Ecología Austral 34:010-024 Abril 2024
Asociación Argentina de Ecología

Fifty years of research on South American drylands: Mapping the scientific contributions of the Argentine Institute for Dryland Research

Solana Tabeni✉; M. Florencia Miguel; Diego P. Vázquez; S. Yasmin Bobadilla; Andrea P. Tarquino-Carbonell; Vanina Egea & Agustina A. Ojeda

Instituto Argentino de Investigaciones de las Zonas Áridas (IADIZA), CCT-CONICET Mendoza, UNCuyo, Gobierno de Mendoza.

Abstract. Dryland ecosystems are among the most widespread biomes on Earth and sustain nearly 40% of the global human population. Knowledge on drylands throughout the world has come from diverse disciplinary fields including natural and social sciences. The use of quantitative tools, such as science mapping or bibliometric analysis, may help to explore the structure of knowledge and to identify emerging issues. Here, we analyzed the dynamics of scientific production on dryland ecosystems throughout fifty years since the creation of the Argentine Institute for Dryland Research (IADIZA). We focused on IADIZA as a case study because it is one of the oldest dryland research institutions in South America whose contributions may exemplify research trajectories in drylands. We conducted a systematic search in Scopus for the 1972-2022 period, complemented with the institute's records, which resulted in 1828 publications. We identified 48 research themes studied at IADIZA. The diversity of themes has increased through time, moving from the early descriptive studies of species and communities to the current focus on patterns and processes. From 2000 to the present, we detected a remarkable incorporation of new concepts, indicating that the conservation and management of natural resources, the systematics and taxonomy of species and ecological interactions constitute the central research themes, along with emerging themes such as genetics, evolution and urban ecology. In conclusion, our synthesis offers a clear description of the dynamics of research themes in the study of drylands and indicates a growing international interest in IADIZA's contributions to dryland functioning.

[Keywords: arid ecosystems; bibliometric analysis; knowledge evolution; scientific knowledge; temporal analysis]

Resumen. Cincuenta años de investigación en las tierras secas sudamericanas: Mapeando los aportes científicos del Instituto Argentino de Investigaciones de las Zonas Áridas. Los ecosistemas de tierras secas se encuentran entre los biomas más extendidos en la Tierra y sostienen casi el 40% de la población humana mundial. El conocimiento sobre las tierras secas en todo el mundo proviene de diversos campos disciplinarios, incluidas las ciencias naturales y sociales. Usar herramientas cuantitativas (e.g., el mapeo científico o el análisis bibliométrico) puede ayudar a explorar la estructura del conocimiento y a identificar problemas emergentes. En este trabajo analizamos la dinámica de la producción científica sobre ecosistemas de tierras secas a lo largo de cincuenta años desde la creación del Instituto Argentino de Investigaciones de las Zonas Áridas (IADIZA). Nos enfocamos en IADIZA como estudio de caso porque es una de las instituciones de investigación sobre tierras secas más antiguas de América del Sur, cuyas contribuciones pueden ejemplificar las trayectorias de investigación en estos ecosistemas. Realizamos una búsqueda sistemática en Scopus para el período 1972-2022, complementada con los registros del instituto, que resultó en 1828 publicaciones. Identificamos 48 temas de investigación estudiados en el Instituto. La diversidad de temas ha aumentado con el tiempo, pasando de los primeros estudios descriptivos de especies y comunidades al enfoque actual en patrones y procesos. Desde el 2000 hasta el presente detectamos una incorporación notable de nuevos conceptos, indicando que la conservación y el manejo de los recursos naturales, la sistemática y la taxonomía de las especies y las interacciones ecológicas constituyen los temas centrales de investigación, junto con otros emergentes como la genética, la evolución y la ecología urbana. En conclusión, nuestra síntesis describe con claridad la dinámica de los temas de investigación en el estudio de las tierras áridas e indica un creciente interés internacional sobre las contribuciones de IADIZA al funcionamiento de estos ecosistemas.

