

Review

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Review

Bibliometric Analysis of Remote Sensing-Based Crop Climate Vulnerability: Trends and Perspectives

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Highlights

What are the main findings?

- Research on remote sensing-based crop climate vulnerability expanded steadily from 1985 to 2026 and accelerated sharply after 2015, reaching a mature and internationally collaborative stage.
- The thematic core is structured around drought, NDVI, GIS, and crop monitoring, with a recent shift toward machine learning and Google Earth Engine for predictive geospatial intelligence.

What are the implications of the main findings?

- Future progress depends on integrating optical, thermal, hyperspectral, SAR, climatic, and socioeconomic data within interoperable vulnerability frameworks.
- Translating remote sensing outputs into decision-ready tools can strengthen agricultural adaptation, irrigation planning, early warning systems, and climate risk governance.

Abstract

Climate change is intensifying droughts, heatwaves, and hydrological extremes, increasing crop vulnerability and threatening global food security. This study analyzes the scientific evolution of research on remote sensing-based crop climate vulnerability, with emphasis on temporal, geographical, and thematic patterns. A quantitative, exploratory, descriptive, longitudinal, and retrospective bibliometric approach was applied to 2,343 documents indexed in Scopus between 1985 and 2026. The dataset was processed using Bibliometrix 5.1.1 and VOSviewer 1.6.20 to evaluate productivity, impact, collaboration, and intellectual structure, including Reference Publication Year Spectroscopy (RPYS). Results show a sustained annual growth rate of 4%, with 627 sources, 10,408 authors, an average of 5.17 co-authors per document, 35.3% international collaboration, and 19.93 citations per document. China, the United States, and India lead scientific production, while key journals concentrate dissemination. Thematic analysis highlights the dominance of drought-related studies and the increasing importance of machine learning and cloud-based platforms such as Google Earth Engine. The findings indicate that the field has reached a stage of scientific and technological maturity, transitioning from descriptive monitoring toward predictive and operational geospatial intelligence. However, challenges remain in methodological integration, geographical representation, and the translation of scientific outputs into decision-oriented tools for agricultural adaptation.

Keywords: remote sensing; crop climate vulnerability; agricultural adaptation; agricultural drought; machine learning; bibliometric analysis

1. Introduction

Climate change constitutes one of the most critical threats to global food security, as it intensifies heatwaves, droughts, and floods that reduce agricultural yields and increase price volatility [1]. Empirical evidence indicates that, for every +1 °C increase in temperature, average yields decline by approximately -6.0% for wheat, -3.2% for rice, -7.4% for maize, and -3.1% for soybean [2]. Furthermore, simulations by Tigchelaar et al. [3] suggest that future warming will increase the likelihood of synchronized production shocks in major maize-producing countries, thereby amplifying systemic risks and market volatility. At the interannual scale, climate variability accounts for between 32% and 39% of global crop yield variability, highlighting the high sensitivity of agricultural systems to thermal and hydrological anomalies [4].

The IPCC [5] Sixth Assessment Report warns that climate change exacerbates risks across the four pillars of food security, increasing exposure in already vulnerable regions. In 2023, between 683 and 733 million people experienced hunger [6], while global losses of up to 5.5×10^{14} kcal year⁻¹ per +1 °C of warming are projected to be only partially mitigated by 2050 and 2100 [7]. These trends underscore an unprecedented challenge for global agricultural resilience.

In this context of increasing production vulnerability, understanding crop responses to climate change in both spatial and temporal dimensions requires tools capable of continuously integrating biophysical and climatic information. This need has positioned remote sensing as a fundamental pillar in agricultural risk assessment [8,9]. Remote sensing technologies generate spatially explicit and temporally consistent indicators of exposure, sensitivity, and adaptive capacity by integrating meteorological and surface variables at unprecedented resolution [10–12].

Driven by the broad expansion of remote sensing in agricultural monitoring, several studies identify the Standardized Precipitation Index (SPI), Crop Water Stress Index (CWSI), and Normalized Difference Vegetation Index (NDVI) among the most recurrent indicators in drought-related research, while the Temperature Condition Index (TCI) and heat-oriented spectral metrics also appear in crop heat-stress applications, with wheat, maize, and rice among the most frequently assessed crops [13–15].

Remote sensing of climatic and biophysical variables also plays a key role in assessing crop resilience and vulnerability to extreme events [16–19]. Kim et al. [20] demonstrated that combined anomalies in temperature and NDVI explain up to 72% of the spatial variability in heat stress in rice systems across Southeast Asia, highlighting the predictive capacity of integrated indices. Similarly, Smith-Tripp et al. [21] quantified drought impacts across 14 million hectares in the Indus Basin using MODIS and ERA5 datasets, reporting mean NDVI declines of -18% and yield reductions of -22% for wheat during El Niño years. In arid environments, the integration of thermal, hyperspectral, and microwave sensors has enabled robust characterization of vulnerability in crops such as maize, barley, and cotton, achieving classification accuracies exceeding 90% under water stress conditions [22].

Despite these advances, several critical challenges remain. The strong thematic focus on drought and productivity indices has limited the exploration of other relevant indicators, such as soil salinity and phenological variability [23]. Heterogeneity in spatial and temporal resolutions also persists, as the integration of MODIS products (250 m, 8-day) with Sentinel-2 data (10-30 m, 5-day) complicates result comparability [24]. Moreover, the lack of standardization in vulnerability frameworks (particularly regarding exposure, sensitivity, and adaptive capacity) restricts reproducibility across regions and studies [25]. Geographical biases further persist, with most research concentrated in Asia, Europe, and North America, while Latin America and Africa remain underrepresented [26].

Despite the exponential growth of remote sensing-based studies, there is still no comprehensive quantitative synthesis capturing how scientific knowledge on crop climate vulnerability has evolved

in terms of thematic structures, dominant conceptual frameworks, and persistent geographical gaps [27]. This limitation constrains the understanding of the field's epistemic maturity and reduces the capacity to guide research agendas toward global climate adaptation goals, particularly SDG 2 (Zero Hunger, target 2.4), SDG 13 (Climate Action, target 13.1), and SDG 15 (Life on Land, target 15.3) [9,28,29].

Understanding the complexity of remote sensing-based crop climate vulnerability and guiding effective agricultural adaptation and climate risk reduction strategies requires a comprehensive assessment of the theoretical, methodological, and technological developments accumulated over the past three decades. This context leads to the central research question: What is the level of scientific development in crop climate vulnerability assessed through remote sensing, and how have its thematic, geographical, and methodological structures evolved over time? From this, twelve specific questions are derived: i) how has scientific output evolved over time? ii) which document types predominate? iii) which subject areas are most closely connected within Scopus? iv) which countries and institutions lead production? v) who are the most influential authors? vi) to what extent does productivity follow Lotka's Law? vii) which journals concentrate dissemination? viii) how is knowledge structured under Bradford's Law? ix) what is the degree of international collaboration? x) what insights does RPYS provide on intellectual roots? xi) which seminal works explain citation peaks? xii) which emerging trends are shaping the research agenda?

