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Responses of Pine and Oak Species to Drought: A Bibliometric Analysis

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ABSTRACT

Pines (*Pinus*, with approximately 113 species) and oaks (*Quercus*, with around 435 species) are key genera that form forests across the entire Northern Hemisphere. These regions are often associated with seasonal drought and forest fires, worsening conditions due to climate change. In this study, we used bibliometric techniques to analyse research patterns regarding the drought responses of pine and oak species from 1977 to 2024. Our analysis relied on the Web of Science (WoS) database, focusing on publications indexed in both the Science Citation Index and the Social Science Citation Index. Our review included 104 studies examining 29 pine and 42 oak species in 58 combinations. Notably, many pine and oak species have yet to be studied. The most researched species include *P. sylvestris* (27 studies), *P. halepensis* (25 studies), and *Q. ilex* (27 studies). Geographically, the Mediterranean basins were found to be the most prominent areas of study. Much of the research originated in the United States and France, while recent contributions have come from China, Spain, and Canada. Research publications on this topic have increased since the 1990s, with noticeable peaks in 2008, 2011, and 2023. The journals contributing significantly to this body of knowledge include Tree Physiology, Forest Ecology and Management, and the Journal of Experimental Botany. Interestingly, while drought is a crucial aspect of plant ecology, much research has focused on physiological and botanical considerations. In the past two decades, there has been a marked increase in integrating climate-related variables with traditional physiological components and water management. The bibliometric analysis concluded that, at the genus level, the primary strategy of pines in response to drought stress is predominantly isohydric, while oaks tend to be anisohydric. This difference allows oaks to maintain gas exchange and carbon fixation, even for increased water loss. The shared occurrence of pine and oak species throughout the Northern Hemisphere suggests that proper management practices can be developed to promote the growth of one species through the other, especially by learning from post-drought recovery processes and succession.

Key words: Hydraulic safety margin; Isohydric and Anisohydric behaviour; *Pinus halepensis*; *P. sylvestris*; *Q. ilex*; Water Potential

INTRODUCTION

Pine-oak forests are ecologically vital ecosystems in the Northern Hemisphere, spanning continents from North America to Eurasia. Interestingly, oak and pine trees often grow together despite a significant gap in their evolutionary history. These forests are rich in biodiversity, supporting numerous species, including many endemics, and play a crucial role in global carbon cycling and climate regulation. They exemplify ecosystem resilience. Many local communities depend heavily on these forests for subsistence (Singh and Singh 1992). The genera *Pinus*, with approximately 113 species (Farjon and Filer 2013), and *Quercus*, with around 435 species (Denk et al. 2017), are among the most important tree-forming groups in the Northern Hemisphere (Gernandt et al. 2005). They significantly contribute to carbon sequestration in temperate and subtropical regions and are essential for maintaining hydrological regimes and soil stability. However, Pine-Oak forests are increasingly facing water stress due to climate change, which is characterised by altered precipitation patterns and rising temperatures. This water stress can have severe implications for these forests, impacting tree physiology, reducing forest productivity, and changing species composition. Therefore, the resilience of Pine-Oak forests to water stress is critical for ecological stability and ecosystem services, such as water filtration, air quality improvement, and carbon storage. Understanding how Pine-Oak species adapt to water stress is essential for developing effective forest management and conservation strategies (Li et al. 2024). As water stress is likely to worsen with ongoing climate warming, forest management practices must include adaptive strategies to enhance the resilience of these ecosystems. Given the ecological importance of Pine-Oak forests and the increasing threats posed by water stress, it is crucial to systematically assess how these forests adapt to changing environmental conditions across the Northern Hemisphere. While several global analyses exist on the ecology of temperate forests, tropical forests, or those dominated by Dipterocarps and conifers, the ecological aspects of pine-oak forests have not been extensively studied. This research employs a bibliometric analysis to quantitatively evaluate the global research landscape regarding Pine-Oak forests' adaptations to water stress. By examining patterns in the scientific literature, we aim to uncover prevalent themes, identify gaps in current research, and highlight the most effective documented strategies (Li et al. 2025). Our main research question is: What mechanisms and strategies do Pine-Oak forests adopt globally under varying water stress conditions? Our hypotheses are: (i) the species within the two genera differ in hydraulic safety margins, thus avoiding direct competition and employing complementary approaches; and (ii) different strategies adopted by pine and oak species in response to water stress are likely to be associated with their respective genera at a global scale. The objectives of this study are: (i) to analyse research trends related to water stress and the social aspects of research approaches and species investigated; (ii) to evaluate the responses of pine and oak species to drought stress globally, focusing on isohydric and anisohydric strategies, hydraulic safety margins, and forms of stomatal regulation and related parameters; and (iii) to examine how global research communities have collaborated to study the responses of pine and oak to drought.

Here, we analyse (i) keywords, citations, and co-authorship networks to determine the evolution of research themes and the interconnections between them and (ii) adaptive strategies which are most frequently explored and which are emerging as potentially vital under current and projected climate scenarios.

MATERIAL AND METHODS

Data collection

This bibliometric study was conducted using the Web of Science (WoS) database, focusing specifically on publications indexed in the Science Citation Index (SCI) and Social Sciences Citation Index (SSCI). A comprehensive search strategy was employed to gather articles discussing Pine-Oak forests' adaptive strategies in response to water stress between 1977 and 2024. The search included a combination of terms targeting Pine and Oak species and their physiological responses to water stress and drought conditions. The exact search string used was: Keywords: (AB = ("Pine" OR "Pinus" OR "Subgenus pinus" OR "Diploxylon" OR "Haploxylon" OR "Subgenus strobus") AND AB = ("Oak" OR "Quercus" OR "Subgenus quercus" OR "Subgenus cerris") AND TS = ("Hydraulic safety" OR "Water potential" OR "Hydraulic safety margin" OR "Water stress" OR "Isohydric behavior" OR "Anisohydric behavior" OR "Predawn tree water potential" OR "Hydraulic conductivity" OR "Xylem cavitation" OR "Osmotic adjustment" OR "Stomatal and leaf conductance" OR "Leaf conductance" OR "Stomatal regulation") OR AB = ("Hydraulic safety" OR "Water potential" OR "Hydraulic safety margin" OR "Water stress" OR "Isohydric behavior" OR "Anisohydric behavior" OR "Predawn tree water potential" OR "Hydraulic conductivity" OR "Xylem cavitation" OR "Osmotic adjustment" OR "Stomatal and leaf conductance" OR "Leaf conductance" OR "Stomatal regulation") AND TS = ("Drought" OR "Water stress" OR "Drought adaptations" OR "Water stress adaptations" OR "Drought resistance" OR "Drought tolerance" OR "Environmental stress response" OR "Tree water potential" OR

"Phenological responses" OR "Timing of seed germination" OR "Leaf expansion" OR "Leaf drop" OR "Flowering"). English Language was selected with no restrictions of publication years, *i.e.*, all the available information on the topic was considered in the database, allowing a comprehensive review of the literature from the database's inception to the present, i.e., April 2024.