[Palabras clave: análisis bibliométrico, análisis temporal, conocimiento científico, ecosistemas áridos, evolución del conocimiento]

Editora asociada: María Vanessa Lencinas
✉ stabeni@mendoza-conicet.gob.ar
Recibido: 3 de Mayo de 2023
Aceptado: 22 de Noviembre de 2023

Introduction

Dryland ecosystems are among the most widespread biomes on Earth, covering almost 41% of the land area (Schimel 2010; Maestre et al. 2021) and sustaining nearly 40% of the global human population (Castro et al. 2018). Drylands are home to a large fraction of global biodiversity; for instance, one third of global biodiversity hotspots occur in drylands (Castro et al. 2018; Hanan et al. 2021). Different types of land use occur in drylands, such as urban settlement, mining, cropland agriculture and grazing (Ramankutty et al. 2008; Kennedy et al. 2019), leading to an increasing interest in the conservation and restoration of degraded land (Miguel et al. 2020; Coban et al. 2022).

Knowledge on dryland ecosystems throughout the world has come from diverse disciplinary fields including ecology, conservation, politics, anthropology and economy (e.g., Whitford 2002; Veth 2005; Davis 2016). This knowledge influences how we perceive and relate to drylands (Behnke and Mortimore 2016). Thus, for example, the notion of drylands as degraded, impoverished, marginal, fragile ecosystems has been questioned, opening new horizons on dryland biodiversity and biotic interactions and their resilience to environmental change (Davis 2016; Silcock and Fens 2019; Reynolds 2021). From the formalization of the concept of desertification (Behnke and Mortimore 2016), views on desert ecosystems have moved from land degradation to the value of their unique environments and the inherent ecological processes that govern their dynamics (e.g., Roig 1991; Whitford 2002; Veth et al. 2005). These changing views on dryland ecosystems should also lead to changing trends in research topics.

Scientific knowledge results from a complex, dynamic process driven by the integration of disciplines, researchers, interests and institutions (Fortunato et al. 2018). The striking growth of scientific production through the massive production of articles —ca. 50 million until 2009 (Jinha 2010)— has generated an increasing interest in capturing the global scenario of scientific activities. Understanding the structure of scientific knowledge is crucial to document its current development and to predict its future trends and emerging topics (Samoylenko et al. 2006). Quantitative tools may help represent the dynamic nature of knowledge production. One such tool, science mapping or bibliometric analysis, uses statistical procedures to explore the structure of knowledge and to identify emerging issues, assessing their impact and their trajectory over time (Shiffrin and Börner 2004; Cobo et al. 2011; Chen and Chen 2016). Knowledge mapping has made possible to explore research trends in environmental science topics such as ecological restoration (Guan et al. 2019), ecosystem services (Zhang et al. 2019; Chen et al. 2020), biodiversity (Liu et al. 2011; Stork and Astrin 2014), biological invasions (Hulme 2022) and disturbance ecology (Gonçalves et al. 2020). However, to date, knowledge on drylands has been poorly mapped, mostly in the context of land degradation (Xie et al. 2020) and drylands of particular regions or countries, such as China (Shi et al. 2021).

Here, we evaluated the dynamics of scientific knowledge on dryland ecosystems by using as a study case the academic production of one scientific institution throughout fifty years since its creation. We focused on the Argentine Institute for Dryland Research (IADIZA) because it is one of the oldest research institutions in South America studying drylands and its contributions may help to exemplify the development of knowledge in South America and worldwide. Specifically, we focused on 1) searching publications on dryland ecosystems generated by IADIZA from its creation in 1972 to the present; 2) analyzing the main research themes on drylands and evaluating theme changes over time, and 3) quantifying the scientific production and global impact of these scientific publications. Ultimately, this synthesis will contribute to identifying and discussing the main research gaps and topics for future research on drylands.