Based on these questions, the main objective of this study is to describe, quantitatively analyze, and interpret the evolution of research on crop climate vulnerability using remote sensing. This includes identifying temporal, geographical, and thematic patterns, collaboration networks, and influential sources, and proposing an interpretive framework that characterizes the current stage of the field, its structural challenges, and its future research agenda in support of agricultural adaptation and sustainable food system management under climate change.

Beyond mapping publication growth and bibliometric structures, this study provides an interpretive contribution by arguing that research on remote sensing-based crop climate vulnerability has entered a new stage characterized by the transition from descriptive spectral monitoring to predictive, multiscale, and increasingly operational geospatial intelligence. However, this transition remains constrained by methodological fragmentation, geographical asymmetries, and the limited translation of satellite-derived outputs into decision-ready vulnerability metrics. By explicitly identifying these patterns, this work not only systematizes existing knowledge but also clarifies priorities for future research and cartographic applications in agricultural climate adaptation.

Accordingly, this article not only maps the bibliometric structure of the literature but also formulates a set of propositions regarding the field's developmental transition, its principal methodological bottlenecks, and the priorities that should guide future research oriented toward cartographic applications and climate adaptation. The novelty of this study lies in its integrative and interpretive approach, which goes beyond conventional bibliometric descriptions by combining quantitative mapping with a critical assessment of the field's epistemic evolution and operational readiness. Unlike previous studies, this research explicitly links bibliometric patterns with the transition toward predictive and decision-oriented geospatial intelligence, highlighting the gap between scientific production and its applicability in real-world agricultural risk management. Furthermore, it provides a systematic identification of thematic asymmetries, methodological fragmentation, and geographical imbalances, offering a coherent framework to guide future research toward more interoperable, scalable, and policy-relevant applications of remote sensing in climate-resilient agriculture.

2. Materials and Methods

2.1. Study design

To characterize the scientific evolution of remote sensing-based crop climate vulnerability, bibliometric mapping was employed as a quantitative approach grounded in mathematical and

statistical models. This method is designed to analyze scientific production, the intellectual structure, and patterns of scholarly communication within the field. It enables the synthesis of research trends, the identification of influential authors, institutions, and countries, the mapping of collaboration networks, and the detection of knowledge gaps and emerging research lines, thereby providing a comprehensive overview of crop vulnerability and resilience studies in the context of remote sensing and climate change.

The study followed a quantitative, exploratory, and descriptive approach, adopting a non-experimental, longitudinal, and retrospective design. The analytical strategy focused on tracing and interpreting the evolution of the literature from its earliest records to the present, including publications up to 2026, with the aim of reconstructing research trajectories, identifying key turning points, and assessing the level of thematic consolidation. The methodological procedure followed the stages proposed by Luna-Morales et al. [30], including the formulation of general and specific research questions, selection of the reference database, construction of a reproducible search query, and the statistical analysis of bibliometric indicators alongside the visualization of networks and thematic structures.

2.2. Data source and search strategy

Scopus was selected as the primary data source due to its broad multidisciplinary coverage, high-quality indexing standards, and the richness of its metadata, including information on authors, affiliations, countries, references, and keywords. These attributes make it particularly suitable for conducting analyses of scientific productivity, impact, and collaboration patterns. The search was conducted on 13 February 2026, without restrictions on language or publication year, in order to maximize the comprehensiveness of the dataset and ensure extensive coverage of the research domain.

The search strategy was based on a structured and reproducible query designed to capture the intersection between remote sensing, climate-related factors, agricultural systems, and vulnerability concepts. The canonical query applied was as follows: (TITLE-ABS-KEY ("remote sensing" OR "satellite imagery" OR "earth observation" OR "NDVI" OR "EVI" OR "Landsat" OR "Sentinel" OR "MODIS" OR "geospatial analysis") AND TITLE-ABS-KEY ("climate change" OR "climate variability" OR "global warming" OR "climate impact" OR "drought" OR "extreme weather") AND TITLE-ABS-KEY ("crop*" OR "agriculture*" OR "cropland" OR "farming system*" OR "food crop*" OR "plant production" OR "yield prediction" OR "crop yield") AND TITLE-ABS-KEY ("vulnerability" OR "resilience" OR "risk" OR "adaptation")).

2.3. Corpus refinement and preprocessing

A total of 2,732 records were initially retrieved and exported in Comma-Separated Values (CSV) format for subsequent statistical processing and visualization. Prior to analysis, a manual thematic screening was performed to exclude non-relevant documents, thereby ensuring the specificity of the corpus and reducing the "noise" associated with publications lacking a clear agricultural or climate-related focus.

Subsequently, the metadata were cleaned, standardized, and organized in spreadsheet format (Excel) to facilitate preprocessing and consistency checks across key fields, including authors, affiliations, keywords, and cited references. This step ensured the integrity, coherence, and reliability of the dataset [31]. After this refinement process, the final corpus consisted of 2,343 records.

2.4. Bibliometric tools and indicators

The bibliometric analysis was conducted using Bibliometrix 5.1.1 (2025), implemented within the R environment, and VOSviewer 1.6.20 (2023), developed by Leiden University. Bibliometrix was employed to compute productivity indicators (e.g., authors, countries, and journals), impact indicators (total citations, average citations per document, and the h, g, and m indices), and scientific

collaboration indicators (co-authorship patterns and institutional networks). Additionally, it supported the application of classical bibliometric laws, including Lotka's Law (author productivity distribution) and Bradford's Law (core journal identification) [32].

VOSviewer was used to construct and visualize keyword co-occurrence networks, co-authorship networks, and bibliographic coupling structures. The analysis was based on association strength normalization and density-based node representation, enabling the identification of thematic clusters and the intensity of relationships among research elements [33,34].

Moreover, the Reference Publication Year Spectroscopy (RPYS) method was applied to identify the historical foundations of the field and to detect citation peaks corresponding to key methodological and conceptual milestones in the evolution of research on agricultural climate vulnerability. The integration of these analytical approaches allowed for a comprehensive mapping of the intellectual structure, thematic development, and collaboration networks within the domain of remote sensing applied to crop vulnerability and resilience. This combined framework provides a coherent and systematic assessment of the current state, major advances, and future directions of scientific knowledge related to agricultural adaptation and climate sustainability.

3. Results

3.1. General bibliometric profile of the corpus

Figure 1 provides a synthetic overview of the development achieved in research on remote sensing-based crop climate vulnerability over the period 1985-2026. The analyzed dataset comprises 2,343 documents distributed across 627 sources, indicating sustained scientific output and broad dissemination of the topic across diverse publication venues. An annual growth rate of 4% reflects steady expansion, driven by the increasing demand for tools capable of monitoring the impacts of droughts, heatwaves, hydrological anomalies, and other climatic stressors on agricultural systems. At the same time, the presence of 5,879 author keywords and 18,119 cited references highlights a wide thematic scope and the progressive consolidation of analytical frameworks for assessing crop exposure, sensitivity, and adaptive capacity.



