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Drought research priorities, trends, and geographic patterns

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Abstract. Drought research addresses one of the major natural hazards that threatens progress toward the Sustainable Development Goals. This study aims to map the evolution and interdisciplinarity of drought research over time and across regions, offering insights for decision-makers, researchers, and funding agencies. By analysing more than 130 000 peer-reviewed articles indexed in SCOPUS from 1901 to 2022 using latent Dirichlet allocation (LDA) for topic modelling, we identified distinct shifts in research priorities and emerging trends. The results reveal that plant genetic research for drought-tolerant genotypes and advancements in drought forecasting are the most dominant and continuously growing areas of focus. In contrast, the relative importance of topics such as ecology, water resource management, and forest research has decreased. Geospatial patterns highlight a universal focus on forecasting methods, with a strong secondary emphasis on policy and societal issues in Africa and Oceania. Interdisciplinarity in drought research experienced a marked decline until 1983, followed by a steady increase from 2007 onward, suggesting a growing integration of diverse fields. Emerging topics in recent years signal evolving priorities for future research. This analysis provides a comprehensive overview of drought research trends across sectors and regions, offering strategic guidance for aligning research efforts with drought resilience goals. The findings are crucial for research funding agencies and policymakers aiming to prioritize areas with the highest potential to mitigate drought impacts effectively.

1 Introduction

Drought is one of the most socio-economically damaging natural hazards (Yin et al., 2023; Zaveri et al., 2023). Contrarily to other climate extremes, drought manifests on a vast spatiotemporal scale, extending up to thousands of kilometres, and can persist for periods lasting up to years (Mondal et al., 2023). Drought episodes are becoming increasingly frequent, extreme, and prolonged, driven by climate change (Hoylman et al., 2022; IPCC, 2021). Drought is significantly tied with other climate-driven hazards, particularly heatwaves, which can amplify drought impacts (Lesk et al., 2022). The emergence of frequent flash droughts in over 74 % of the globe during the last 64 years has also recently been revealed (Yuan et al., 2023). This pattern is largely linked to elevated anomalies in evapotranspiration and precipitation deficits, which are confirmed consequences of human-induced climate change (Yuan et al., 2023). Drought as the state of water shortage is exacerbated by anthropogenic activities such as unsustainable water use, allocation, and extraction (Van Loon et al., 2022,, 2016a; Chiang et al., 2021). This led to the reconsideration of the definition of drought as being a process rather than a system state (Van Loon et al., 2016a; AghaKouchak et al., 2021; Van Loon et al., 2024). Drought therefore poses a substantial risk for and across sectors and systems (Voosen, 2020; Walker and Van Loon, 2023; Hagenlocher et al., 2023), including agriculture, water supply, health, energy, ecosystem services, and socio-political stability.

Drought impacts ecosystems by modifying ecological processes, altering community structures and compositions (Canarini et al., 2021). These changes can lead to adaptations such as improved water use efficiency in response to water storage (Poppe Terán et al., 2023). The total land area and population affected by severe terrestrial water storage drought could more than double by the end of the 21st century (Pokhrel et al., 2021). Over the first 20 years of the 21st century, extreme drought and drinking-water shortages have plagued more than 80 major cities worldwide (Savelli et al., 2023). Food production and security have already been largely compromised by drought (Spinoni et al., 2020; Rossi et al., 2023). For instance, the size of the dry zones across the global grain production area increased by 1.1 % per decade in the period from 1951 to 2011 (Wang et al., 2018). Globally, the average national cereal production shrank by 10 % over the period 1964 to 2007 as a result of extreme drought and heat (Lesk et al., 2016). In Europe, the adverse impacts of droughts and heatwaves on crop production have tripled in the last 50 years (Brás et al., 2021).

Without climate action, annual drought damages for the EU and the UK could escalate from EUR 9 billion to over EUR 65 billion per year by 2100, doubling in terms of financial impact (Naumann et al., 2021). Drought also impacts human health (Vins et al., 2015), e.g. through reducing streamflow, increasing the concentration of pathogens, and enabling some vector-borne diseases (Cann et al., 2013) and as a risk factor of child undernutrition, particularly in low-income conditions (Belesova et al., 2019). The impacts of drought are scale specific and event specific and are often difficult to quantify due to their indirect and often systemic character, affecting not only human health and agriculture but also energy and social systems (Van Loon et al., 2019; Blauhut et al., 2015).

This study is motivated by the need to enhance our understanding of the evolving landscape of drought research, particularly in light of the escalating challenges posed by climate change and water scarcity. While previous reviews outlined the need to synthesize the immense body of literature on drought research (Stein et al., 2022), our analysis distinguishes itself through the use of a data-driven, unsupervised machine learning approach to examine over 130 000 peer-reviewed articles. By exploring long-term research trends, we identify critical shifts in thematic focus, fundamental and emerging trends, and interdisciplinary collaboration opportunities that have shaped the field. This unique approach allows us to reveal previously overlooked patterns and gaps in the literature, offering insights into how research priorities have been set by the global research communities. Our findings contribute to the development of more effective and systemic drought resilience frameworks by quantifying the connections between diverse research topics, ultimately guiding more strategic alignment of efforts among scientists, funding bodies, and policymakers.

2 Methods

2.1 Data

We based the analysis on 131 748 abstracts curated in the licensed SCOPUS database under the search term “drought” on 22 March 2023. Data on title, keywords, language, abstract, and publication year were retrieved from the SCOPUS database via the SCOPUS Search API and the elsapy search library. We removed duplicates, copyright information, and non-English abstracts. SCOPUS provides a curated database of scientific literature and grants access to data and text mining to licensed users for academic purposes. The following alternative large databases for meta-information on scientific literature were considered: OpenAlex, Web of Science, Dimensions, and Semantic Scholars. We chose SCOPUS because of its high quality of information and the granted access for research purposes.

2.2 Topic modelling by unsupervised machine learning

To discern pertinent topics and subtopics within the dataset, we used the latent Dirichlet allocation (LDA) (Blei et al., 2003; Rehurek and Sojka, 2010) method. LDA, an iterative Bayesian method of unsupervised machine learning, identifies multiple topic clusters within documents based on keyword distribution, co-occurrence, and frequency. Depending on the chosen granularity, classification can yield either broad or highly specific topics. Remarkably, while LDA is an established method (Eker et al., 2018; Ewert et al., 2023; Cebral-Loureda et al., 2023; Rahman et al., 2022; Callaghan et al., 2020), its application to vast scientific abstract corpora is rare. Compared to other alternatives, LDA allows for multiple topics within a single document. Also, LDA represents a compromise between computationally more expensive and more costly topic modelling approaches such as BERTopic (Ogunleye et al., 2023) and simpler and computationally less expensive approaches such as latent semantic analysis (Deerwester et al., 1990). To explore the drought research areas, we identified rather general topics and mores specific topics. This was done by pre-defining the number of topics in the algorithm. We then calculated topic distributions with LDA for the documents and for a given number of topics based on the overall and document-specific keyword distributions. We assessed coherence scores for a consecutively increasing number of topics; found that coherence increases until 50 topics; and decided to cap granularity at 50 topics, which would still yield 2634 documents, on average, per topic. We then selected 5 topics as a reasonable number for the general classification level, 12 topics for a median level of granularity, and 50 topics for the finest-level granularity (see Results section and Fig. 2). Naming conventions for topics were derived from pivotal keywords within the context of drought research. To evaluate the evolving significance of research

themes over time, we charted the relative shares of each topic annually.