Materials and Methods

Bibliographic searches and data sources

We systematically searched the Scopus database (scopus.com) using the following term combinations: "Instituto Argentino de Investigac* de Zonas Aridas" OR "Instituto Argentino de Investigac* en Zonas Áridas" OR "Instituto Argentino de Investigac* de las Zonas Aridas" OR "Instituto Argentino de Investigac* de Zonas Áridas" OR "Instituto Argentino de Zonas Aridas" OR "Instituto Argentino de Zonas Áridas" OR "IADIZA" OR "Argentine Institute for Dryland Research" OR "Argentine Dryland Research Institute"

OR (instituto AND argentino AND ("Zonas Aridas" OR "Zonas Áridas")) OR (argentin* AND institute AND (dryland OR "Arid" OR "Arid Land" OR "Arid Lands" OR aridland OR "Arid Zones" OR "Arid Zone") AND research) OR "Institute for Aridland Research". The searches, limited to the 1972-2022 period, were done in May 2022 and returned 984 articles. We used the institute's annual reports to complement the above searches with scientific publications not covered by Scopus, resulting in an additional 844 publications. Thus, the final database contained a total of 1828 publications used for this synthesis, including scientific articles, books and book chapters. We included publications with at least one author affiliated with the Argentine Institute for Dryland Research. To analyze the global impact of these studies, we downloaded from Scopus the list of 15850 published articles that cited IADIZA articles (i.e., those articles with one of the authors affiliated with the Argentine Institute for Dryland Research; n=984). In our comprehensive review of the literature generated over 50 years by IADIZA, we found that certain fields are missing in articles published in the 1970s and 1980s, such as author keywords, article citation counts, affiliations, etc. This omission hinders their inclusion in topic detection analyses, topic networks, or international impact assessments. For this reason, this citation analysis was restricted to the 984 IADIZA publications found in Scopus.

Data extraction

We extracted the following primary information from each study: 1) authors' affiliations; 2) title, year, publication source and number of citations, and 3) keywords provided by authors. The affiliation information included the name of the institution and its geographical location. Using this information, we analyzed global spatial patterns of co-authorships in publications citing IADIZA's publications. For scientific articles, we used the year and journal of publication to study the temporal trends in the distribution of articles and to describe the frequency of publication in different journals. Moreover, we calculated the publication frequency in different journals weighted by citations by considering the number of citations for each article.

Data analysis

We performed bibliometric analysis using SciMAT software (sci2s.ugr.es/scimat) (Cobo et al. 2012). SciMAT performs two types of analyses: science mapping and performance analysis (Noyons et al. 1999; Chen 2017). Science mapping consists in visualizing the structure and dynamics of research topics over time. Through maps, this method provides a spatial representation of the relationships between disciplines, thematic areas, authors and institutions through time (Cobo et al. 2011; Chen 2017). Performance analysis aims to evaluate the impact of scientific research based on citations by authors, countries or institutions, the volume of scientific production per theme and the degree of interdisciplinarity involved in the development of the research topics (Cobo et al. 2011). Before performing the science mapping analysis, we reviewed the database to detect and correct errors related to duplicate literature, misspelling in the author names, title, journal and affiliation and to add missing data. Subsequently, we defined theme groups based on the author's keywords as the unit of analysis. In this way, bibliometric techniques allow defining 'themes' of research interest, thus avoiding the formation of arbitrary themes or only referring to disciplinary fields. In contrast, the themes are investigative spaces that are delimited by interconnections between keywords and that represent a network structure whose evolution can be visualized over time.

To this end, we filtered all the keywords from the database to identify and exclude duplicate and synonymous words (e.g., Monte desert, Monte, Monte Desert). To build the thematic groups we used the Scimat tool manual set group manager, which assigns each keyword to a user-defined group. To define the groups we previously identified the following thematic criteria: drylands geographic areas (which includes keywords related to America, Argentina, aridlands, Monte Desert, Patagonia, Chaco, Puna, ecosystems); disciplinary fields (which includes keywords related to zoology, botany, taxonomy-systematics-morphology, biogeography, social science-education-philosophy of science, landscape ecology, physiology, genetic, evolution, geography, edaphology, behavior, archaeology-paleoecology, functional ecology, microbiology, isotopic ecology, ecological interactions, population ecology, community ecology and trophic ecology); taxonomic groups (including keywords related to plant, invertebrate, bird, mammalia, amphibia, pisces and reptile); land use and conservation (conservation-management, agroecosystems-land use, global-change-climate, water

resource, pollution-chemistry, biological invasion, urban land use, indicators, protected areas, forestry, tourism, fire and ecosystem service), and applied methods (including keywords related to different surveys and statistical methods).