Figure 1. General bibliometric indicators of the corpus.

This body of research is also characterized by a strongly collaborative structure. The corpus includes 10,408 authors, with an average of 5.17 co-authors per document and 35.3% international collaboration, while only 116 authors are associated with single-authored publications. This pattern suggests that the assessment of agricultural climate vulnerability through remote sensing inherently requires the integration of agronomic, climatic, geospatial, and computational expertise. The mean document age of 4.28 years and an average of 19.93 citations per document position the field within a relatively recent, dynamic, and increasingly influential research agenda. Collectively, these indicators demonstrate that remote sensing has evolved beyond a supporting role to become a fundamental scientific and technical framework for understanding, anticipating, and managing crop vulnerability under climate change.

3.2. Annual scientific production

Figure 2 illustrates the temporal trajectory through which research on crop climate vulnerability assessed using remote sensing has evolved from a marginal topic to an increasingly prominent research axis within the agricultural and climate agenda. Between 1985 and 2004, scientific output remained low and irregular, fluctuating between zero and four publications per year. This early phase reflects fragmented efforts and the limited use of satellite data to investigate climate impacts on crop yield, water stress, and spatial crop responses. From 2005 onward, a clear shift is observed, with annual production increasing from eight publications in 2005 to 46 in 2014, indicating the growing integration of Earth observation technologies into the analysis of droughts, thermal anomalies, and production variability.

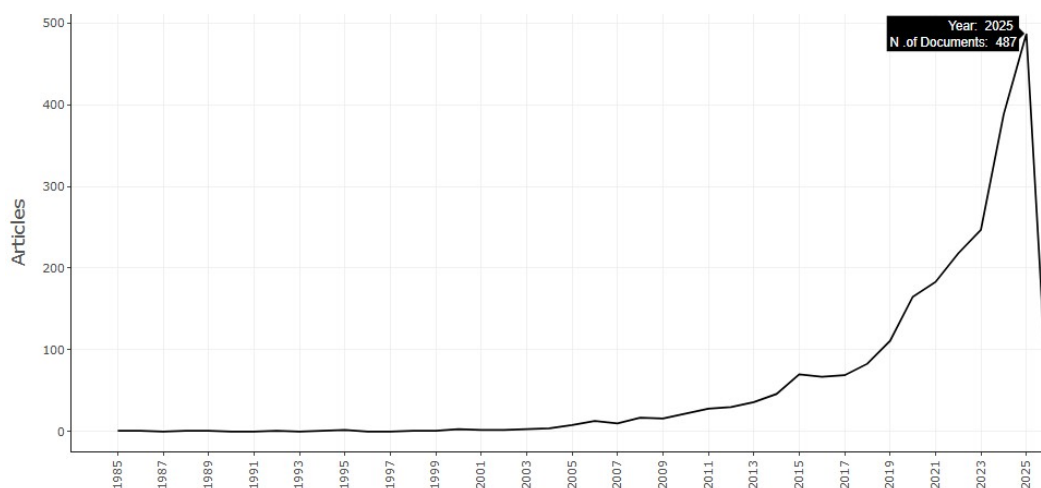


Figure 2. Annual scientific production.

The expansion became significantly more pronounced after 2015. Annual output increased from 70 articles in 2015 to 111 in 2019, followed by 165 in 2020, 218 in 2022, 247 in 2023, 388 in 2024, and reaching a peak of 487 publications in 2025. This rapid growth reflects a transition from descriptive analyses toward more advanced approaches aimed at anticipating patterns of exposure, sensitivity, and risk in agricultural systems under intensifying climatic pressures. The lower value recorded for 2026, with five publications, is attributable to the database cut-off and does not affect the overall upward trend. Taken together, these findings confirm that remote sensing has become firmly established as a critical analytical framework for assessing crop climate vulnerability across spatial and temporal scales that are increasingly relevant for agricultural adaptation.

3.3. Authors and productivity concentration

Figure 3 identifies a small core of authors with recurrent presence in the study of remote sensing based crop climate vulnerability. The highest individual output reaches 13 documents, while Aqil Tariq and Paolo Tarolli each record 11. They are followed by Bijay Halder with eight contributions, and José Luís Araus, Natvar R. Patel, and M. P. Reynolds with seven each. Giriraj Amarnath, Jatisankar Bandyopadhyay, and Josef Eitzinger each contribute six papers. This distribution shows that the topic has been driven by a group of specialists with continuity in a field where agriculture, climate, Earth observation, and spatial analysis converge.

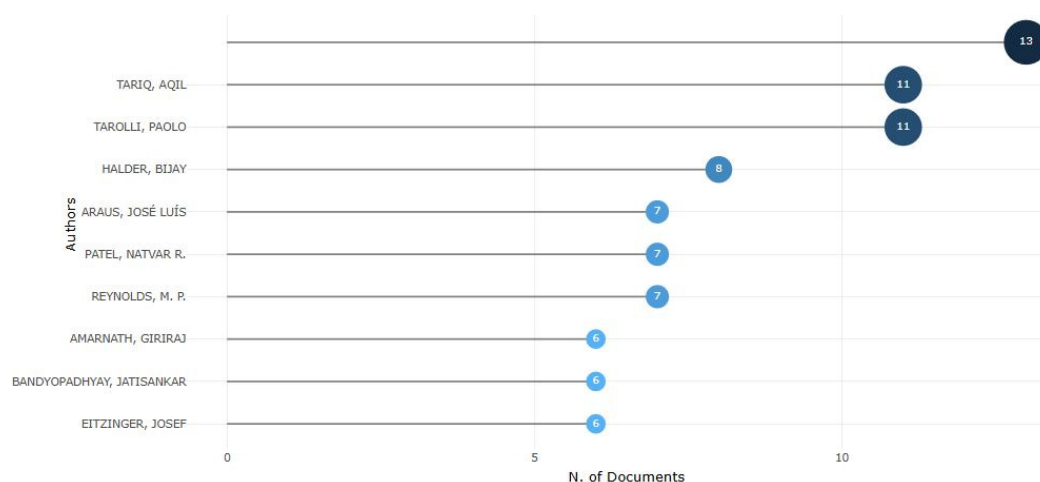


Figure 3. Relevant authors.

The pattern also indicates that knowledge construction on agricultural vulnerability does not depend on isolated authorship or extreme concentration. Although recognisable leadership exists, the differences among the main contributors are moderate, which suggests a distributed scientific base and expansion across several lines of work. This matters because assessing crop responses to droughts, extreme heat, water stress, and climate variability requires cumulative evidence and continuous refinement of observation methods. In this sense, remote sensing applied to crop climate vulnerability advances on the basis of a specialised community that already gives the field stability and supports its consolidation as a technical basis for agricultural adaptation.