2.3 Data post-processing

For topic congruence, we calculated the cosine similarity between topic pairs within each individual document. A high similarity score indicates that two topics appear together more frequently in the same document. A low similarity score indicates fewer joint appearances. Cosine similarity normalizes the similarity score by the overall share of the two topics. This allows for a better direct comparison of topics with high shares and those with low shares. The topical overall similarity index is calculated as the mean cosine similarity of a topic for the other $n-1$ topics. Heatmaps of cosine similarity are ranked by the overall similarity score of a topic, starting with the highest and moving to the lowest. We visualized the topic trajectory using a Sankey diagram to highlight how general topics with coarse granularity narrow down to more specific topics. Consistently with Sankey diagrams, the width of the connecting lines is proportional to the document counts they represent. The geographic reference of drought research to individual continents was identified by keyword search. Abstracts were associated with a region if a specific continent or country (or, for the US, a specific state) was mentioned in the title, keyword, or abstract. One document could be associated with several regions in cases of several mentions. Topical shares by region were then calculated based on the documents found.

3 Results

3.1 Major and specific topics in drought research

The number of drought-related peer-reviewed publications has increased exponentially, with the addition of 12 338 articles in 2022 alone (Fig. 1). The proportion of articles focusing on drought increases year by year compared to the general scientific literature. This is expressed by the ratio of drought-related research compared to the available scientific publications in SCOPUS (Fig. 1). We let the LDA identify 5 major topics across the document pool (tier 1), 12 more focused yet still rather general topics (tier 2), and 50 even more specific topics (tier 3, Fig. 2). While keyword frequency and co-occurrence generate topic clusters, they also allow domain experts to name the topics according to their context. A list of publications with the highest share of each topic (i.e. topical relevance $>98\,\%$) confirms the topic naming.

The five general topics were categorized as plant genetics and physiology, agricultural production systems, ecosystems, risk management and policy, and precipitation and drought types. At the medium granularity, with 12-topic classification, we identified forecasting methods, including drought types and events on the one end and plant genetics at the other end, as the most dominant research topics. For the 12-topic classification, a network graph visualizes the connections of topics and keywords (Fig. 3). Here, the dataset's structure is visualized with a limited number of the most important keywords in two-dimensional space. As a result of the LDA and topical distribution, forecasting is mainly associated with risk management and policy and precipitation and drought types from tier 1, with a lesser association with the other three topics of tier 1 (Fig. 2). This reflects how forecasting focuses on answering questions on risk using quantitative methods. In contrast, water use efficiency is strongly associated with three topics of tier 1, reflecting a higher transdisciplinarity and positioning it at the intersection of natural ecosystems, agriculture, and plant physiology. Farming, as a tier-2 topic, is particularly interesting as it bridges the gap through its strong association with risk and agricultural production systems (Fig. 2). Other tier-2 topics at are geomorphology, forests and fire, climate records and seasonality, water resource management, and policy and society (Fig. 3).

Topic identification and naming at the finest granularity reveal 50 specialized, potentially emerging, topics, with an average of 2634 papers per topic. For these 50 topics, shares by topic ranged between 134 documents and 5901 documents, with a median of 2337 documents. In the Sankey diagram (Fig. 2), the association of tier-3 topics with tier-2 topics is indicated by (a) their vertical alignment and (b) the strength of the links. The topics gene expression and stress tolerance are at the top, with a strong link to plant genetics. At the bottom of Fig. 2, the topics monsoon and hydrologic modelling have a strong link to forecasting. These results quantify the extent, importance, and role of research topics with respect to drought research. The results demonstrate the importance of rendering and limiting the topical scope of reviews.

Other categorizations and classifications are possible. For example, research can be grouped into publications focusing on the analysis of methods and processes, current and historical events, and impacts on socio-ecosystem compartments. Method-related research focuses on processes, tools, and methods for adaptation and mitigation of drought. Event studies focus on specific event types and historical analysis to guide the development of methods. Topics focusing on impact mostly focus on specific socio-ecosystem compartments. Following this categorization, tier-3 topics with a strong link to forecasting can be grouped, for example, into method-related topics (e.g. remote sensing, hydrologic modelling, meteorological drought) and event-related topics (e.g. historic drought records and chronology, monsoon (Fig. 2)). The density of method-related topics is much higher in the areas of plant genetics, physiology, and agricultural management than in forecasting-related topics. Impact-related topics for tier 3 are mostly found in the centre, while topics related to events are predominantly situated in the lower section. This categorization was assessed for tier-1 and tier-2 topics (Fig. 2). The results highlight a significant interconnection between research on events, impacts, and methods. This interplay, however, sometimes leads to challenges in distinctly

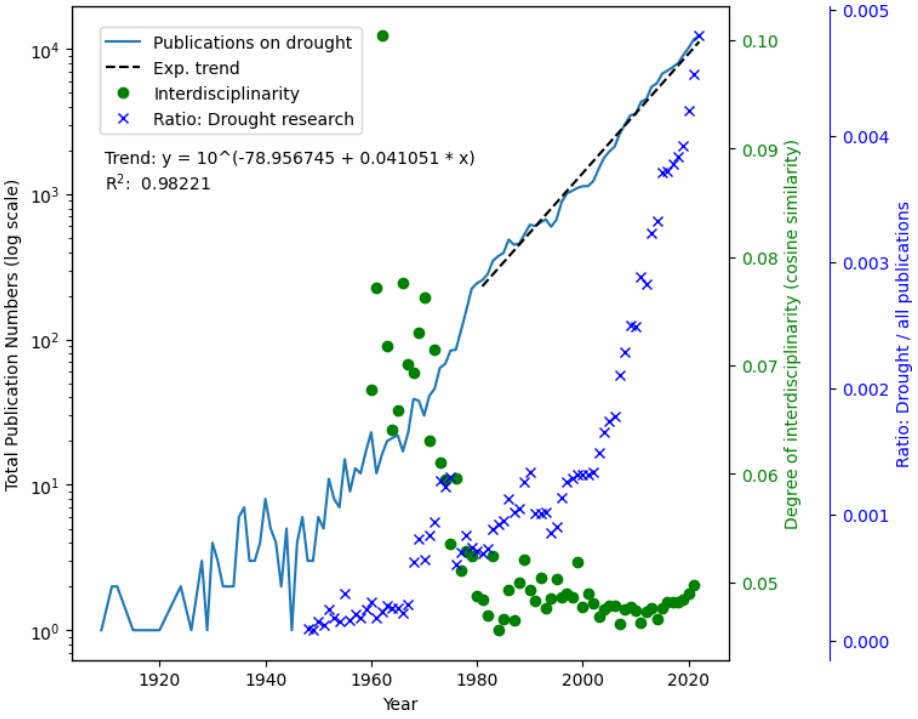

Figure 1. Publications by year in drought research. Research abstracts listed in SCOPUS and analysed over the past century with regard to interdisciplinarity. Drought research exhibits an exponential trend ($R^2 = 0.98$). This trend is highlighted by the increasing ratio of drought research to overall research publications. Interdisciplinarity is calculated as the cosine similarity index, which is the normalized cross-topic intersection within a document. Focus on specific topics increased until the 1980s, which is marked by a decline in interdisciplinarity. From 1980 onward, plant genetics saw a rise in interest, leading to ups and downs in interdisciplinarity. From 2007 onward, interdisciplinary consistently rose again.

categorizing topics, as evidenced by occasional overlaps and blurred boundaries among these categories.