Bibliometric analysis

The collected data were analysed using statistical methods and bibliometric software. Descriptive statistics were employed to assess trends over time and understand publications' distribution by geography and authorship. VOSviewer tool was used to construct and visualise bibliometric networks. It helped identify the major keywords and their interrelationships, highlighting the core areas of research within the studies collected. Another advanced bibliometric method was applied using the Bibliometrix R package, facilitating comprehensive data analysis, including citation analysis, co-authorship networks, and thematic mapping (Li et al. 2022).

Data extraction and further analysis

Data on publication year, author details, institutional affiliations, and geographical information of the studies were extracted. Key findings related to hydraulic adaptations and other physiological responses to drought and water stress were categorised and tabulated for further analysis.

RESULTS

Species investigated

Across all the studies 71 pine and oak species have been studied out of total 548 known of which 29 (25.7% of total *Pine* species of the world) were pine and 42 (9.6% of the total oak species globally) were oak species. There were 58 combinations, of which 18 had two oak species, and two had more than two. For pines, there were five studies with two pine species, and three had more than two pine species, and in the remaining combinations, there was a pair of one pine and one oak species. Among the pines, *P. sylvestris* occurs in 27 studies and *P. halepensis* in 25 studies. Among the oaks, *Q. ilex* was most frequently investigated. Among the species combinations, *P. halepensis* – *Q. ilex* was the most common (studied 13 times). However, *P. halepensis* also occurred with *Q. coccifera, Q. faginea, Q. petrea, Q. calliprinos*. *Q. pubescens, Q. ithaburensis, Q. robur* and *Q. suber*. *P. sylvestris* occurred with *Q. robur, Q. faginea, Q. ilex, Q. pyrenaica, Q. subpyrenaica, Q. pubescens,* and *Q. petrea*.

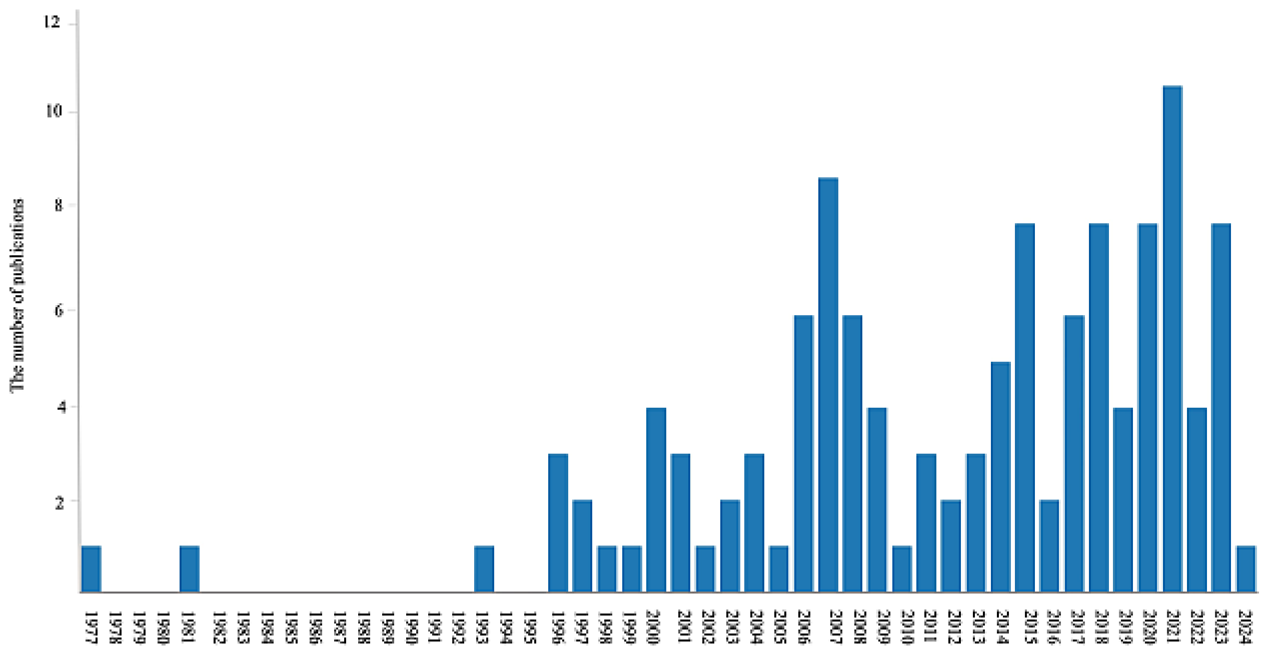
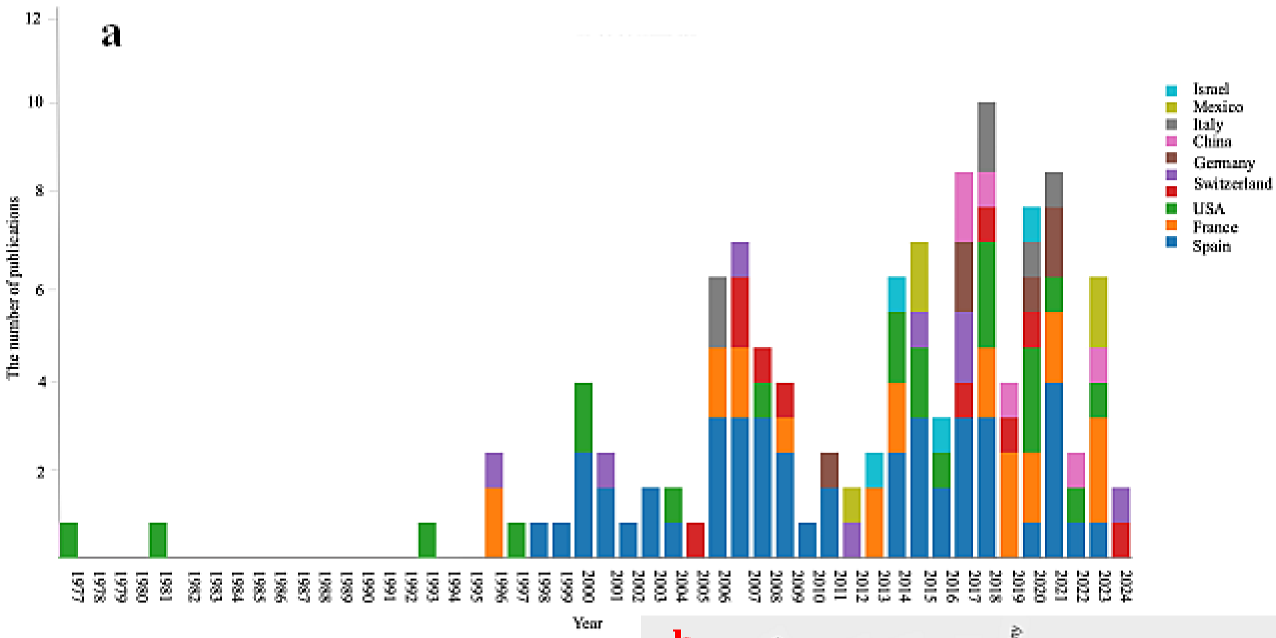