3.4. Lotka distribution of author productivity

Figure 4 shows that research on remote sensing-based crop climate vulnerability is supported by broad participation, although with uneven continuity among contributors. Most authors are associated with a single publication, while the proportion decreases sharply as the number of publications per author increases. Beyond the second contribution, the distribution declines rapidly and becomes marginal at higher productivity levels. This pattern indicates that, although the field attracts a large number of researchers, only a relatively small group maintains sustained scholarly engagement.

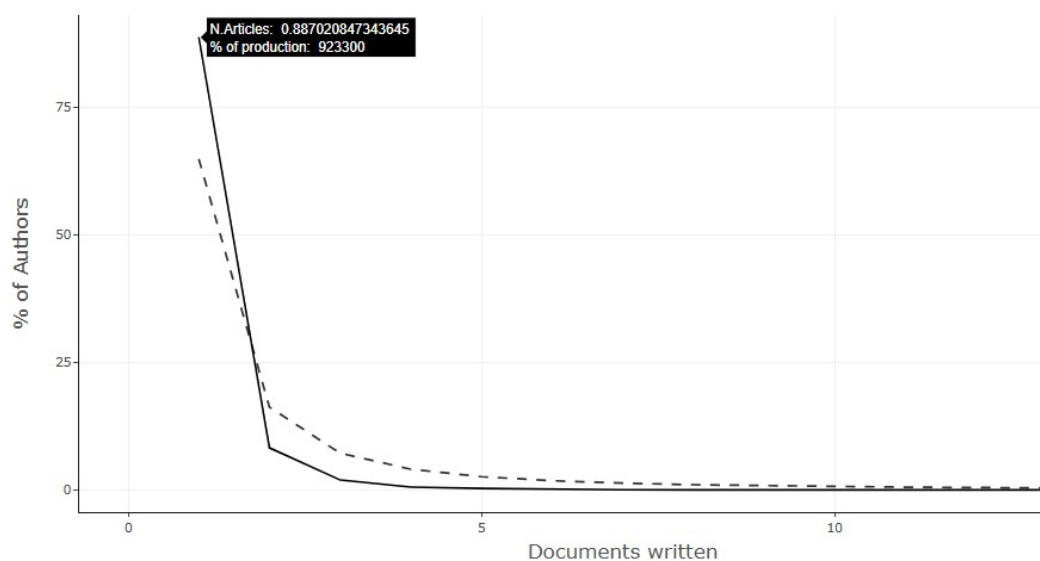


Figure 4. Distribution of authors by productivity according to Lotka's law.

This distribution is consistent with the interdisciplinary nature of the topic. Assessing agricultural vulnerability to droughts, extreme heat, water stress, and other climatic pressures requires contributions from fields such as agronomy, remote sensing, climatology, spatial modeling, and data science. However, sustained participation in this research area demands the accumulation of methodological expertise, access to long-term datasets, proficiency in sensor technologies, and the capacity to integrate biophysical and climatic variables within coherent analytical frameworks. As a result, sustained productivity tends to be concentrated among a limited number of authors, while a broader group contributes intermittently through case studies or region-specific applications. Overall, the field is undergoing an expansion phase characterized by a wide collaborative base, yet it continues to rely on a specialized core of researchers who ensure analytical continuity and methodological advancement.

3.5. Leading journals and Bradford dispersion

Figure 5 shows that research on remote sensing-based crop climate vulnerability is primarily disseminated through publication venues closely associated with Earth observation and applied environmental assessment. A leading source accounts for 253 documents, followed by Remote Sensing with 126 and Science of the Total Environment with 66. Environmental Monitoring and Assessment contributes 48 publications, Sustainability 43, Proceedings of SPIE 41, and the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 35. Ecological Indicators, Land, and Water also appear with 33, 31, and 31 publications, respectively. This distribution indicates that the field does not evolve within a single disciplinary stream but rather at the intersection of remote sensing, environmental monitoring, land management, and the analysis of agroecosystems under climate change pressures.

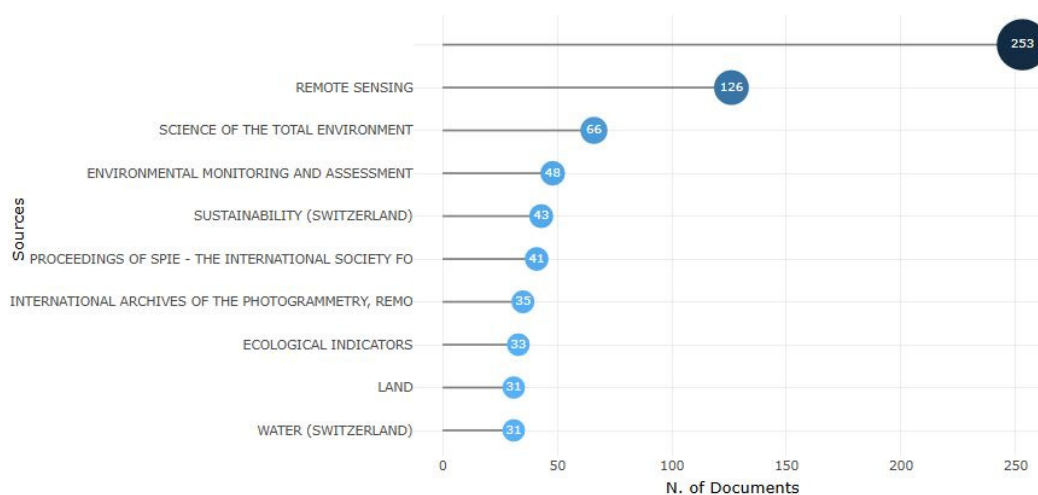


Figure 5. Leading journals.

Figure 6 complements this pattern by demonstrating that scientific output is unevenly distributed across journals. Production is initially concentrated within a well-defined core of leading journals and subsequently disperses across a wide range of lower-volume sources. This pattern reflects a diffusion structure organized around specialized publication venues that serve as key references for the study of droughts, extreme heat, hydrological anomalies, and crop responses under adverse climatic conditions. The extended tail of secondary sources further indicates that the field has expanded beyond its original technical focus into broader domains related to sustainability, water resource management, territorial planning, and environmental assessment. Overall, this distribution reflects not only editorial concentration but also a clear indication of the field's thematic consolidation and maturity.