3.2 General and emerging trends

Interest in research topics fluctuates over time. Shifts in research priorities are influenced by societal interest and advancements in technological capabilities. We explored the development over time of drought-related research topics and their relative contributions over the past 4 decades (Fig. 4) and, more specifically, over the recent years of 2012–2022. We chose the last 4 decades because the data showed a rather high variation in relative contribution for the years before 1982. Plant genetics and forecasting, as well as crop breeding, experienced an increasing relative share of the research over the last 4 decades (Fig. 4 and Fig. A2 in the Appendix). Ecology and water use efficiency have received comparatively less attention, with declining shares. Surprisingly, water use efficiency is not the specific aim of plant genetics and crop-breeding efforts but rather stands next to these in tier 2. Crop scientists have long targeted drought-tolerant crops to tackle food production challenges in dry regions. The introduction of new genomic technologies has greatly enhanced this effort (Anders et al., 2021), a trend reflected in our analysis. Amongst plant genetic and plant breeding, specific research on cellular and molecular functions exhibits positive trends for recent years, such as the epigenetic and circadian regulation in plant development or the role of antioxidants, which may reduce oxidative damage during drought stress (Bailey-Serres et al., 2019). Plant physiological processes such as plant phenology, stomata conductance, and photosynthesis recently became less relevant, although these are strongly related to plant genetics and plant breeding.

Other tier-2 topics, such as water resource management, geomorphology, and policy and society, have also demonstrated a generally declining relative contribution to drought research over the last 40 years (Figs. 4 and A2). It is vital to clarify that the decrease in relative shares for, for example, ecology or water resource management topics does not imply a decrease in the absolute number of research studies on these subjects. Instead, the number of documents on these topics continues to grow, but the rate of growth has been comparatively slower (Fig. A1). In tier 2, forecasting methods and events represented the largest contribution among all topics across the study period (Fig. 3).

Looking at tier-3 topics, we identified the top 10 emerging topics. Meteorological drought, remote sensing, climate change, natural disasters, and Palmer drought index are the

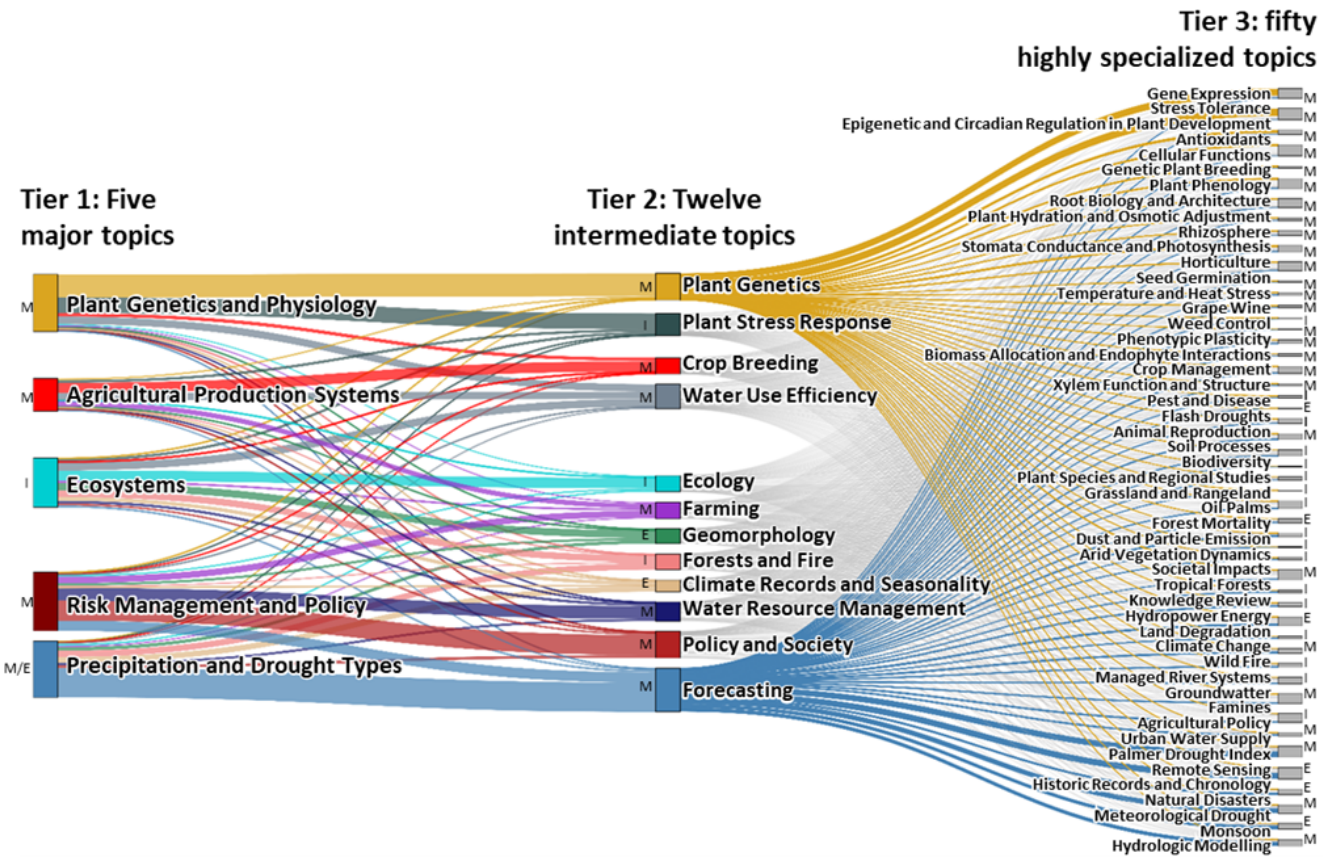

Figure 2. Hierarchical depth of research topics in drought research. The breadth of drought research encompasses a diverse array of subjects. Each column represents the entire research corpus, encompassing 131 748 articles. This figure displays the share of each topic compared to the whole corpus. Three levels of specificity are distinguished: 5 broad topics (left), 12 intermediate topics (centre), and 50 highly specialized topics (right). Visual emphasis is placed on the flows of plant genetics and forecasting, given their upward trends and dominance in the research field. Line width and bar width are proportional to the share per topic. Topics are categorized into methods and processes (M), events and historical analysis (E), and impacts on socio-ecosystem compartments (I).

five emerging topics, with strong associations with forecasting. Antioxidants, epigenetic and circadian regulation in plant development, and gene expression are the three emerging topics with strong links to plant genetics. Agricultural policy and the rhizosphere are also amongst the top 10 emerging topics. Here, agricultural policy is strongly associated with policy and society. Interestingly, the rhizosphere is the only topic out of these with rather evenly strong links to many of the tier-2 topics.