To analyze the evolution of the research themes, we organized the database into five 10-year subperiods: 1972-1981, 1982-1991, 1992-2001, 2002-2011 and 2012-2022. We worked with a reduced version of the database, which allowed us to focus on the most frequent keywords, discarding those below a given frequency threshold (minimum frequency: three author keywords). Subsequently, we built a co-occurrence network to establish the relationship among the keywords that constituted the research topics. We calculated the frequency of co-occurrence of keywords from the number of articles in which two keywords appear together. After building the keyword relationship network, we applied the equivalence index (Callon et al. 1991) as a similarity measure to normalize the network.

Thematic network and evolution of themes

We applied a clustering algorithm to the whole thematic network to perform the science map of the clusters or subnetworks. We used the simple centers algorithm, the simplest and most used tool in science mapping (Cobo et al. 2011). In each subperiod, we conducted network analyses to visualize theme development, based on the number of published documents and their interrelationships. To obtain the degree of interaction of a subnetwork with other subnetworks, we applied density and centrality measures, available in Scimat, to the clusters of the same subperiod (Callon's density and centrality) (Callon et al. 1991; Cobo et al. 2011). Centrality is a measure of the degree of interaction of a network of themes with other networks and density refers to the internal strength of the network through the keywords that define the thematic area (Callon et al. 1991).

To visualize the structure of the research topics and their networks, we drew a strategic diagram: a two-dimensional space that ordinates themes according to their centrality and density values (Cobo et al. 2011). This diagram allows identifying motor-themes (i.e., topics relevant for the development of a research area) (upper-right quadrant), specialized topics with little external connection (upper-left quadrant), underdeveloped topics, either emerging or not consolidated (lower-left quadrant) and transversal themes of general importance (lower-right quadrant).

We performed a temporal analysis (also called longitudinal analysis) to analyze the evolution of the research topics over time. To this end, we applied an inclusion index implemented in Scimat that allows establishing common elements or a connection between the themes through different subperiods. Furthermore, we calculated the stability index to measure overlapping between two consecutive subperiods based on their shared keywords.

Performance analysis: Scientific production

To analyze the scientific production of IADIZA in 50 years, we quantified the total number of scientific articles per subperiod and their distribution in indexed and nonindexed journals. In addition, we considered the average number of staff members (researchers, technicians and graduate students or post-docs) of the institute in each period. To analyze the main journals of publication of IADIZA throughout all periods of study, we calculated the publication frequency of the scientific articles by journals. Finally, we calculated the weighted publication frequency by the number of citations of articles published in different journals. The graphs were made using the ggplot2 (Wickham 2016) and vcd (Meyer et al. 2020) packages in R statistical software (R Core Team 2022).

Global impact of scientific production

Because the topics represented in IADIZA's publications do not necessarily match the global impact of those topics in the broader scientific community, we calculated the frequency of keywords in the publications as a way to represent the topics studied in the institute (hereafter "keyword frequency in IADIZA's publications") and compared it with the frequency of keywords weighted by the citations of the publications in which they appeared (hereafter "keyword frequency weighted by citations"). Thus, for example, the keyword "habitat loss" appeared in only three of IADIZA's publications included in Scopus, yet it had a high frequency weighted by citations, as the publications in which they appear were cited 1593 times, which placed this keyword in the third position in the keyword

citation ranking, only after "Monte Desert" and "Argentina". In contrast, the keyword "taxonomy" appeared in 40 publications, yet it had a relatively low frequency weighted by citations, as the publications in which they appeared were cited only 339 times. We conducted this analysis in R statistical software (R Core Team 2022) and illustrated it graphically using the wordcloud package in R statistical software (Lang and Chien 2018). Furthermore, to assess whether the keyword frequency in IADIZA´s publication differed statistically from the frequency weighted by citations, we conducted a chi-square test with the R chisq.test function in the stats package, using the simulate.p.value=TRUE option, which allows generating an expected distribution of the chi-squared statistic without assumptions and with a simulation sample size of 10000.