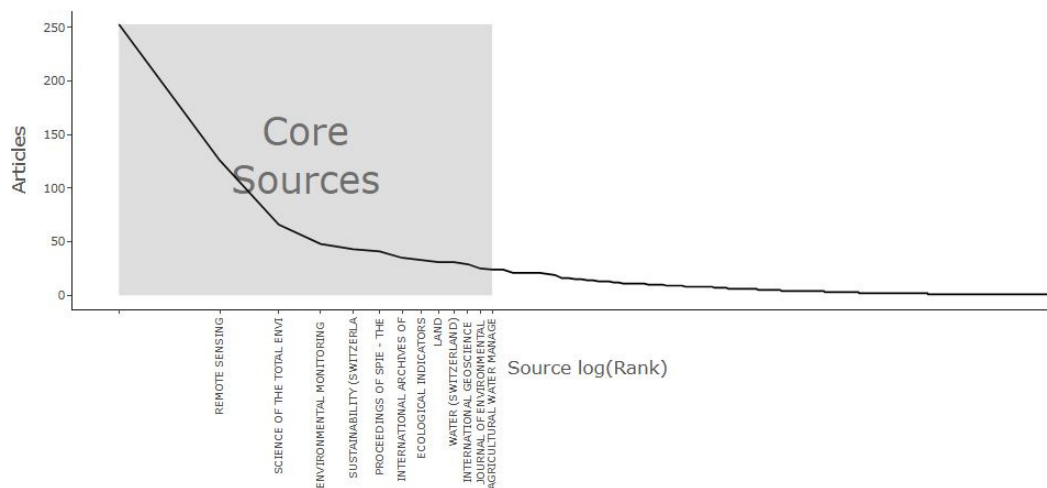


Figure 6. Article dispersion according to Bradford's law.

3.6. Institutions and countries

The institutional distribution presented in Figure 7 reveals a marked concentration of research activity within organizations possessing strong capabilities in Earth observation, geospatial analysis, and agricultural sciences. The University of Chinese Academy of Sciences leads with 178 publications, followed by Beijing Normal University with 130, Northwest A&F University with 76, and the Institute of Geographic Sciences and Natural Resources Research with 69. A second tier includes the International Maize and Wheat Improvement Center and Wuhan University, each with 59 contributions, while China Agricultural University and Northeast Normal University both register 52 publications. Overall, this distribution indicates that knowledge production in remote sensing-based crop climate vulnerability is largely driven by institutions with established expertise in environmental monitoring, spatial modeling, and agricultural responses to climatic stress.

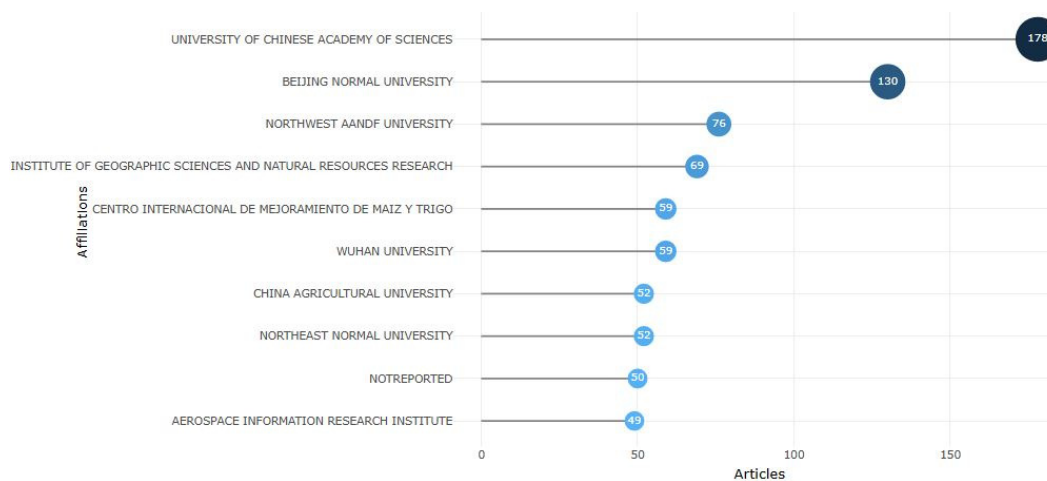


Figure 7. Institutional affiliations.

At the national level, the pattern observed in Figure 8 reflects a similarly pronounced concentration of scientific output. China ranks first with nearly 500 publications, followed by the United States with slightly over 400 and India with more than 300. Germany, the United Kingdom, and Italy occupy an intermediate position, while Australia, France, Ethiopia, and Spain form a secondary group with lower but still significant contributions. The predominance of countries in Asia and North America suggests that research advances more rapidly in contexts where strong scientific infrastructures, consistent access to remote sensing data, and active agricultural adaptation agendas are present. Notably, Ethiopia's inclusion among the leading contributors highlights the importance

of this research area in regions where agricultural vulnerability directly affects food security, rural livelihoods, and production resilience.

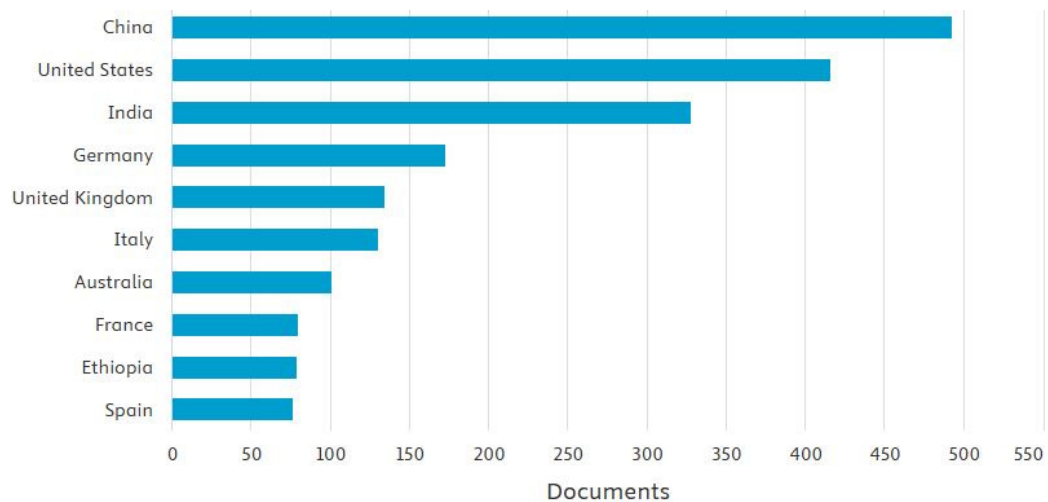


Figure 8. Output by country.

3.7. Keyword dynamics over time

The temporal distribution of keywords presented in Figure 9 illustrates the cumulative evolution of the terms that have structured research on remote sensing-based crop climate vulnerability, revealing a shift from observation-centered terminology toward language increasingly focused on climate risk assessment and decision support. The highest frequencies correspond to remote sensing (501 occurrences) and climate change (373), confirming that the field is fundamentally built on the integration of satellite monitoring and climatic pressures. Within this framework, drought reaches 245 occurrences and emerges as the most prominent issue in the thematic agenda, indicating that agricultural vulnerability has been predominantly interpreted through the impacts of water deficit on crop functioning and production stability. In parallel, NDVI (167) and agriculture (110) reflect the combined emphasis on biophysical measurement of vegetation dynamics and the applied evaluation of agricultural performance under environmental stress.