Figure 1. Annual scientific articles on the adaptive strategies to water stress of Pine-Oak forests



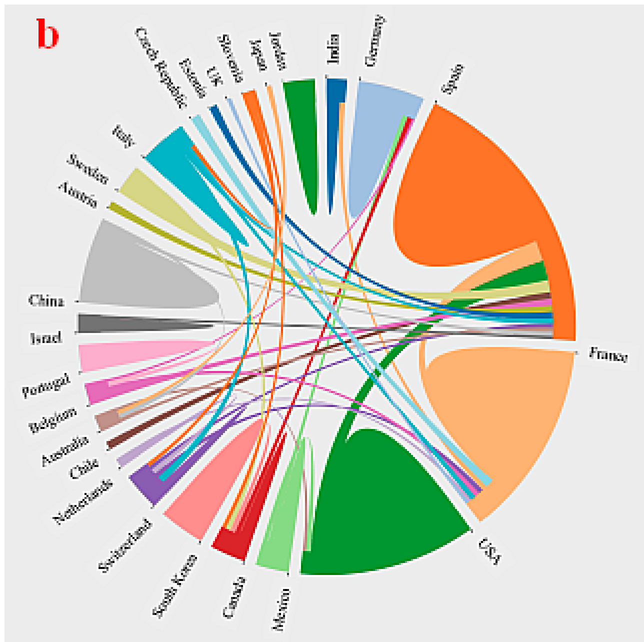


Figure 2. Articles on the adaptive strategies to water stress of Pine-Oak forests include (a) Year-wise distribution of articles published by different countries and (b) inter-country partnerships for articles to be published

Publication trends

The number of publications on adapting pine and oak species to water stress has steadily increased since the 1990s. The results show noticeable peaks in 2008, 2011, and 2023. The overall trend of research publications shows an upward increase but with several fluctuations (Fig. 1).

Geographic distribution

Contributions from various countries have shown fluctuations year to year, with a notable increase in the number of articles published, particularly between 2007 and 2009, as well as between 2021 and 2023 (Fig. 2a). The United States and France are prominent in this field of research, with their combined efforts accounting for a substantial proportion of research outputs, especially during the 2007-2009 period. Furthermore, contributions from Canada, China, and Spain have seen significant growth in the recent period between 2021 and 2023. In the research network depicted (Fig. 2b), the United States (indicated by the green area) and France (represented by the orange area) occupy a considerable proportion. The strong and extensive connections between France and countries such as Spain and Germany and those between the US and its neighbours Mexico and Canada underline robust bilateral research collaborations. Additionally, smaller countries like Israel, Belgium, and Portugal have made noteworthy contributions to research through their networking and cooperative efforts with more established nations. In summary, networking at the country level has been instrumental in advancing research on water relations in pine-oak forests.

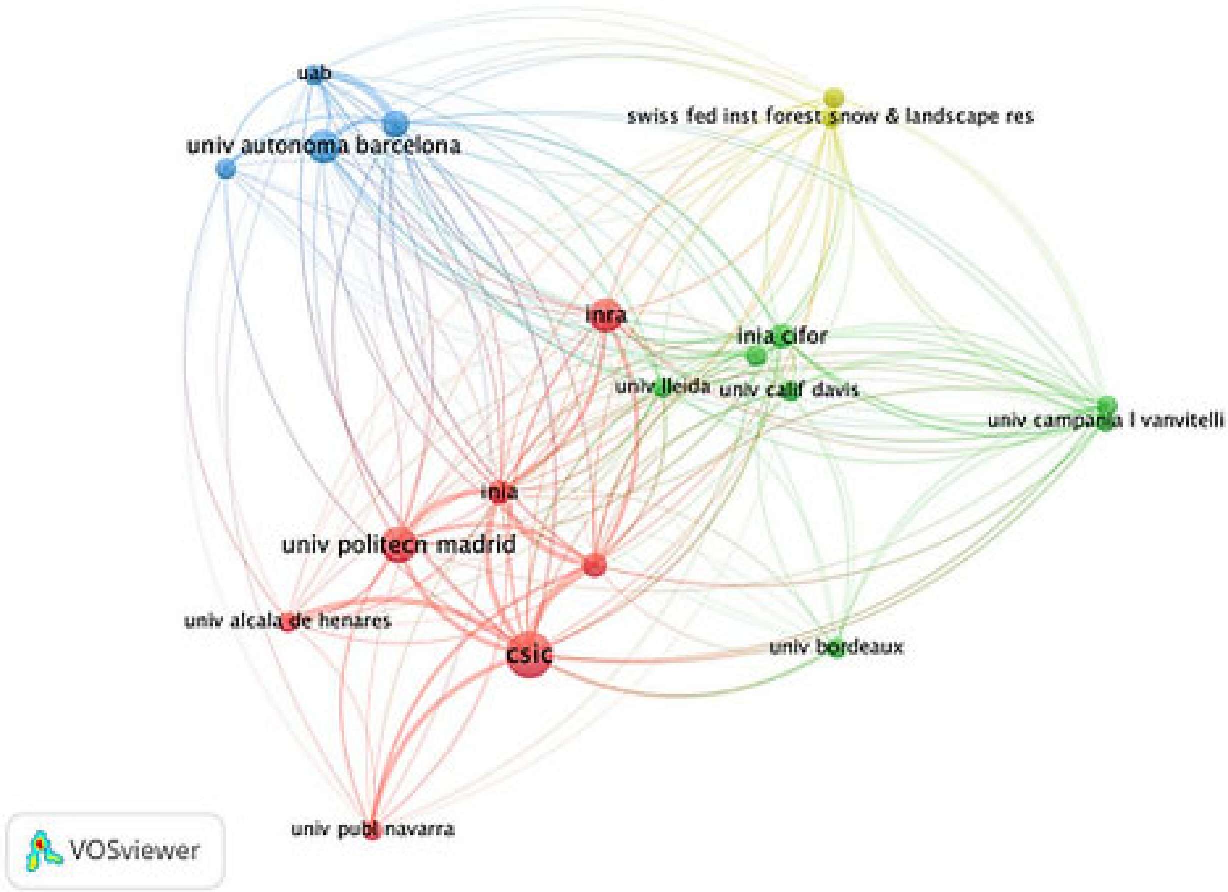


Figure 3. Research institutes collaborate with a network of scientific articles on the adaptive strategies to water stress of Pine-Oak forests

