is mainly concentrated in the United States and China.
2. There are two main areas of research. One is the study of the water tolerance mechanism, which is closely related to adventitious root, root knot, nutrient dynamics, photosynthesis, nutrient utilization, and morphological adaptation. The other is the new variety breeding, closely related to cross-breeding and clonal-cutting propagation.
3. Early research on *T. distichum* focused on growth, wetland afforestation, water tolerance, and ecosystem services. After the 20th century, studies began to focus on climate change, sea-level rise, atmospheric CO₂, acid rain, and pollution.
4. In *T. distichum* research, the emergence of chemistry, medicine, and pharmacy indicates additional advancements for future cross-disciplinary research.

On the basis of the bibliometric survey of trends in this area, we believe that future direction is likely to focus on the following areas. 1) The active interinstitutional and interdisciplinary communication and cooperation among the core authors benefit the research of *T. distichum*. 2) *T. distichum* has a remarkable ability to withstand flooding, but the mechanism research is mainly at the physiological level, whereas molecular-level research is scarce. 3) Climate change will exacerbate the length and depth of *T. distichum* flooding. The research on *T. distichum*’s underwater photosynthesis is still lacking. 4) How to use molecular breeding and transgenic breeding to make up for the shortcomings of traditional breeding methods and achieve the precision of breeding goals is a challenge.

References Cited