3.3 Interdisciplinarity of drought research

Each document consists of a variety of topics expressed as a percentage, i.e. a share, with a total sum of 1 for each document. While the algorithm for topic identification aims to discern individual topics within the corpus, the major share of a specific topic may dominate a specific document. In another case, the topical shares may be dispersed across many topics. We measure interdisciplinarity by cosine similarity, a measure of the similarity between two topics and a measure that scales well with the size of the two topics. We find for tier-2 topics (Fig. 5) several robust thematic overlaps. For example, plant stress response and water use efficiency showed the highest thematic overlap. Also, climate records and seasonality are strongly manifested in sedimentary records and tree ring records, causing a high similarity with forests and fire. Pronounced similarity is also found between policy and society and the topics farming and water resource management (Fig. 5). Here, water resource management, which is crucial for freshwater supply and energy systems (Jasechko et al., 2024), as well as for irrigation and food security, has a strong impact on and link to policy and society (Fig. 5).

In contrast, forecasting is focused on short-term responses, with less pronounced similarities. Surprisingly, geomorphology and water use efficiency possess the highest overall interdisciplinarity, indicating that these are generally important topics with impacts across most drought research topics (Figs. 5 and 2). For example, research where geomorphology and water use efficiency overlap well focuses on soil processes, soil formation, and impacts on plant water uptake

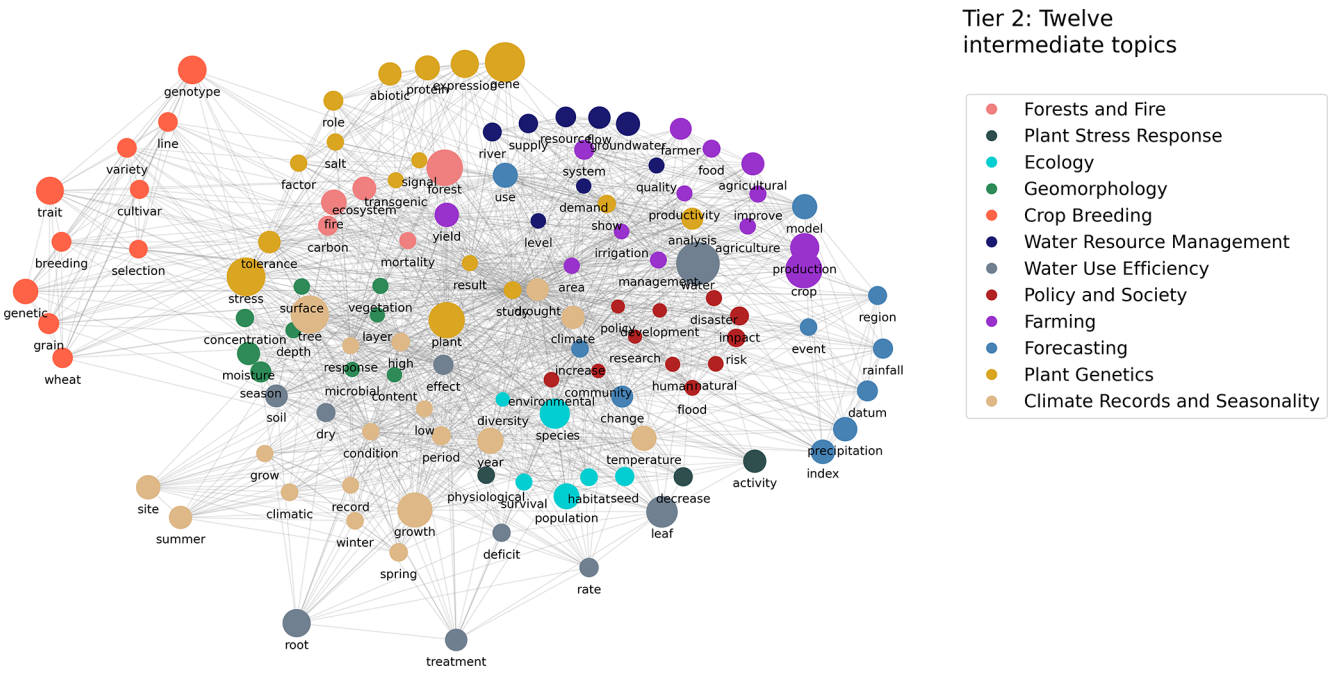

Figure 3. Network graph of drought research. Visualizes the network of the 12 drought research topics. Colours denote topics with the strongest association, and bubble size denotes the abundance of keywords. Keywords are located below the bubbles, links between keywords denote the strongest co-occurrences, and keywords are located in order to minimize connection lengths.

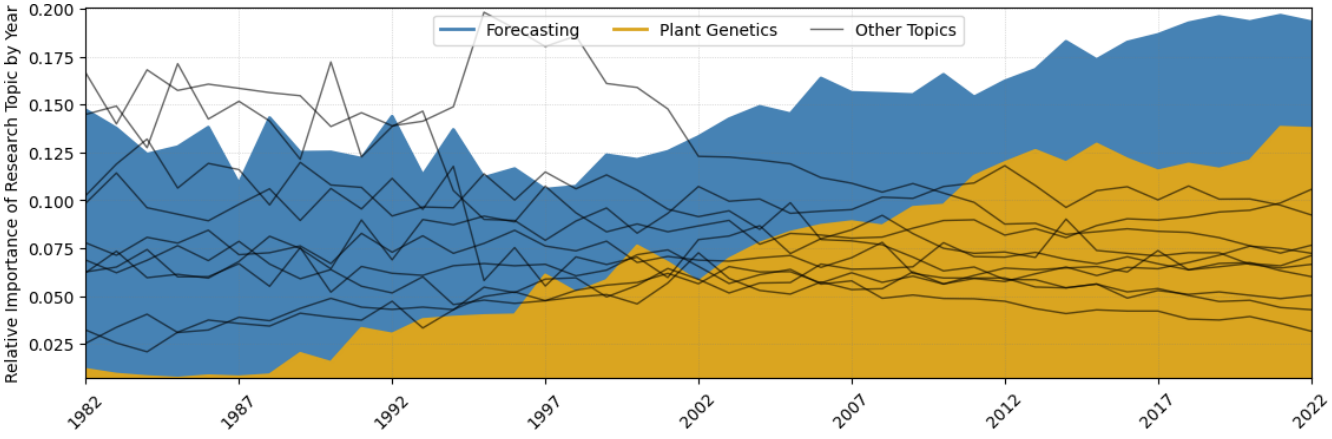

Figure 4. Temporal dynamics of research topics. The evolution of research topics and their proportionate dominance from 1982 onward, highlighting the ascendance of plant genetics and forecasting as dominant trending topics.

and irrigation. In contrast, plant genetics and crop breeding, jointly with plant stress response, are less interdisciplinary, with some similarities amongst each other. In this context, forecasting is only marginally linked to these three topics (Figs. 5 and 2).