We also analyzed the global impact of scientific publications by country. We identified countries and main regions associated with institutions that have cited the publications and institutions by country that have collaborated as authors. Thus, we used the Scopus results database filtered by affiliation in both cases. We built two data sets: a) institutions listed in Scopus that cite publications from IADIZA and b) institutions associated with external authors that collaborated with IADIZA publications. We obtained georeferenced data from these institutions (latitude, longitude) downloaded from Google Maps and we mapped this spatial data using QGIS software (QGIS 2022). We recorded the geographic coordinates of the institutions with a unique coordinate system (WGS:84) and delimited influence areas from a shape file buffered by 2° using QGIS software (QGIS 2022). Finally, we plotted world countries with these buffers and coordinates to identify and visualize these main regions.

Results

The database included a total of 5097 keywords (4038 author keywords) represented at different frequencies (Figure 1), of which 48 research themes were delimited for the period 1972-2022 (Supplementary Material 1-Table S1). The keywords most frequently represented were related to locations of drylands (e.g., Argentina, Monte desert, South America), taxonomic groups (e.g., Tenebrionidae, *Prosopis flexuosa*, rodents) and main research topic (e.g., taxonomy, granivory, conservation) of the publications (Figure 1). Based on the number of articles in which they appear, the top 10 themes during IADIZA's 50 years have focused on research carried out in drylands of Argentina (hereafter, "Argentina"), studies on the natural history of vertebrates ("Zoology"), invertebrates ("Invertebrates") and desert plants ("Botany"), the structure and function of dryland ecosystems ("Ecosystems"), taxonomy and systematics of desert plants ("Plant"), first descriptions of species and biological communities in

Figure 1. Keyword frequency in IADIZA's publications.

Figura 1. Frecuencia de palabras clave en las publicaciones del IADIZA.