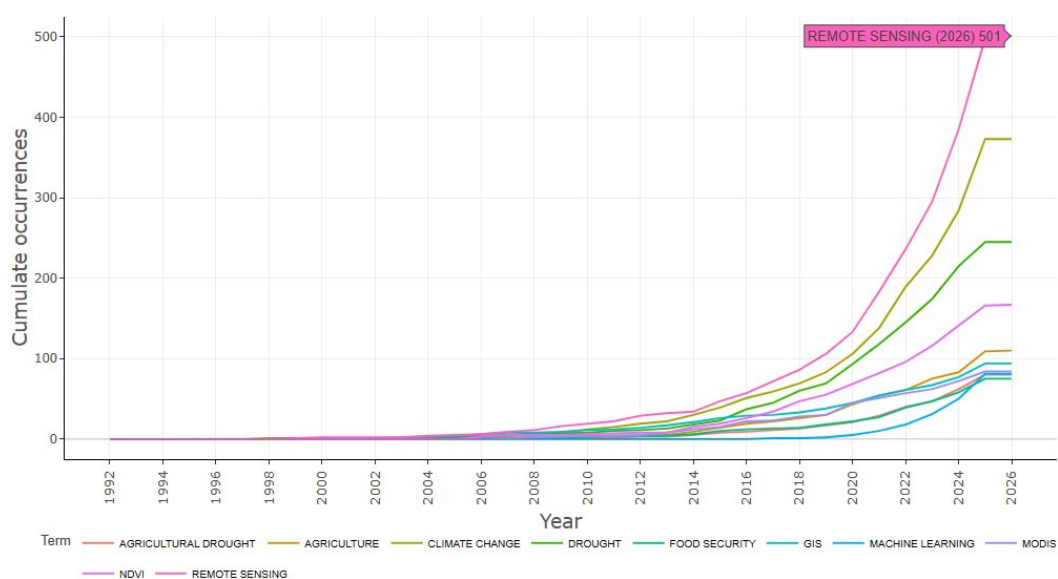


Figure 9. Word frequency over time.

A complementary perspective highlights a clear methodological and operational transition over time. Terms such as GIS (94 occurrences) and MODIS (84) underscore the importance of spatial

platforms and satellite time series in multitemporal monitoring of crop responses. However, the most significant shift is the rapid emergence of machine learning, which has grown markedly since 2017 to reach 81 occurrences, approaching the frequencies of agricultural drought (80) and food security (75). This trend indicates a transition from descriptive analyses toward predictive frameworks capable of integrating climatic variables, sensor data, spatial patterns, and agricultural performance. Overall, the figure demonstrates that the field has evolved toward a more analytical and integrative paradigm, in which drought assessment, spectral monitoring, and intelligent modeling converge as key components for anticipating risk and supporting agricultural adaptation.

3.8. Subject areas

The disciplinary distribution illustrated in Figure 10 confirms that remote sensing-based crop climate vulnerability has evolved into a distinctly interdisciplinary field, although it remains primarily anchored in environmental and Earth sciences. Environmental Science accounts for 25.0% of the total output, while Earth and Planetary Sciences represent 19.3%, indicating that nearly half of the research is concentrated in domains focused on environmental processes, surface dynamics, climate systems, and territorial observation. Agricultural and Biological Sciences contribute an additional 15.0%, demonstrating that the analysis extends beyond physical landscape characterization to directly address crop behavior and sensitivity to droughts, extreme heat, and variations in water availability.

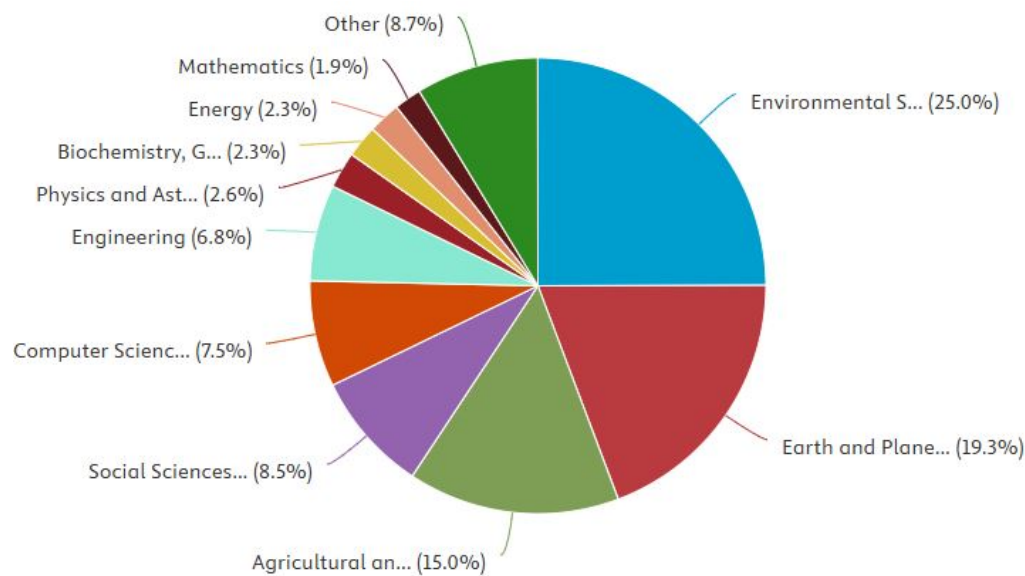


Figure 10. Publications by subject area.

A broader disciplinary perspective reveals the growing integration of complementary fields. Social Sciences (8.5%), Computer Science (7.5%), and Engineering (6.8%) expand the analytical scope toward risk management, algorithm development, spatial automation, and the design of applied solutions. Additional contributions from Physics and Astronomy, Biochemistry, Genetics and Molecular Biology, Energy, and Mathematics, although smaller in proportion, provide essential support to the methodological and analytical foundations of monitoring and modeling processes. Overall, the field is characterized by the convergence of multiple disciplines, enabling a comprehensive understanding of agricultural risk through interconnected environmental, technological, and socio-ecological perspectives.

3.9. Keyword co-occurrence network

references in 2019. This trajectory suggests that the field did not emerge from a single disciplinary tradition, but rather from the gradual convergence of drought climatology, land surface remote sensing, hydrological modeling, and agronomic evaluation of crop performance. The decline observed in 2022 and 2023 does not alter this interpretation, as it reflects the shorter citation accumulation period associated with more recent publications.