More specific tier-3 topics reveal a different picture regarding interdisciplinarity (Fig. 6). These topics are more specific than the tier-2 topics. Here, climate change, knowledge review, remote sensing, and soil processes lead the field in terms of overall interdisciplinarity (Fig. 6). We note that these topics are highly interdisciplinary based on the topical analysis results. The knowledge review topic seems to not only review a specific topic but also make interconnections beyond single topics. Climate change does relate to several topics, e.g. through cause and impact. The soil process topic affect a large number of fields apart from itself. The same is seen for remote sensing, albeit, here, with emphasis on two specific topics: meteorology and Palmer drought index, which also possess a high similarity index themselves (Fig. 6). In contrast to interdisciplinary topics, flash droughts, oil palm, and plant species and regional studies are rather narrow in scope, with low overall interdisciplinarity within

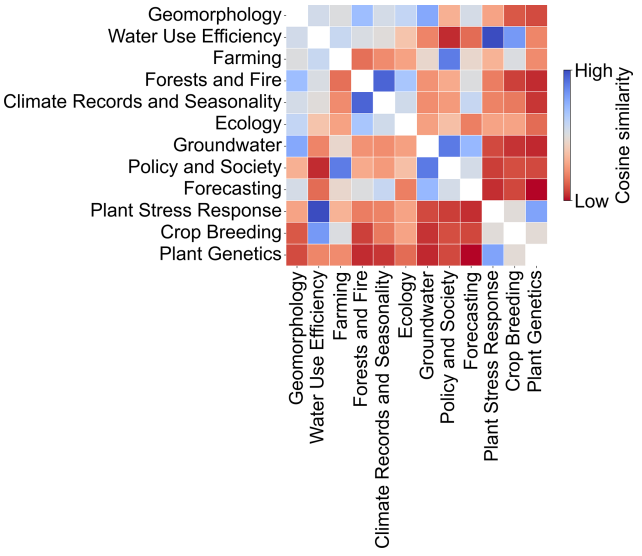

Figure 5. Thematic overlap of 12 research topics. Cosine similarity shows strength of overlaps between topics. It is the topic-wise similarity score that is the numerical value for cross-topic intersection. Stronger thematic overlaps (e.g. plant genetics and plant stress response) are identified by higher similarity, while a minimal similarity score also stands for minimal intersections between two topics (e.g. plant genetics and forests and fire). Topics are sorted from the highest overall similarity score (geomorphology) to the lowest overall similarity score (plant genetics).

drought research (Fig. 6). Cosine similarity highlights further topics with strong similarities, while, for other topics, we identify major difference and little overlap in terms of content. Here, interdisciplinarity appears to be more challenging rather than being an opportunity to form larger content clusters.

The multi-system impact of drought as a natural hazard challenges the often topic-specific approach of research projects by requiring a multi-system response. The trend shift in 2007 toward drought research becoming more systemic again may acknowledge this multi-system property of drought hazard, exposure, and vulnerability. Until 2007, drought research evolved to become more disciplinary, as explained by the annual similarity index (Fig. 1). Notable trend shifts occurred in the 1980s when the topic of genetics was introduced into drought research and started to become a major topic in the 30 years following. This led to a first trend shift, with research becoming more disciplinary by 1983 and then again becoming more interdisciplinary, with high volatility throughout. The second trend shift happened in the years around 2007, when similarity was lowest, and succeeded again from a stable upward trend. Noting the systemic impact of drought, we welcome the trend of drought research becoming more interdisciplinary because only systemic approaches can properly enhance drought impact resilience across systems.

3.4 Geographic patterns and priorities

Research priorities vary with regard to geographic context. We analysed continent-specific topical signatures in drought research (Fig. 7). The largest number of studies refers to Asian (18.0 %) and African countries (11.2 %), although research budgets in Europe and North America are generally higher than in Africa. This indicates that drought is well recognized as a challenge to many African countries, with this being even more so in Asia. As a major pattern, forecasting dominates drought research in a geospatial context in all regions. In Africa and Oceania, forecasting is closely followed by research on policy and society. This pattern is less pronounced for Europe, Asia, and South America (Fig. 7). In Africa, farming is the third largest topic, constituting 12.5 % of research, and the other topics are less relevant. North American drought research prioritizes water resource management, ecology, and forests and fire just after forecasting, with less weight on policy and society as compared to in the other regions. In Oceania and Antarctica, ecology is the third major topic. Although there are distinct regional differences amongst the geographic regions, the Southern Hemisphere and the Northern Hemisphere do not show distinct topical patterns (Fig. 7). Forecasting and policy and society are the two major topics within a geospatial context. The topic of plant genetics is the major topic for research with no geospatial context, just before plant stress response and water use efficiency, due to the focus on biological, physiological, genetic, and molecular scales.

4 Discussion

This study analysed over 130 000 peer-reviewed articles on drought research published between 1901 and 2022, identifying key trends, emerging topics, and interdisciplinary shifts within the field. The analysis revealed that drought research has undergone significant transformations, with increasing attention being paid to plant genetics and forecasting methods, while traditional areas like ecology, water resource management, and forestry have seen a relative decline. Regional analysis showed that forecasting methods are a dominant focus globally, whereas policy and societal dimensions play a particularly important role in Africa and Oceania. Furthermore, interdisciplinarity in drought research decreased until 1983, followed by a rise from 2007 onward, signalling a growing trend toward more integrative approaches. These findings provide a foundation for evaluating the evolving priorities in drought research and their implications for addressing drought risk in diverse contexts.

4.1 Definition and use of drought in literature

An important aspect of analysing the results is understanding the definition, mention, and meaning of the word drought. The definition of drought has been widely discussed in the