Table 1. Institute wise details of published articles on the adaptive strategies to water stress of Pine-Oak forests

Institute	**TN**	**TC**	**AC**	**NF**	**FTC**	**FAC**
CSIC	12	24	2	7	3	0.43
Univ Complutense Madrid	2	22	11	1	11	11
INRA	11	16	1.45	4	7	1.75
Univ Autonoma Barcelona	7	14	2	6	12	2
Univ Bern	3	13	4.33	1	5	5
INIA CIFOR	5	12	2.4	4	8	2
Univ Lleida	4	11	2.75	2	11	5.5
Swiss Fed Inst Forest Snow & Landscape Res	3	10	3.33	2	8	4
Univ Publ Navarra	3	9	3	3	9	3
INIA	4	8	2	1	2	2

TN: Total number of articles; TC: Total number of citations; AC: Average number of citations; NF: Total number of first authorship; FTC: Number of citations in first authorship; FAC: Average citations in first authorship.

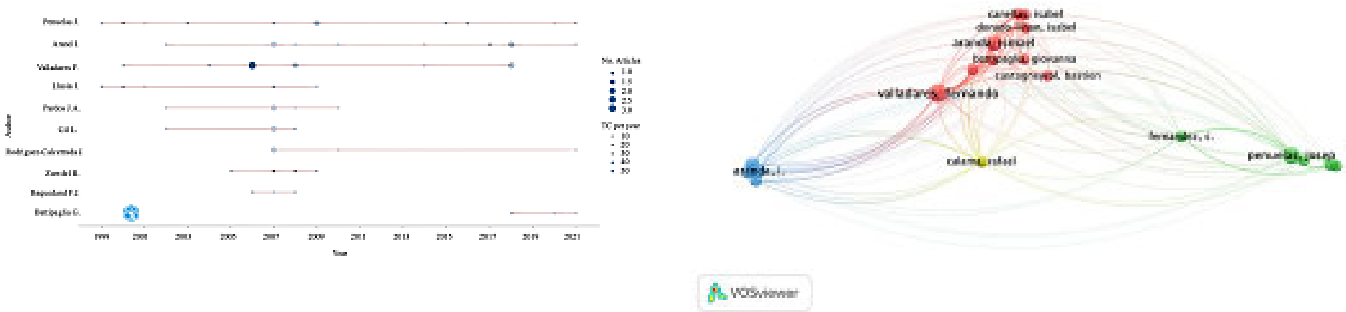


Figure 4. Temporal publication trends and leading author network for scientific articles on the adaptive strategies to water stress of Pine-Oak forests

Table 2. Main authors wise scientific articles on the adaptive strategies to water stress of Pine-Oak Forests.

Author	TN	TC	AC	NF	FTC	FAC	NC	NCC
Valladares, F	10	27	2.7	1	0	0	2	4
Aranda, I	10	17	1.7	1	0	0	3	7
Zweifel, R	4	15	3.75	3	13	4.33	3	13
Martínez-Ferri, E	2	15	7.5	2	15	7.5	1	11
Balaguer, L	2	15	7.5	0	0	0	0	0
Manrique, E	2	15	7.5	0	0	0	0	0
Peñuelas, J	11	14	1.27	3	6	2	2	6
Llusià, J	5	13	2.6	1	6	6	0	0
Ferrio, JP	3	12	4	1	5	5	1	6
Chico, JM	1	11	11	0	0	0	0	0

TN: Total number of articles; T: Total number of citations A: Average number of citations; NF: ~~Total~~ number of first authorship; FTC: Number of citations in first authorship; FAC: Average citations in first authorship; NC: number of corresponding author articles; NCC: citation of the corresponding author articles.

Leading institutions

Several well-known universities and forest research institutes in North America and Europe have shown concentrated effort to address the ecological challenges of pine and oak forests (Fig. 3). Collaborative research is the key strategy in these institutions. Among the key institutions, CSIC (Consejo Superior de Investigaciones Científicas, Spain) leads in publication volume with 12 articles, although its per-paper citations are low (Table 1). In contrast, Univ Complutense Madrid boasts the highest citation rate with only two publications, indicating substantial impact per paper. Other notable contributors like INRA and the University of Autonoma Barcelona also show consistent output with moderate citation metrics, illustrating a vibrant academic exchange and a networked research community across these institutions.

Primary research authors and journals

The timeline showcases the scholarly output of prominent researchers from 2002 to 2022. José Peñuelas is particularly notable for his substantial volume of articles, especially around 2016, indicated by a larger circle that signifies more articles and citations in that year (Table 2). Other researchers, including Fernando Valladares and Ismael Aranda, also demonstrate consistent contributions, with peaks indicating years of heightened productivity or impact. The co-authorship network illustrates the collaborative interactions among researchers, with Fernando Valladares positioned as a central node,

Table 3. Journal wise details of published articles on the adaptive strategies to water stress of Pine-Oak Forests

Journal name	TN	TC	AC
Tree Physiology	14	37	2.64
Forest Ecology and Management	9	12	1.33
Journal of Experimental Botany	3	9	3
Trees-Structure and Function	5	8	1.6
Environmental & Experimental Botany	3	7	2.33
American Journal of Botany	1	6	6
Frontiers in Plant Science	2	5	2.5
Plant Cell and Environment	1	5	5
Oecologia	1	5	5
Plant Ecology	2	5	2.5

TN: Total number of articles; TC: Total number of citations; AC: Average number of citations

highlighting his role as a key collaborator within this research community. The thickness and colour of the lines denote the strength and frequency of collaborations among authors, with José Peñuelas also exhibiting strong connections with other researchers, reflecting a vibrant network of scholarly communication and collaboration.

Among the journals, Tree Physiology stands out with the highest number of articles and total citations, emphasising its role as a primary source for impact physiological research. Forest Ecology and Management and the Journal of Experimental Botany also make substantial contributions, with the latter showing a high impact per article. Specialised journals like Trees-Structure and Function and Environmental and Experimental Botany highlight focused research on tree structure and environmental interactions (Table 3). Some of the journals with an ecological focus, other than Forest Ecology and Management, are missing.