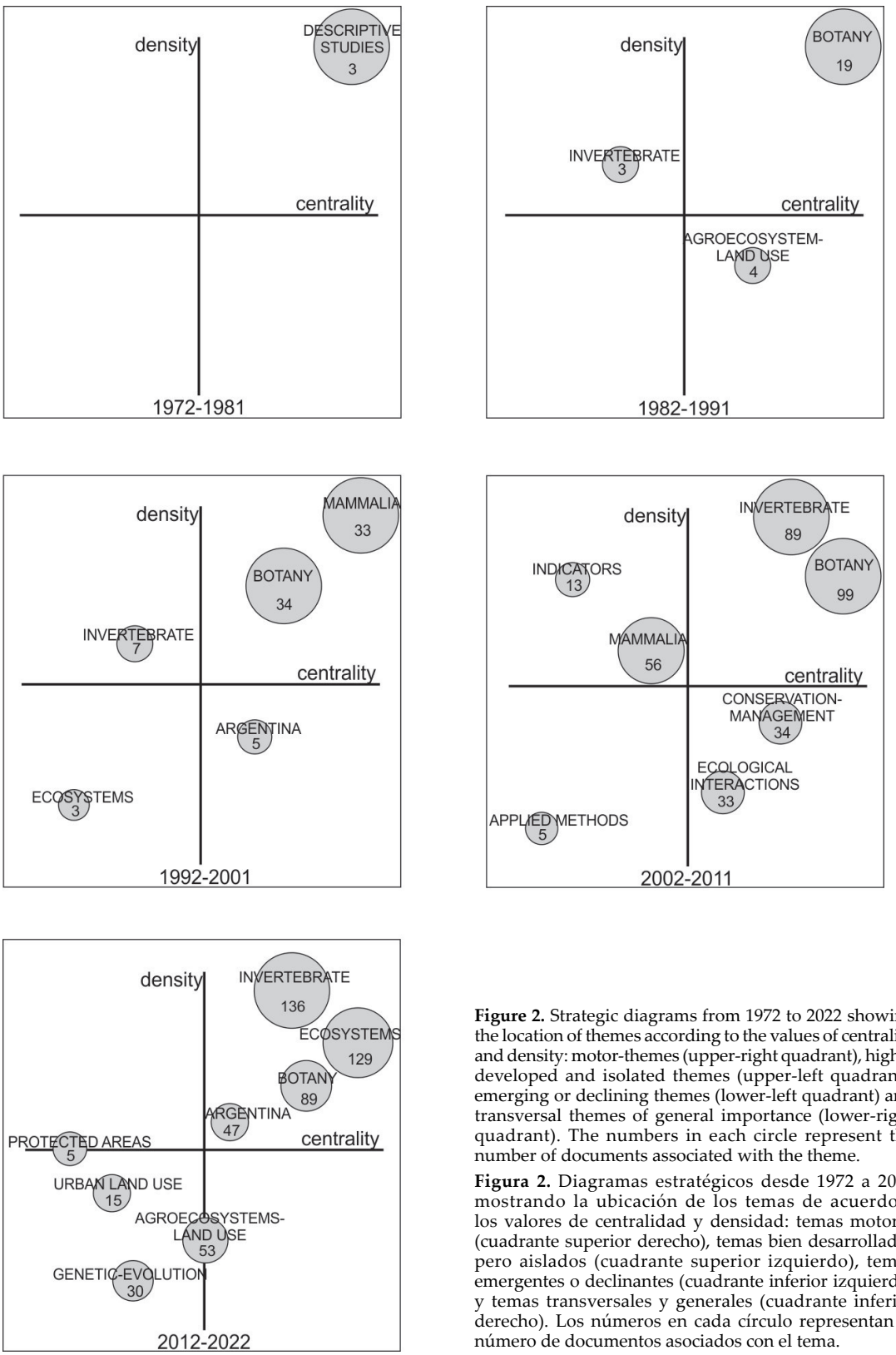

Figure 2. Strategic diagrams from 1972 to 2022 showing the location of themes according to the values of centrality and density: motor-themes (upper-right quadrant), highly developed and isolated themes (upper-left quadrant), emerging or declining themes (lower-left quadrant) and transversal themes of general importance (lower-right quadrant). The numbers in each circle represent the number of documents associated with the theme.

Figura 2. Diagramas estratégicos desde 1972 a 2022 mostrando la ubicación de los temas de acuerdo a los valores de centralidad y densidad: temas motores (cuadrante superior derecho), temas bien desarrollados pero aislados (cuadrante superior izquierdo), temas emergentes o declinantes (cuadrante inferior izquierdo) y temas transversales y generales (cuadrante inferior derecho). Los números en cada círculo representan el número de documentos asociados con el tema.

the South American drylands ("Descriptive studies"), the ecology and evolution of desert mammals ("Mammalia"), interspecific interactions ("Ecological interactions") and studies on agricultural practices and land uses in drylands ("Agroecosystems-Land use").

Figure 2 shows the strategic diagrams obtained in the five-time subperiods analyzed. In the first subperiod (1972-1981) the research areas were mostly driven by a single motor theme ("Descriptive studies") (Table 1). This theme included studies referring to plants and animal species and the first descriptions of desert plant communities from a broad geographic perspective. We identified a strong research trend at the regional level indicated by keywords. In the second subperiod (1982-1991) we observed a change of direction in the motor themes with a shift towards the study of dryland plant communities ("Botany") (Table 1). Research in entomology ("Invertebrate") emerged in this decade as a developing research field. Research focused on agricultural-livestock systems ("Agroecosystem-Land use") also emerged during this period, becoming a transversal theme. The third subperiod (1992-2001) was characterized by the development of studies on the ecology of species and communities of desert mammals, which constituted motor research themes together with botany. Invertebrate studies continued to grow but remained specific and with little interaction with other themes. In the area of transversal themes, we identified the studies carried out throughout Argentina. The focus on different dryland ecosystems emerged during this period as a theme of incipient development. During the 2002-2011 subperiod, themes

Table 1. Description of themes in each ten-year subperiod from 1972 up to 2022.
Tabla 1. Descripción de los temas en cada subperiodo de 10 años desde 1972 hasta 2022.