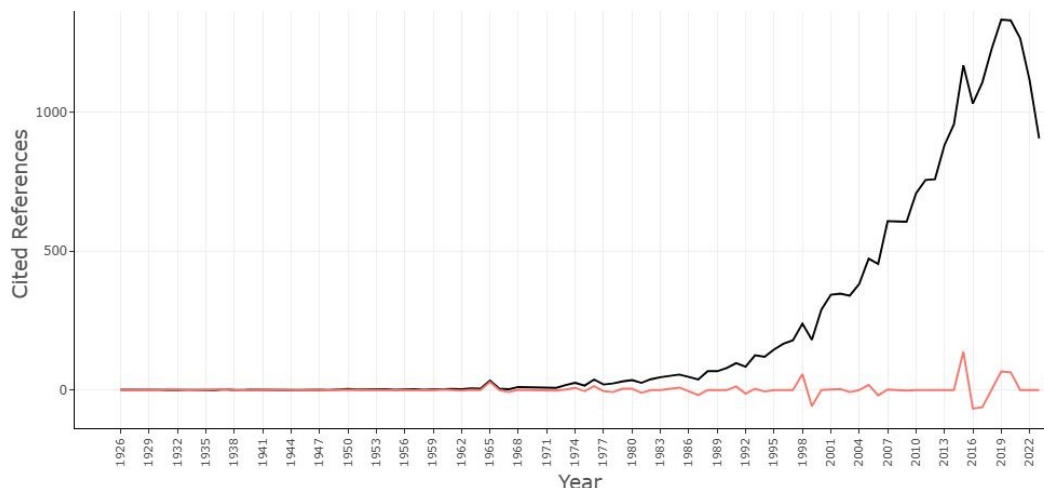


Figure 12. Annual distribution of cited references.

A closer examination of the deviation from the median curve highlights specific years that function as intellectual turning points. Among the earliest milestones, 1965 is notable for the foundational formulation of meteorological drought, while 1976 marks advances in land use and land cover classification using remote sensing data, and 1985 reflects improved understanding of drought and its hydrological metrics. The early 1990s, particularly 1991 and 1993, correspond to key developments in the validation of remote sensing classifications and the application of NDVI profiles for agricultural analysis. The year 1998 represents a major milestone with the establishment of guidelines for evapotranspiration and crop water requirements. Subsequently, 2005 strengthened the conceptual linkage between vegetation dynamics, drought, and vulnerability, while 2015 marks a significant turning point associated with the central role of remote sensing in drought research. Finally, 2019 signals the transition toward a more integrated phase characterized by operational monitoring and impact assessment.

3.11. Thematic map

The thematic configuration presented in Figure 13 illustrates how research on remote sensing-based crop climate vulnerability is organized into four clusters, each fulfilling distinct roles within the field. The cluster with the highest centrality and density (comprising remote sensing, drought, and NDVI) represents the most consolidated axis, where spectral monitoring of water stress serves as the primary framework for interpreting crop responses under adverse climatic conditions. This cluster constitutes not only a frequent association but also the conceptual core that links the biophysical assessment of vegetation status with the operational detection of agricultural drought. In parallel, climate change, agriculture, and machine learning occupy a position of high centrality but relatively lower density, suggesting that these are foundational themes with strong integrative capacity and significant potential to reshape the research agenda toward predictive, integrative, and adaptation-oriented approaches.

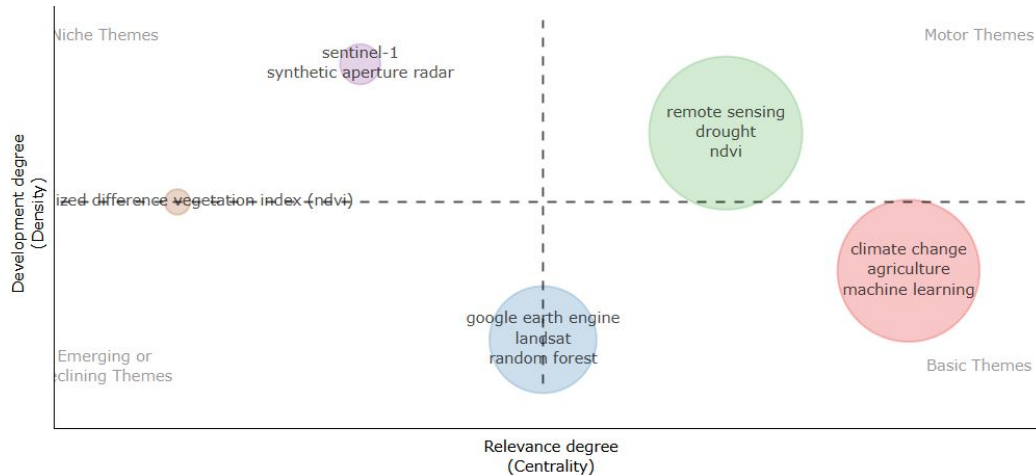


Figure 13. Thematic map.

From a structural perspective, a transitional cluster composed of Google Earth Engine, Landsat, and random forest reflects a methodological base that, while still consolidating, is already critical for scaling analyses, automating processing workflows, and improving the spatial estimation of agricultural risk. In a more specialized quadrant, Sentinel-1 and synthetic aperture radar (SAR) represent technically advanced developments, particularly valuable in conditions where soil moisture, canopy structure, or atmospheric interference limit the effectiveness of optical sensors. Meanwhile, NDVI appears displaced toward an area of lower centrality, indicating that, although it retains historical and operational relevance, it no longer dominates thematic innovation. Overall, the field is transitioning from an approach centered on traditional vegetation and drought indices toward a more advanced stage in which cloud-based platforms, diversified sensor integration, and machine learning techniques converge to enhance the precision and predictive capacity of crop climate vulnerability assessments.

4. Discussion

4.1. Interpretation of field development

An integrated reading of Figures 1 and 2 indicates that the expansion of the field is not solely driven by an increase in publication volume, but by the progressive incorporation of Earth observation into the core of agricultural adaptation strategies [35,36]. The acceleration observed after 2015 reflects not merely a methodological trend, but the consolidation of a scientific infrastructure focused on impact monitoring, yield forecasting, and risk-informed decision support [35,37]. In this context, Figures 3 and 4 suggest that the relative concentration of recurrent authors should not be interpreted as thematic closure, but rather as evidence of the high technical demands required to sustain research in this domain. Continued engagement requires access to long-term datasets, cross-scale validation, and the integration of agronomic, climatic, and geospatial information within consistent analytical frameworks [36,39].

From the perspective of knowledge dissemination, Figures 5 and 6 show that the field is structured around a core group of journals in which remote sensing, applied hydrology, and environmental assessment converge, a pattern consistent with the broader cross-disciplinary consolidation described in recent reviews [37,39]. This editorial nucleus has provided technical robustness and accelerated the diffusion of methodologies applicable to drought analysis, thermal stress assessment, and crop monitoring [38,39]. At the same time, Figures 7 and 8 highlight a marked geographical concentration of scientific production, led by China, the United States, and India, along with a smaller group of countries with strong geospatial capabilities. However, this pattern reflects not only scientific leadership but also structural inequalities in access to standardized data, analytical infrastructure, and technical capacity, which constrain broader territorial representation [36,43].