Topics and themes

The evaluation of the water stress theme began in 1993, leading to the emergence of various related themes, including climate change, drought, gas exchange, growth, light, and water relations (Fig. 4a). The trend chart illustrates the evolution of research on the multifaceted aspects of water stress in Pine-Oak Forests from 2000 to 2022. Key topics such as "sap flow" and "water-use efficiency" have shown a consistent presence over the years, with their frequency peaking in the later years, indicating a sustained and growing interest. In contrast, topics like "chlorophyll fluorescence" and "drought stress" initially attracted significant attention but have declined interest in recent years. The increase in topics related to "climate change" and "drought" starting around 2010 and their continued relevance thereafter suggests a parallel with global concerns regarding climate impacts. Overall, the chart reveals a dynamic shift in research priorities, highlighting a growing emphasis on integrating climate-related variables with traditional studies of physiological traits and water management in forest ecosystems. The accompanying bar chart displays the temporal changes in keyword frequencies related to adaptive strategies for addressing water stress in Pine-Oak Forests from 2000 to 2024 (Fig. 4b). Noteworthy keywords such as "drought stress," "water-use efficiency," and "climate change" exhibit fluctuations in frequency, with peaks occurring in specific years. A notable peak for "drought stress" and "water-use efficiency" around 2012 was followed by a significant rise in discussions surrounding "climate change" beginning in 2020, suggesting a shift in research focus driven by evolving environmental conditions and scientific priorities. Other terms, including "chlorophyll fluorescence" and "sap flow," have maintained a more consistent presence, reflecting their ongoing relevance within the research community (Fig 5).

Research hotspots and keyword network analysis

Using VOSviewer, the keyword co-occurrence network was constructed, and four distinct clusters were found based on keyword co-occurrences. The network visualisation identifies four prominent clusters of co-occurring keywords in adaptive strategies to water stress in Pine-Oak forests, as depicted by different colours. The red cluster centres around "drought" with associated terms like "drought stress", "drought tolerance", and "water potential", indicating a focus on the plant's physiological responses to dry conditions. The green cluster focuses on water dynamics and efficiency, including "water-use efficiency", "sap flow", and "hydraulic architecture", reflecting research on plant water management mechanisms. The blue cluster

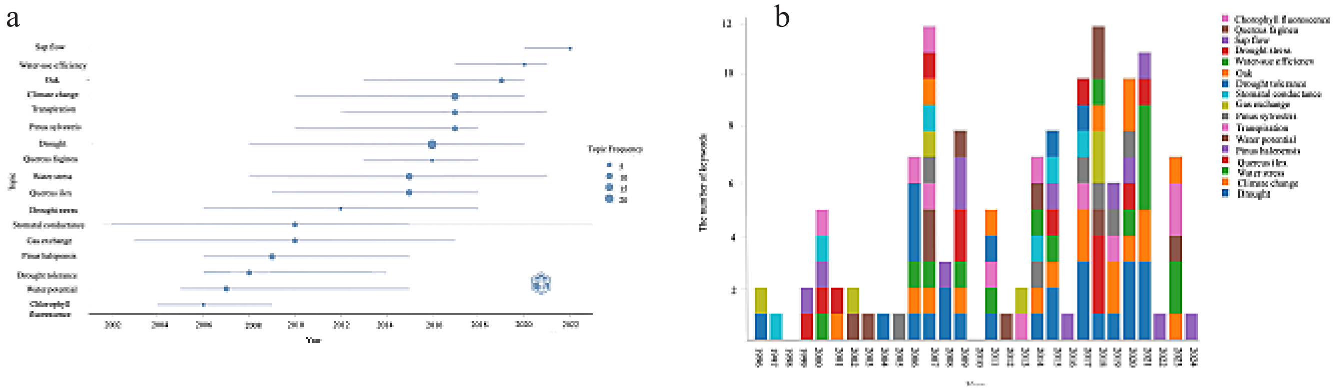


Figure 5. Temporal topic trends and characteristics of primary keywords for scientific articles on the adaptive strategies to water stress of Pine-Oak forests

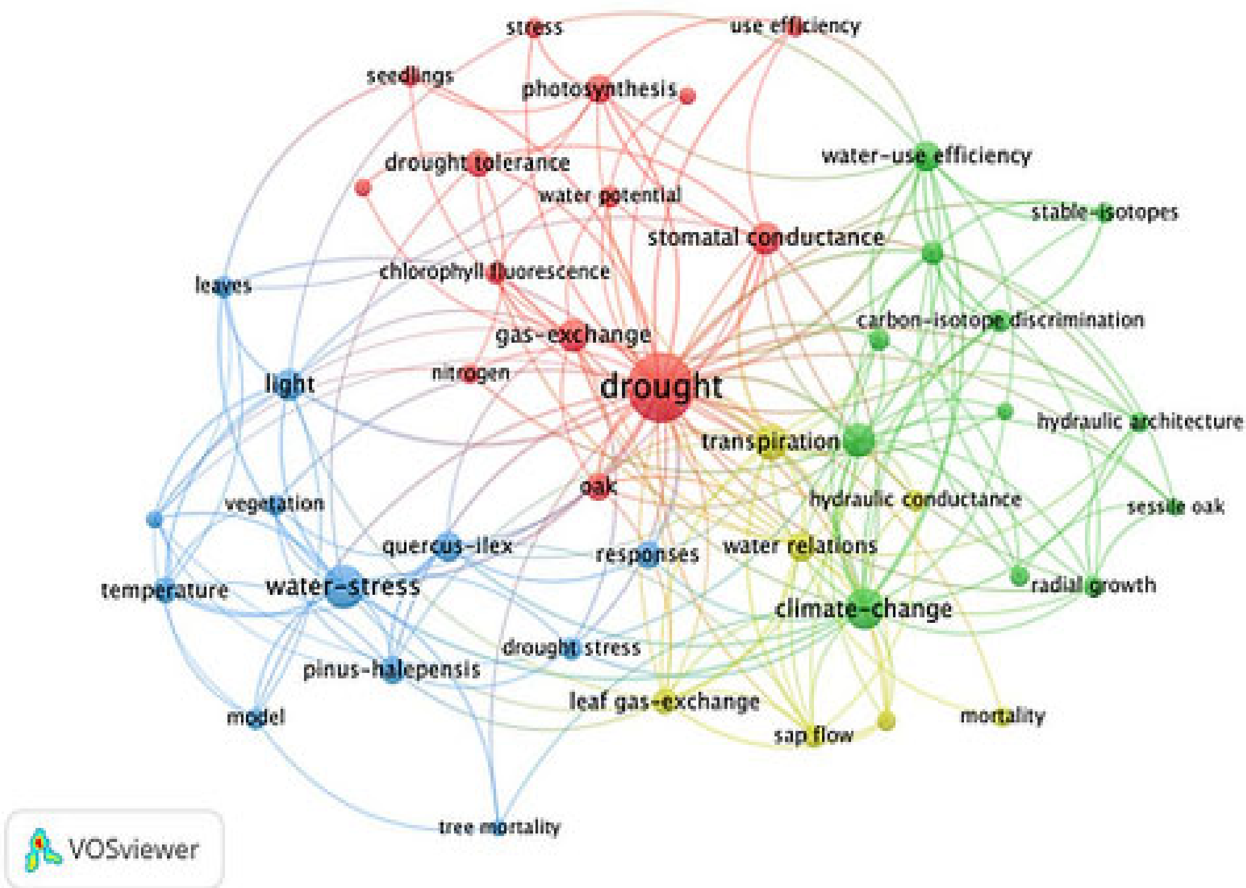


Figure 6. Keyword distribution and cluster formation of scientific articles on the adaptive strategies to water stress of Pine-Oak forests