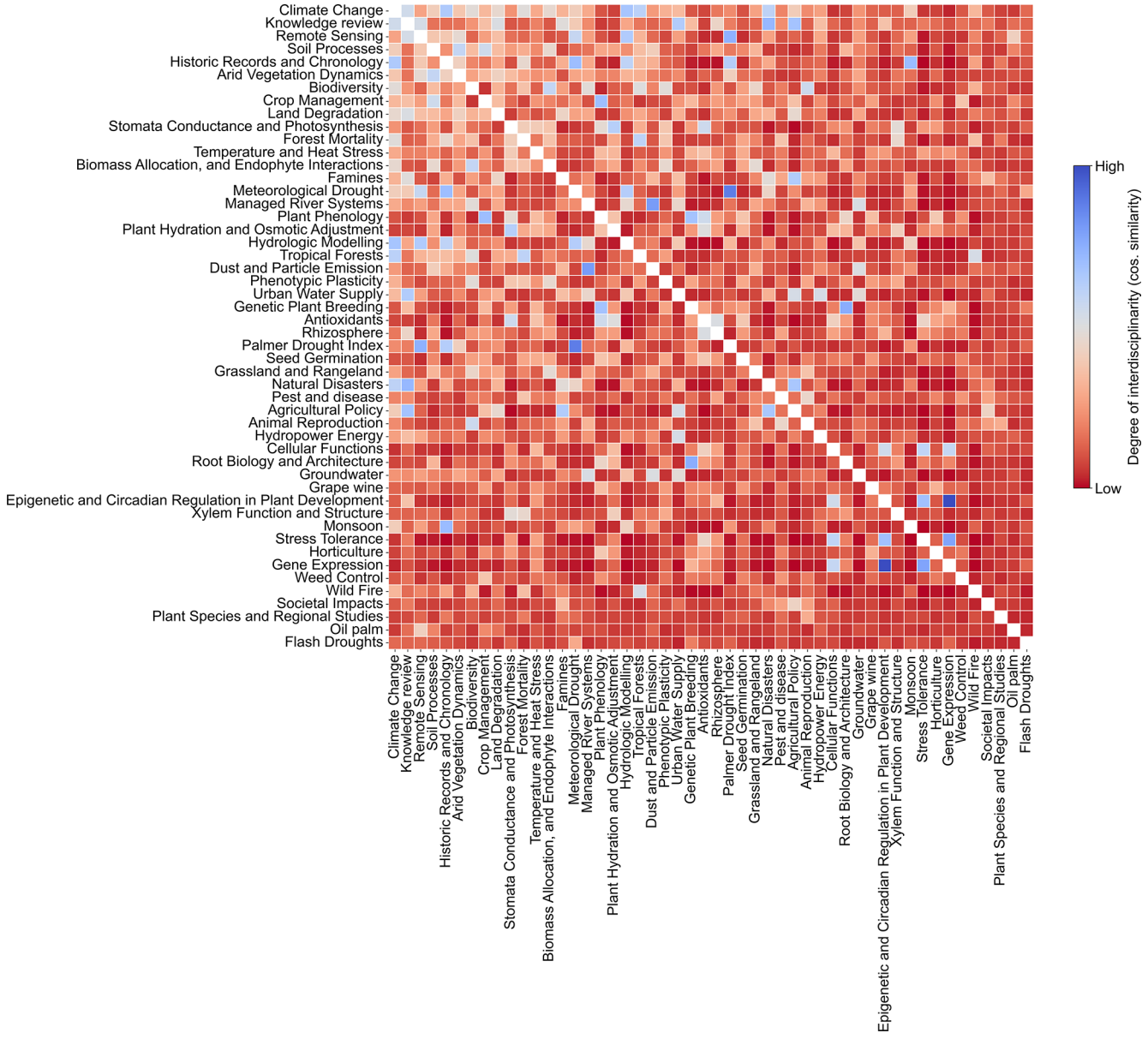

Figure 6. Thematic overlap of the 50 highly specialized research topics. Overlap of the 50-topic clustering results is based on the cosine similarity between topics as a metric for similarity and interdisciplinarity (high to low). The vertical axis is sorted from highest to lowest overall similarity score. Highest overall similarity score was calculated for climate change and knowledge review. Some topics such as gene expression exhibit very low overall similarity scores, marked by mostly dark red, although there can, at times, be a strong relation to individual topics (dark blue) for instance gene expression and epigenetic and circadian regulation in plant development.

literature. The discussions cover quantitative aspects, such as different drought indicators (Satoh et al., 2021), specific drought events such as flash droughts (Schwartz et al., 2023), and a more generalized concept of drought as driven by and as a threat to societal systems (Mishra and Singh, 2010; Van Loon et al., 2016b). In line with these discussions, our results identify flash droughts, the meteorological drought index, and the Palmer drought index as distinct, highly specialized topics within the broader drought research literature (see, for example, highly specialized topics in Fig. 2). At a more general level, drought is perceived as systemic, encompassing ecosystem, societal, and economic dimensions. At this level, case studies are particularly useful for quantifying connection strengths and impacts within specific environments (Van Loon et al., 2019, 2024). In genetic and plant physiological research, drought is defined as a system state that hampers plant growth (Gaudin et al., 2013; Moran et al., 2017). In plant genetics, highly specialized topics focus on methods to

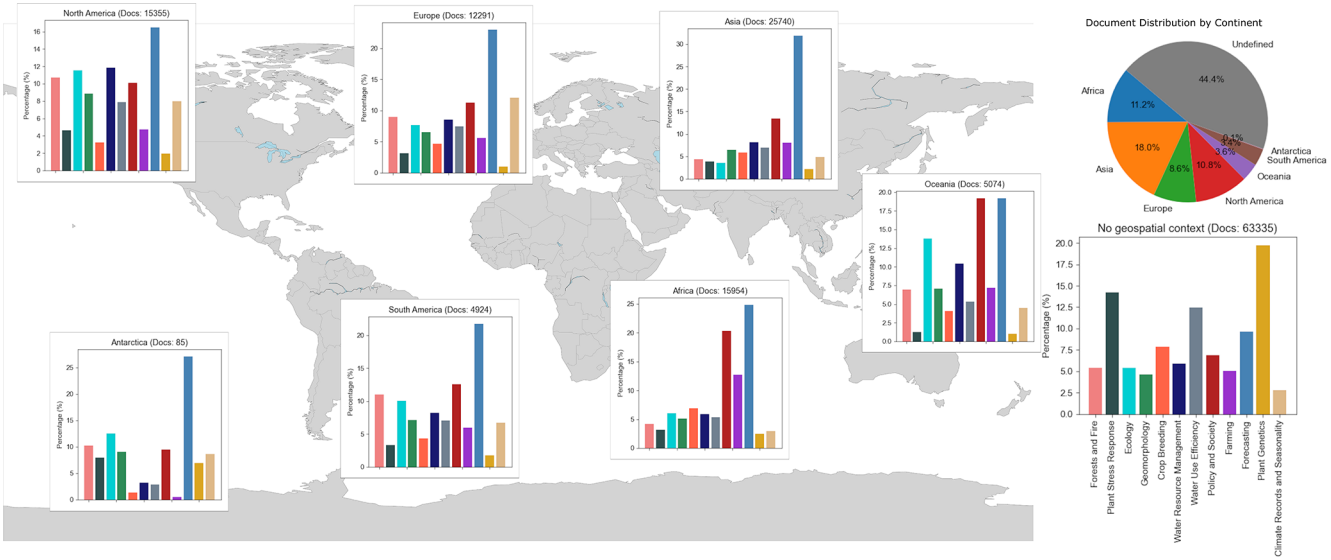

Figure 7. Geospatial distribution of drought research foci for all years. Distribution of the 12 research topics differs depending on the region of the world. Distributions were calculated based on mentions of the name of continents or states. Oceania and Africa exhibit a remarkably high share of policy-and-society-related research. Forecasting is the topic with the strongest weight in all regions, particularly in Europe and Asia. In North America, forests and fire, ecology, and geomorphology are almost at the level of forecasting. The topic of plant genetics dominates research with no geospatial reference.

foster the drought tolerance and drought resistance of plants through, for example, enhancing water use efficiency.