A thematic perspective derived from Figures 9 and 11 confirms that drought remains the central organizing concept within the field, although its analysis has evolved beyond reliance on a limited set of traditional indices [37,40]. The prominence of terms such as agricultural drought, soil moisture, food security, and crop yield, together with the rapid emergence of machine learning and Google Earth Engine, indicates a shift toward predictive, scalable, and increasingly operational analytical systems [37,40,41]. Additionally, Figures 10 and 11 suggest that the field has adopted a more comprehensive understanding of vulnerability, in which crops are no longer treated as isolated entities but as components of complex socioecological systems influenced by multiple climatic stressors and shaped by interactions among water availability, land use, and management practices [26,42]. Finally, Figures 12 and 13 reveal a clear trajectory from initial approaches centered on drought monitoring and vegetation assessment toward more advanced frameworks focused on compound risk analysis, adaptation zoning, and model transferability across temporal and spatial contexts [39,41].

4.2. Propositions, future perspectives, and main challenges

The findings of this study support four key propositions that contribute to advancing the state of the art. First, research on remote sensing-based crop climate vulnerability has evolved beyond descriptive monitoring and is now entering a stage characterized by predictive and operational geospatial intelligence [36,38,39]. Second, this transition remains geographically uneven and epistemically asymmetric, with scientific leadership concentrated in Asia and North America, while Latin America and Africa continue to be underrepresented in terms of publication output, calibration efforts, and research funding networks [36,43]. Third, the next frontier in the field lies in methodological interoperability rather than the continued accumulation of data. Future progress will depend on the integration of optical, thermal, hyperspectral, SAR, climatic, and socioeconomic datasets within consistent vulnerability frameworks based on exposure, sensitivity, and adaptive capacity [39,42,43].

From an operational perspective, the most critical unresolved challenge is the transformation of remote sensing outputs into decision-ready vulnerability intelligence [35,36]. Although the field demonstrates strong capabilities in detecting and modelling climatic stress, it still requires stronger in situ validation, region-specific calibration, standardized and interoperable data workflows, and more effective translation into cartographic products that support adaptation planning, early warning systems, irrigation management, and territorial agricultural risk governance [35,36,40,43]. Collectively, these propositions suggest that the current state of the field is no longer defined by the expansion of remote sensing applications alone, but by the capacity to generate transferable, multiscale, and policy-relevant geospatial intelligence that integrates Earth observation, vulnerability theory, and climate adaptation decision-making under diverse environmental conditions [35,39,42].

5. Conclusions

This study demonstrates that research on remote sensing-based crop climate vulnerability has evolved from a fragmented body of monitoring-oriented studies into a mature and increasingly consolidated scientific domain, supported by a robust technological and collaborative infrastructure. The sustained growth in scientific output, the consolidation of a clearly defined editorial core, the expansion of international collaboration networks, and the progressive integration of machine learning, cloud computing platforms, and multi-sensor approaches collectively confirm that the field has reached a stage of significant analytical and methodological sophistication.

A central contribution of this work lies in interpreting this evolution as a structural transition from descriptive spectral monitoring to predictive and operational geospatial intelligence. This transformation represents a substantive advancement in the state of the art, as it repositions remote sensing from a primarily observational tool to a comprehensive analytical framework capable of anticipating crop vulnerability, modeling complex climate-crop interactions, and supporting climate-informed agricultural decision-making. In this sense, remote sensing emerges not only as a data

source, but as a strategic component in the development of adaptive and resilient agricultural systems under conditions of increasing climatic uncertainty.

At the same time, the findings reveal that the consolidation of the field remains incomplete and uneven. Methodological fragmentation persists, particularly in the integration of multi-sensor data and the application of heterogeneous vulnerability frameworks. Geographical asymmetries continue to shape knowledge production, with a strong concentration in Asia and North America, while regions such as Latin America and Africa remain underrepresented despite their high vulnerability to climate change. Additionally, limitations in cross-scale comparability, inconsistencies in temporal and spatial resolutions, and the lack of standardized approaches to defining and operationalizing vulnerability constrain the reproducibility and transferability of results across different contexts.

Another critical limitation identified is the gap between scientific production and its practical application. Although remote sensing has demonstrated strong capabilities in detecting, monitoring, and modeling climatic stress, the translation of these outputs into decision-ready vulnerability metrics remains insufficient. Bridging this gap requires stronger in situ validation, region-specific calibration, and the adoption of FAIR-oriented data governance principles to ensure accessibility, interoperability, and reuse of geospatial information. Furthermore, there is a need to strengthen the link between scientific outputs and policy frameworks, enabling the effective incorporation of remote sensing-based indicators into adaptation planning, early warning systems, irrigation management, and agricultural risk governance.

Looking forward, future research should prioritize several strategic directions. First, the integration of biophysical, climatic, and socioeconomic variables within unified and interoperable analytical frameworks is essential to capture the multidimensional nature of vulnerability. Second, advancing methodological interoperability across sensors (optical, thermal, hyperspectral, and SAR) will be critical for improving the accuracy and scalability of assessments. Third, expanding empirical validation in underrepresented regions will enhance the global relevance and applicability of findings. Fourth, the development of user-oriented cartographic products and decision-support tools will be key to translating scientific knowledge into actionable insights for stakeholders, including farmers, policymakers, and resource managers.

In this context, the future of the field depends not only on technological innovation, but also on its capacity to generate knowledge that is transferable, scalable, and operational across diverse environmental and socio-economic settings. The true advancement of remote sensing-based crop climate vulnerability research will therefore be measured not by the volume of data produced, but by its effectiveness in supporting real-world adaptation strategies and improving the resilience of agricultural systems. Ultimately, the integration of Earth observation, vulnerability theory, and decision-oriented geospatial intelligence represents a critical pathway for addressing the challenges of food security and climate change in the coming decades.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial intelligence
CWSI	Crop Water Stress Index
EVI	Enhanced Vegetation Index
GIS	Geographic information system
HIS	Heat Impact Stress Index.
IPCC	Intergovernmental Panel on Climate Change.
MDPI	Multidisciplinary Digital Publishing Institute.
MODIS	Moderate Resolution Imaging Spectroradiometer.
NDVI	Normalized Difference Vegetation Index.
RPYS	Reference Publication Year Spectroscopy.
SAR	Synthetic aperture radar.
SDG	Sustainable Development Goal.
SPI	Standardized Precipitation Index.
TCI	Temperature Condition Index.
VCI	Vegetation Condition Index.
VHI	Vegetation Health Index.

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