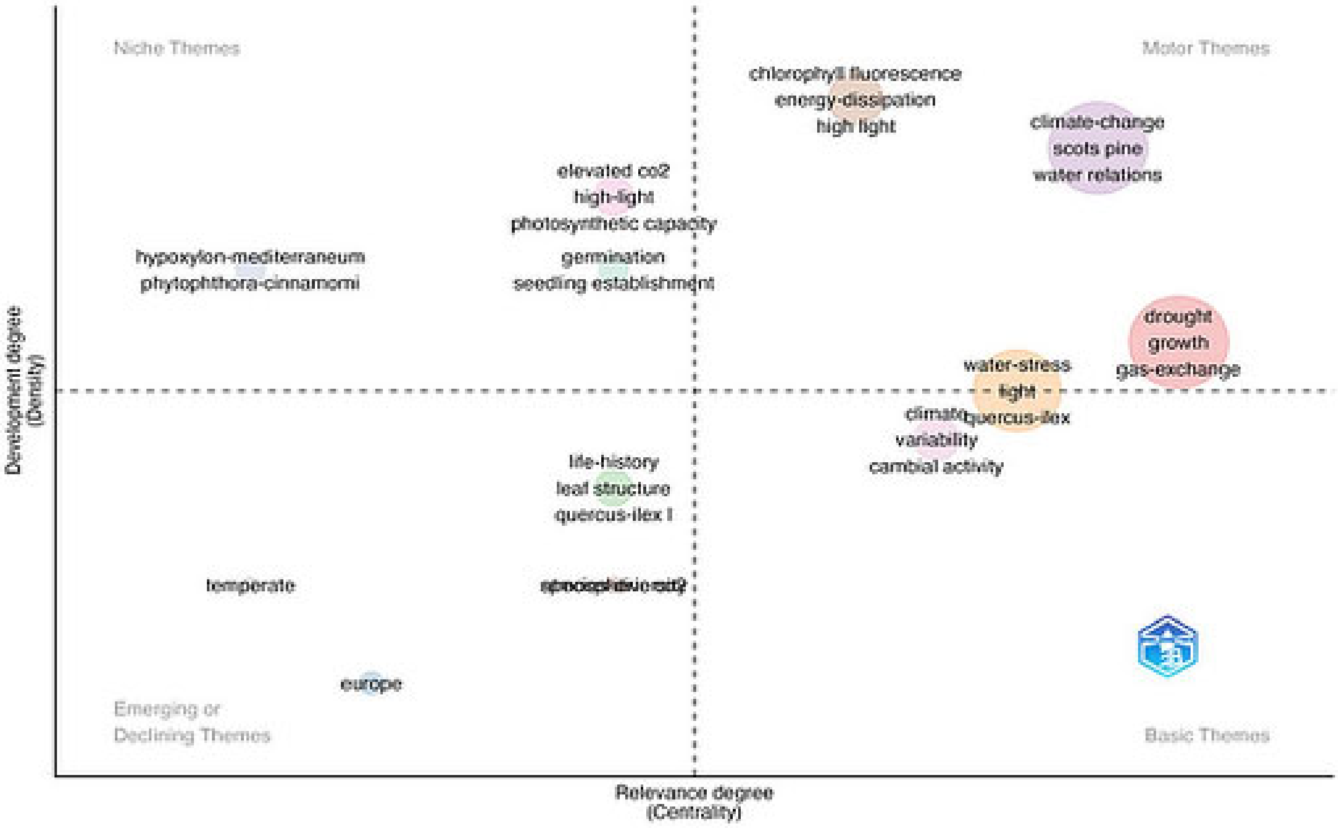


Figure 7. Thematic map of the scientific articles on the adaptive strategies to water stress of Pine-Oak forests

highlights environmental factors and responses, with keywords like "water stress", "temperature", and "vegetation", suggesting studies on the broader ecological impacts of water stress. Lastly, the yellow cluster includes "mortality", "climate change", and "radial growth", linking plant survival and growth patterns to changing climatic conditions. These clusters illustrate a comprehensive research landscape addressing various aspects of ecological resilience and adaptation to water stress (Fig. 6).

Cluster 1: Red - Physiological adaptations and stress responses in young trees

This cluster focuses on the physiological responses of young trees (seedlings) to drought conditions. It encompasses studies on photosynthesis efficiency, stomatal behaviour, and gas exchange under varying environmental stresses, including shade and nitrogen availability.

Cluster 2: Green - Tree growth and physiological ecology

This cluster deals with tree growth and its physiological underpinnings, particularly how trees adjust their water use efficiency and hydraulic architecture in response to climate change.

Cluster 3: Blue - Environmental stressors and tree physiology

This cluster explores the broader environmental stressors affecting tree physiology, including temperature, light availability, and their combined effects with drought stress on tree mortality.

Cluster 4: Yellow - Water transport and regulation mechanisms

This cluster focuses on the detailed mechanisms of water transport and regulation in trees, studying aspects like sap flow, transpiration, and hydraulic conductance.

Themes and strategies analysis

The thematic map in Figure 7 categorises research themes related to the adaptive strategies of Pine-Oak forests to water stress into four quadrants based on their centrality and density. "Drought", "gas exchange", and "water stress" emerge as Basic Themes, underscoring their foundational role in the

Table 4. Cluster characteristics for the scientific articles on the adaptive strategies to water stress of Pine-Oak forest

Cluster	Color	Name	Number of Articles	Top 10 keywords in the cluster
1	Red	Physiological adaptations and stress responses in young trees	47	chlorophyll fluorescence, drought, drought tolerance, gas-exchange, nitrogen, patterns, photosynthesis, seedlings, shade tolerance, stomatal conductance
2	Green	Tree growth and physiological ecology	35	carbon-isotope discrimination, climate-change, fagus-sylvatica, hydraulic architecture, norway spruce, pinus sylvestris, radial growth, scots pine, sessile oak, stable-isotopes
3	Blue	Environmental stressors and tree physiology	33	biogenic emissions, drought stress, leaves, light, model, pinus-halepensis, quercus-ilex, responses, temperature, tree mortality
4	Yellow	Water transport and regulation mechanisms	27	hydraulic conductance, leaf gas-exchange, mortality, sap flow, stomatal control, transpiration, water relations

literature. Motor Themes like “growth” and “photosynthesis” are identified as pivotal areas driving ongoing research due to their extensive development and central connectivity within the field. Niche Themes such as “chlorophyll fluorescence” and “highlight” highlight specific, emerging areas of interest with significant centrality but lower density, suggesting growing importance in recent studies. Lastly, themes like “eupeptic” and “hypoxylon mediterranean” are noted as Emerging or Declining Themes, indicating sectors that are either gaining attention or receding in focus. This mapping effectively illustrates the diverse and dynamic nature of research into the ecological responses of Pine-Oak forests to environmental stresses.