In agreement with the literature, this analysis' results and the topological maps of drought research indicate that there is not a unique understanding of drought. Rather, the different understandings, scales, and concepts are interconnected at both general and specific levels. The results build on the strength of LDA as a method to calculate connection strengths based on the co-occurrence and frequency of multiple keywords and topics rather than focusing on specific terms and meanings. Hence, this method results in maps of connection strengths between different systems, foci, and perspectives (Figs. 5 and 6).

4.2 Forecasting methods

Forecasting has emerged as a major and increasingly relevant topic in drought research. This growing importance is driven by several factors, including the substantial data requirements, the need for data integration platforms, environmental monitoring systems, and the application of artificial intelligence to generate indices. The identified emerging trends in the highly specialized tier-3 topics and the abovementioned factors contribute significantly to the rising prominence of drought forecasting (Wardlow et al., 2017; Pasteris et al., 2005). Additionally, recent occurrences of rapidly developing and large-scale drought events, such as in the La Plata basin in South America and in West Africa (Geirinhas et al., 2023), highlight the need for enhanced mechanistic understanding and forecasting capabilities. Improved forecasting will improve the readiness to manage more frequent drought conditions and to support food security for a growing global population (Krishnamurthy R et al., 2022).

Despite the increasing application of machine learning approaches in drought forecasting (Al Mamun et al., 2024; Prodhan et al., 2022), our analysis did not identify machine learning and artificial intelligence as distinct topics. Similarly, early-warning systems (Funk et al., 2019) and compound events (Ridder et al., 2022; Yin et al., 2023; Lesk et al., 2022) were not identified as distinct topics, although an urgency for progress in relation to these topics is perceived (FAO-WFP, 2020). There are two possible explanations for this. First, these topics may not have emerged as distinct areas within the drought research domain and could be distributed across broader research themes. Second, the volume of research on these topics may be insufficient to form distinct clusters. To make a meaningful impact on drought research, these emerging topics need to gain further momentum through increased publication numbers, research focus, and funding mechanisms.

4.3 Bridging the gap in drought research

Given the challenges in food and water security, it is now the time to bridge the gap between forecasting drought impacts, e.g. under climate change, and the consideration of genetic advances in drought tolerance for agricultural production. However, it is particularly challenging to bridge this gap given the so far limited interactions between the topics of plant genetics and forecasting (Fig. 2). Some projects al-

ready address this challenge by aiming to include the genetic variability of plants in crop models or to use crop growth models for identification of climate-adapted varieties (Parent and Tardieu, 2014; Chenu et al., 2017). Hence, crop yield forecasts under climate change scenarios must give stronger consideration to genetic advances and plant molecular processes than what is currently being explored (Stella et al., 2023). Nevertheless, increasing crops' drought resilience and drought forecasting will not suffice as the sole mechanisms. Other mitigation strategies at the political and ecosystem levels can provide equally important and case-specific solutions. Knowledge reviews are one tool for this and are required to bridge interdisciplinarity, which they already do, as illustrated by reviews relating to the overall interdisciplinarity score (Fig. 6).

4.4 Implications for research, policy, and institutions

These findings have significant implications for the scientific community, policymakers, and institutions addressing drought issues. The current topical research emphasis lies on drought forecasting methods and plant genetics (Fig. 4). Both topics guard food security and imply that food security is a human priority for funding and research interests. The topic of plant genetics provides methods to identify genes and produce variants with higher drought tolerance by altering a variety of physiologic processes (Fig. 2). Forecasting explores methods to forecast drought with regard to risk monitoring, often in relation to agricultural impacts and drought indicators and for specific events (Fig. 2). In contrast, topics that address drought impacts on socio-ecosystem compartments such as ecology and water resource management held greater importance in the past compared to their current relevance. Policy and funding agencies must decide based on their priorities whether this is a desirable trend or not and align funding strategies accordingly.

4.5 Limitations of Latent Dirichlet Allocation

The data for this research were limited to abstracts, titles, and keywords. While this approach allowed for a large volume of articles to be analysed over an extended temporal period, it comes with certain limitations. The primary advantage is that abstracts, titles, and keywords are well standardized and harmonized. A key disadvantage is the uncertainty regarding how accurately these abstracts and keywords reflect the full content and findings of the articles (see, for example, Westergaard et al., 2018). The results are heavily dependent on the effectiveness of the peer-review process, underscoring the critical role of abstracts in research communication.

A more in-depth study, potentially utilizing more advanced models or normalization procedures, would require additional computational resources (e.g. compare Callaghan et al., 2020, and Ogunleye et al., 2023). For instance, normalizing word frequency could help account for differences in document length. It is important to note that a full-text analysis might reveal that specialized research is more interdisciplinary than it appears based on abstract-only analysis. Additionally, the use of semantic analysis could extract further insights with regard to, for example, uncovering interdisciplinary connections, analysing the connotations and perceptions of terms, and distinguishing more granular subtopics due to the larger information base (Geeganage et al., 2024; Niu et al., 2022).

5 Conclusions and future directions

This study offers a comprehensive data-driven topology of drought research, providing valuable insights for decision-makers, researchers, and institutions. By mapping the current topical priorities, geographical distributions, emerging trends, and interconnections between research areas, we contribute to the development of systemic drought resilience frameworks. These frameworks ideally embrace the increasing interdisciplinarity observed following 2007, ensuring a holistic approach to drought resilience (Hagenlocher et al., 2023). Key topics to consider in this context include climate change impacts, reviews, and remote sensing, which exhibited the highest overall interdisciplinarity and are potentially critical to the effectiveness of systemic drought resilience frameworks (Hagenlocher et al., 2019). Additionally, central components of drought research, such as water resource management, essential for societal applications like drinking-water supply, cooling, and irrigation, must be integral to these frameworks (Jasechko et al., 2024).

While this analysis highlights current trends, it also identifies areas that are potentially overlooked in drought research. Future research directions should also focus on underrepresented areas, such as the integration of drought impacts on less-studied ecosystems, which are critical to the Earth's life support system (IPCC, 2021). Furthermore, the sociopolitical implications of water scarcity and the development of more localized and culturally sensitive drought resilience strategies deserve greater attention. Notably, this study did not identify machine learning approaches, studies of compound events, and early-warning systems as distinct topics despite their recognized importance in the field. Addressing these gaps will ensure that future drought research not only follows trends but also explores crucial areas that are currently underrepresented, leading to more comprehensive and effective strategies for mitigating drought impacts.

The trends, geographic patterns, and connection strengths between the topics revealed in this study serve as a tool to guide the development of future drought resilience frameworks. While much of the drought research falls into highly specialized areas, our results highlight where topical connections are stronger and where they are weaker.

Although this study is grounded in natural language processing of a large scientific corpus, it does not replace a qual-

itative assessment of scale- and event-specific impacts. Instead, it offers a broad overview that complements more specialized research by revealing the overarching connections and trends within drought research. Decision-makers, policy institutes, and researchers working on response strategies to address drought issues would potentially do well by considering the full breadth of the outlined topics.