DISCUSSION

The isohydry-anisohydry continuum has emerged as an accepted way to characterise plant drought responses and recovery processes (Kannenberg et al. 2019). It is recognised that isohydric species are expected to close stomata and reduce carbon (C) assimilation. At the same time, plant water potential is still high, so they are not exposed to hydraulic failure. However, isohydric plants may suffer from carbon depletion, which is important for recovering damaged plants after a drought. On the other hand, anisohydric species are understood to maintain gas exchange while running the risk of hydraulic damage because of low water potential. The tradeoff between sustaining safer water potential and sustaining carbon assimilation is critical for managing forests in the changing global climate change, where extremes are likely to be more frequent, combining such a contrasting species into a functional system. There is scope for utilising plant-plant facilitation to promote species regeneration. For example, seedlings of *P. palustris* were to be facilitated by oaks (*Quercus* species) in NE United States (Loudermilk et al. 2016). The evolution of the pine and oak ecosystem in the Mediterranean Basin over 3.5-2.3 million years indicates how resilient systems with contrasting drought responses can be developed (Sheffer 2012).

There has been a significant increase in several articles, particularly between 2007 and 2009, 2021 and 2023, largely because of research conducted in the USA and France. Research contributions from Canada, China and Spain have increased significantly between 2021 and 2023. These countries focus on networking, particularly the USA and France. Some small countries like Israel, Belgium, and Portugal have also collaborated in research. Because of the concentration of studies in certain areas and institutions, the number of species studied remains small, generating much literature on a few species studied. While it enables scientists to investigate numerous aspects of a few species, the knowledge of oak and pine for many species remains low (87% of pine-oak combined species).

Research on water stress as a theme started in 1993 and was joined by several other themes, such as drought, gas exchange, growth and climate change. Between 2000 and 2022, the period saw a marked rise in research on various aspects of water stress, including sap flow and water use efficiency. Subsequently, the rise of the topic of climate change and drought around 2020 was notable. In recent years, drought and climate change and predictions on the impact of climate change on vegetation reflect the global concern of the climate change crisis. Interestingly, these terms fluctuated frequently until the significant rise in climate change discussions from 2020 onwards.

The occurrence of two basic strategies referred to as isohydric and anisohydric and the concept of wider and narrow safety margins, respectively, have increased rapidly in recent years. Since stomatal regulation is a key factor in these strategies, it became a key research area, along with other factors that influence hydraulic conductance. In general, pines (e.g. *P. halepensis*) follow a saving strategy characterised by early and prolonged stomatal closure, whereas oaks (e.g. *Q. coccifera*) follow water spending strategy manifested by high stomatal conductance that results in a marked depletion of stem water (Chirino et al. 2011). A more excellent ability of oaks to tolerate drought favours them in regeneration. Studies show that climate change, by and large, may lead to an increase in oak importance in mixed pine-oaf forests. Oaks generally maintain a lower Ψstem than pines, and they also undergo wider daily change. Climate change-induced drought in oaks (*e.g. Q. ilex*) decreases their conductance by 28% (*Q. ilex*) and of pine (*P. halepensis*) by 42% (Blanch et al. 2007). The stomatal closure in pines (*e.g. P. halepensis*) may result in carbon depletion to support respiration, while in oaks, the drought may restrict growth but not carbon reserve (Sanz-Parez et al. 2009, Schuldt et al. 2020). Referred to as "hot drought" (Schuldt et al. 2020) as water scarcity combined with high air temperature, the summer drought of 2018 was one of Central Europe's most severe drought events. It caused leaf discolouration, leaf shedding, slow stem shrinkage due to depleted water, and xylem failure, which weakened tree recovery and caused rapid tree mortality of several species. *P. sylvestris* stores and emits monoterpenes and sesquiterpenes (Kreuzwieser et al. 2021) for plants against biotic and abiotic stress. Mass seedling mortality in pinyon pine is reported under climate change events (Poulos 2014).

The strong stomatal regulation in pines such as *P. virginiana* may reduce the cooling effect, causing high canopy temperature (1.3°C) (Yi et al. 2020). Such conditions do not occur under the cooling effect of oak forests. The pine daily change to zero while the oaks keep scope for change. While there are several advantages in tolerating water stress by oaks, in a year of climate change, like severe drought, the oaks may face mass mortality (Singh and Singh 1992). The research on pine and oak species' responses to drought has increased rapidly in recent decades of climate change. It is apparent from their findings that pine and oak species are separable in their strategies for drought: pines are isohydric with a wide safety margin, while oaks are anisohydric, showing a negative safety margin. This differentiation in their basic water-use strategies might be complementary to their long-term co-existence and resilience as a system. However, the research approach has primarily been lopsided, involving a few species studied frequently. We hardly know anything about many pine and oak species, particularly those in the humid forests of Vietnam, China, and other tropical regions. The fact that pines and oaks of relatively humid Himalayan forests retain the basic traits of the two genera highlighted above shows that species of pine and oak genera have safeguarded their species traits from water stress across a wide range of habitats.

CONCLUSIONS

Our bibliometric analysis reveals that pine and oak species are linked to characteristics known as isohydry and anisohydry. However, the studies conducted so far involve only a small fraction of the globally present species and are primarily limited to specific geographical regions, particularly the Mediterranean Basin. Regions with relatively humid conditions, like China, Vietnam, and the Himalaya, have not been adequately investigated. Even Mexico, recognised as a rich centre for pine-oak forest types, remains under-researched. The co-occurrence of these pine and oak species varies across different floristic, climatic, anthropological, and evolutionary scales. The regions studied do not encompass evergreen oaks from mesic habitats or pines with shorter leaf lifespans. There is a pressing need to expand the research to cover more species and samples to understand better how pine and oak species respond to drought in a changing climate, as well as drought-induced factors like fire, agricultural abandonment, and ecological succession. The species from the two co-occurring genera, Pinus and Quercus, exhibit distinct basic strategies in responding to drought. Pines typically exhibit isohydric responses, characterised by a wider hydraulic safety margin, while oaks display anisohydric responses with a narrower safety margin. This divergence in drought response strategies has been demonstrated at the individual species level, and for the first time, this analysis connects isohydry and anisohydry at a broader general level. However, the species studied for their water relations represent only about 13% of the total pine and oak species. Notably, a few species from Mediterranean regions account for an unusually high percentage of the research conducted. Studies focused on the drought responses of pine and oak species have addressed various themes, including access to deeper water, root growth, drought damage, recovery after drought, terpene emissions, and the concentration of antioxidative compounds in response to drought stress. In addition to the intensifying drought factor, these studies have also examined the impact of climate change on species growth and community-level dominance. Collaboration among institutions and scientists from France, Spain, Germany, and the USA has been instrumental in advancing the study of pine and oak. More recently, contributions from Canada and China have significantly increased from 2021 to 2023. Networking is robust in the USA and France, with bilateral studies involving multiple countries, including Spain, Germany, the USA, and Mexico. Despite the Mediterranean regions facing severe summer droughts being disproportionately represented in drought stress studies, the sample size and geographical coverage should be broader to test hypotheses at a global level effectively. This is especially relevant for the heterogeneous genera of pine and oak, which differ morphologically and geographically. Oaks are categorised as deciduous or evergreen, while among pines, the Haploxylon group typically has much longer leaf longevity than the Diploxylon group. Research on regions outside the Mediterranean is sparse. For instance, little is known about the relatively humid, monsoonal Himalayan pine, P. roxburghii, and oak, Q. leucotrichophora, illustrating the two distinct responses to drought.