Appendix A

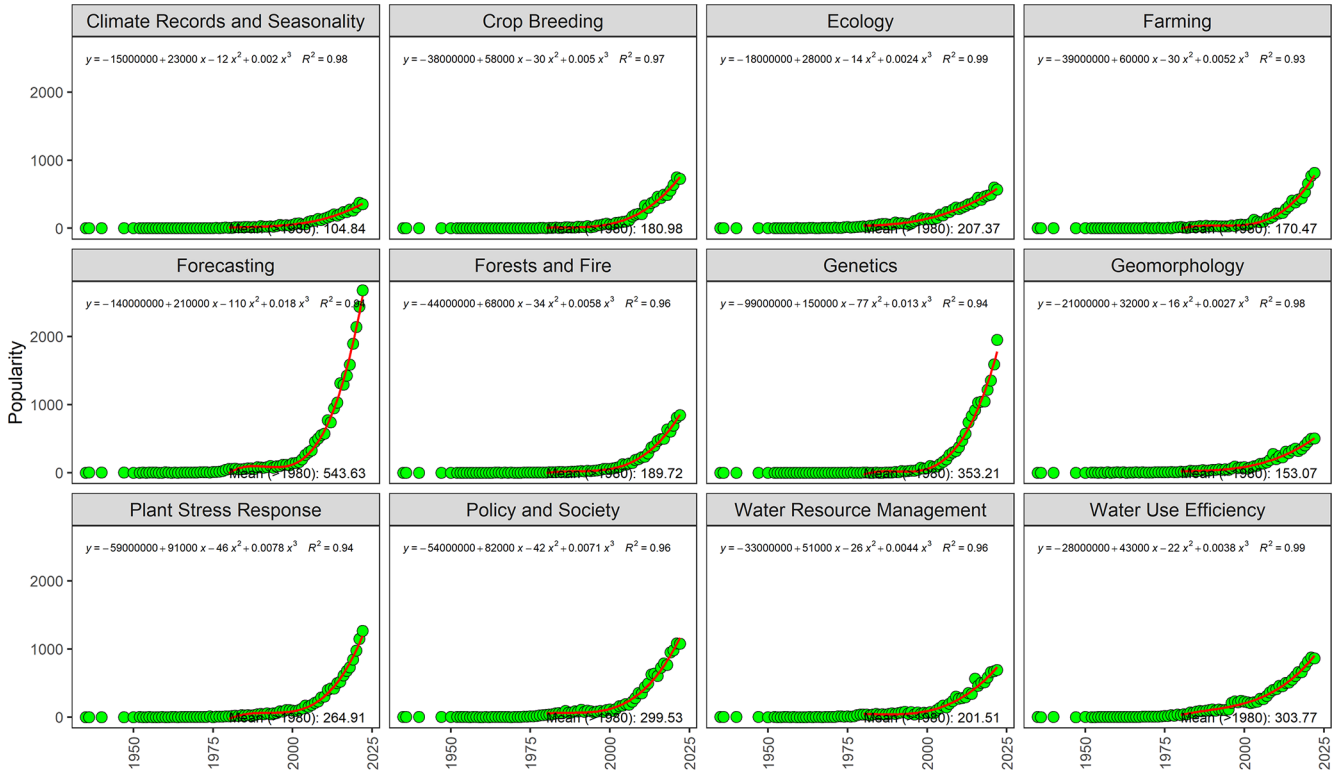

Figure A1. Data and trends of total annual publications. Data and polynomial trends of annual publications by major topics per document. Popularity is the number of publications on the particular topic, with the polynomial fitted function to indicate the trend since 1980 to 2022, and the mean for this period is given.

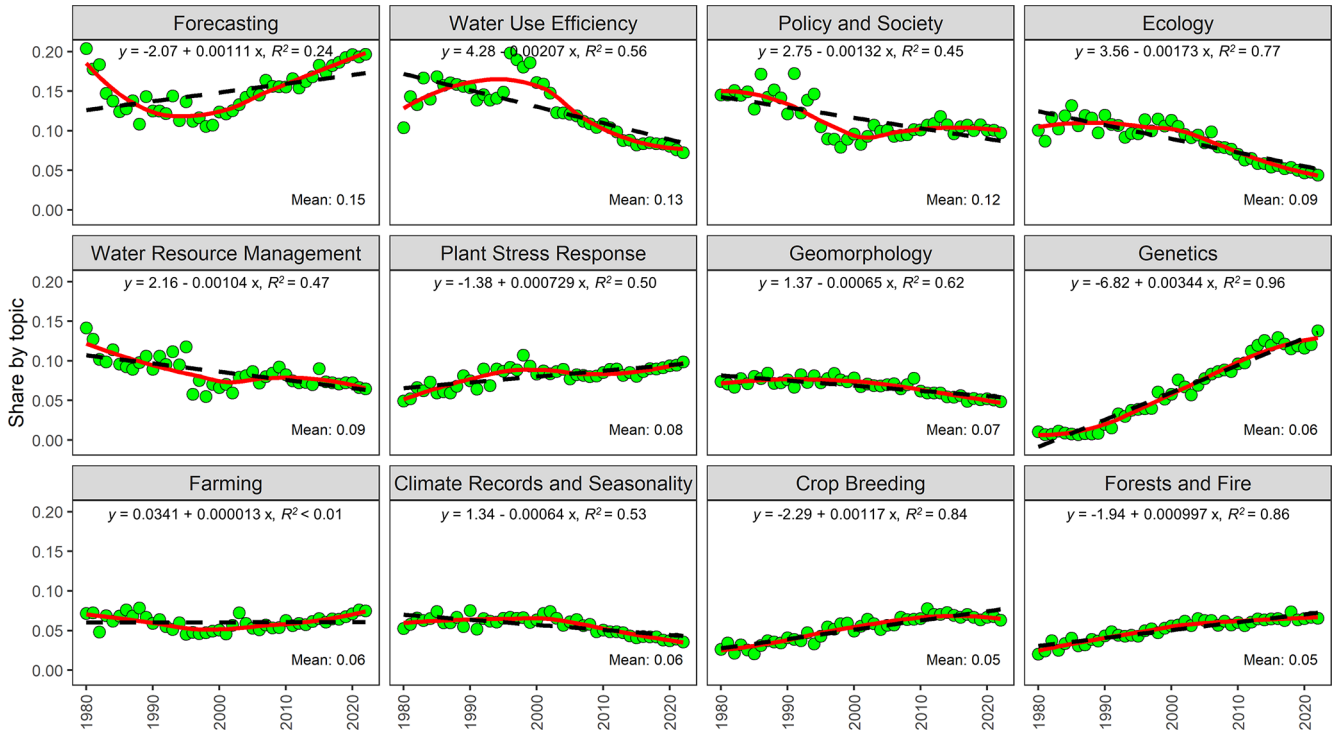

Figure A2. Annual share of topics in drought research. Annual shares of research topics ranked by mean annual share. The formula for linear regression provides the trend over the last 4 decades (dashed black line). The topic of genetics has the highest positive trend, with the highest Pearson correlation coefficient. Total publication growth is exponential, while annual share refers to the single year, which leads to forecasting and genetics being the topics with highest overall share.

Code availability. Supporting information and code availability are available upon reasonable request from the corresponding author.

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Competing interests. The contact author has declared that none of the authors has any competing interests.

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