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REFERENCES

Blanch, J.S., Peñuelas, J. and Llusià, J. 2007. Sensitivity of terpene emissions to drought and fertilization in terpene storing *Pinus halepensis* and non storing *Quercus ilex*. Physiologia Plantarum, 131(2), 211-225. https://doi.org/10.1111/j.1399-3054.2007.00944.x

Chirino, E., Bellot, J. and Sánchez, J.R. 2011. Daily sap flow rate as an indicator of drought avoidance mechanisms in five Mediterranean perennial species in semi-arid southeastern Spain. Trees, 25, 593-606. https://doi.org/10.1007/s00468-010-0536-4

Denk, T., Grimm, G.W., Manos, P.S., Deng, M. and Hipp, A.L. 2017. An updated infrageneric classification of the oaks:

Review of previous taxonomic schemes and synthesis of evolutionary patterns. pp. 13-38. In: Gil-Pelegrín, E., Peguero-Pina, J. and Sancho-Knapik, D. (Eds.), *O*aks Physiological Ecology. Exploring the Functional Diversity of Genus *Quercus* L. Tree Physiology. Springer, Cham. https://doi.org/10.1007/978-3-319-69099-5_2

Farjon, A. and Filer, D. 2013. An Atlas of the World's Conifers: An analysis of their distribution, biogeography, diversity and conservation status. Brill, Berlin. 512 pages. https://brill.com/display/title/20587

Gernandt, D.S., López, G.G., García, S.O. and Liston, A. 2005. Phylogeny and classification of *Pinus*. *Taxon,* 54(1), 29-42. https://doi.org/10.2307/25065300

Kannenberg, S.A., Novick, K.A. and Phillips, R.P. 2019. Anisohydric behavior linked to persistent hydraulic damage and delayed drought recovery across seven North American tree species. New Phytologist, 222(4), 1862-1872. https://doi.org/10.1111/nph.15699

Kreuzwieser, J., Meischner, M., Grün, M., Yáñez-Serrano, A.M., Fasbender, L. and Werner, C. 2021. Drought affects carbon partitioning into volatile organic compound biosynthesis in Scots pine needles. New Phytologist, 232(5), 1930-1943. https://doi.org/10.1111/nph.17736

Li, T., Cui, L., Scotton, M., Dong, J., Xu, Z., Che, R., Tang, L., Cai, S., Wu, W., Andreatta, D. and Wang, Y. 2022. Characteristics and trends of grassland degradation research. Journal of Soils and Sediments, 22(7), 1901-1912. https://doi.org/10.1007/s11368-022-03209-9

Li, T., Cui, L., Wu, Y., Pandey, R., Liu, H., Dong, J., Wang, W., Xu, Z., Song, X., Hao, Y. and Cui, X. 2025. Unveiling and advancing grassland degradation research using a BERTopic modelling approach. Journal of Integrative Agriculture, 24(3), 949-965. https://doi.org/10.1016/j.jia.2024.11.008

Li, T., Singh, R.K., Cui, L., Pandey, R., Liu, H., Xu, Z., Tang, L., Du, J., Cui, X. and Wang, Y. 2024. Beyond grassland degradation: Pathways to resilience for pastoralist households in alpine grassland ecosystems. Journal of Environmental Management, 368, 121992. https://doi.org/10.1016/j.jenvman.2024.121992

Loudermilk, E.L., Hiers, J.K., Pokswinski, S., O'Brien, J.J., Barnett, A. and Mitchell, R.J. 2016. The path back: Oaks (*Quercus* spp.) facilitate longleaf pine (*Pinus palustris*) seedling establishment in xeric sites. Ecosphere, 7(6), e01361. https://doi.org/10.1002/ecs2.1361

Poulos, H.M. 2014. Tree mortality from a short-duration freezing event and global-change-type drought in a Southwestern piñon-juniper woodland, USA. PeerJ*,* 2, e404. https://doi.org/10.7717/peerj.404

Sanz-Perez, V., Castro-Diez, P. and Joffre, R. 2009. Seasonal carbon storage and growth in Mediterranean tree seedlings under different water conditions. Tree Physiology, 29, 1105-1116. https://doi.org/10.1093/treephys/tpp045

Schuldt, B., Buras, A., Arend, M., Vitasse, Y., Beierkuhnlein, C., Damm, A., Gharun, M., Grams, T.E.E., Hauck, M., Hajek, P., Hartmann, H., Hiltbrunner, E., Hoch, G., Holloway-Phillips, M., Korner, C., Larysch, E., Lubbe, T., Nelson, D.B., Rammig, A., Rigling, A., Rose, L., Ruehr, N.K., Schumann, K., Weiser, F., Werner, C., Wohlgemuth, T., Zang, C.S. and Kahmen, A. 2020. A first assessment of the impact of the extreme 2018 summer drought on Central European forests. Basic and Applied Ecology, 45, 86-103. https://doi.org/10.1016/j.baae.2020.04.003

Sheffer, E. 2012. A review of the development of Mediterranean pine–oak ecosystems after land abandonment and afforestation: Are they novel ecosystems? Annals of Forest Science*,* 69, 429-443. https://doi.org/10.1007/s13595-011-0181-0

Singh, J.S. and Singh, S.P. 1992. Forests of Himalaya. Structure, Functioning and Impact of Man. Gyanodaya Prakashan, Nainital, India.

Yi, K., Smith, J.W., Jablonski, A.D., Tatham, E.A., Scanlon, T.M., Lerdau, M.T., Novick, K.A. and Yang, X. 2020. High heterogeneity in canopy temperature among co-occurring tree species in a temperate forest. Journal of Geophysical Research: Biogeosciences, 125(12), e2020JG005892. https://doi.org/10.1029/2020JG005892

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