Period	Theme	Description
1972 to 1981	Descriptive studies	Description of species and biological communities
1982 to 1991	Agroecosystem-Land use	Studies on palatable species; cattle production; biodiversity conservation and land use
	Botany	Plant species descriptions; primary productivity; ecology of plant communities
	Invertebrate	Invertebrate taxon descriptions
1992 to 2001	Argentina	Studies on grazing; wood production; species distribution and diet; vegetation of different geographic regions
	Botany	Phenology, physiology, ecology, taxonomy, genetics of plants; species used as cattle forage; urban vegetation
	Ecosystems	Studies on different ecosystems and biogeographic regions
	Invertebrate	Morphology, taxonomy and biogeography of invertebrates
	Mammalia	Ecology, taxonomy, ethology, physiology and conservation of mammals
2002 to 2011	Applied methods	Application of different survey methods
	Botany	Studies on phenology, physiology, native and exotic species
	Conservation-Management	species and communities' conservation and management; landscape management; cattle production and management; water use; rural development
	Ecological interaction	Studies on mutualism, antagonism and competition
	Indicators	Species as bioindicators of disturbance and degradation
	Invertebrate	Description of new taxa; biogeography, taxonomy and ethology of invertebrates
	Mammalia	Ecology, taxonomy, genetics, phylogeny and taphonomy of rodents and small mammals
2012 to 2022	Agroecosystem-Land use	Cattle production; conservation and management of woodlands; biological invasions; climate change; underground water; nutrient cycles
	Argentina	Review of taxa; research in Argentinian architecture; studies on rural populations
	Botany	Description of new taxa; physiology and ecology of plant species
	Ecosystems	Studies on different types of ecosystems
	Genetic-evolution	Phylogeny and molecular genetics of different taxa
	Invertebrate	taxonomy, species descriptions and distributions, forensic entomology
	Protected areas	Ecological studies on protected areas; effects of roads on mammal species; species conservation
	Urban land use	Agriculture; rural and urban areas

related to the study of invertebrates and plants developed substantially, becoming motor themes. Research on mammals became more specialized and with greater scientific production, methodological and analytical challenges became emerging themes ("Applied Methods"), while conservation and management of natural resources and ecological interactions became transversal themes of general importance. The 2012-2022 subperiod reinforces the observed trend of the emergence of new research themes over time, adding two research areas to the motor themes: the study of different ecosystems and regions of Argentina. The themes related to land uses occupied an intermediate position between transversal and emerging areas. Similarly, the study of protected areas represents a highly developed theme in the institution underlying various research fields related to conservation and land use but in this subperiod it emerged as an independent theme. Finally, we found two additional themes representing developing, incipient research areas: genetics and evolution and urban ecology (Table 1).

Temporal stability of research themes

The number of keywords increased over time, as did the number of words shared between subsequent subperiods (from 6 between 1972-1981 and 1982-1991, to 431 between 2002-2011 and 2012-2022). The similarity index increased over time, from 0.15 in 1982-1991 and 1992-2001 to 0.28 in 2002-2011 and 2012-2022. This increased similarity over time indicates that more keywords are shared between different articles in recent periods. In addition, some keywords used in early publications disappeared in later subperiods, for example, 1131 keywords present in 2002-2011 were no longer used, while 1441 new keywords were incorporated (Figure 3).

Thematic evolution

The temporal evolution analysis showed an increase in the number of themes and a greater interconnection among them through 50 years of scientific research (Figure 4). The initial period (1972-1981) was characterized by descriptive studies of biological communities and species that provided baseline aspects of biodiversity and the functioning of South American drylands given the scarcity of data that characterized this stage. Later (1982-1991), studies moved away from characterization of plant communities, their response to disturbances (such as fire and urbanization) and their role in nutrient cycling. New records of desert plants and terrestrial invertebrates and studies on the ecology and distribution of these groups are also incorporated. The impact of land use and livestock management constituted an emerging theme ("Agroecosystems-Land use").

During 1992-2001, botanical studies continued their development while expending to include studies on plant communities in different regions of the country ("Argentina") and highland ecosystems (mountain) (in addition to the already studied lowland ecosystems; "Ecosystems"). Invertebrate studies continued their development, indicated by the solid line linking it to the previous period, while a new theme, the study of desert mammals ("Mammalia"), emerged connected to the study of land use.

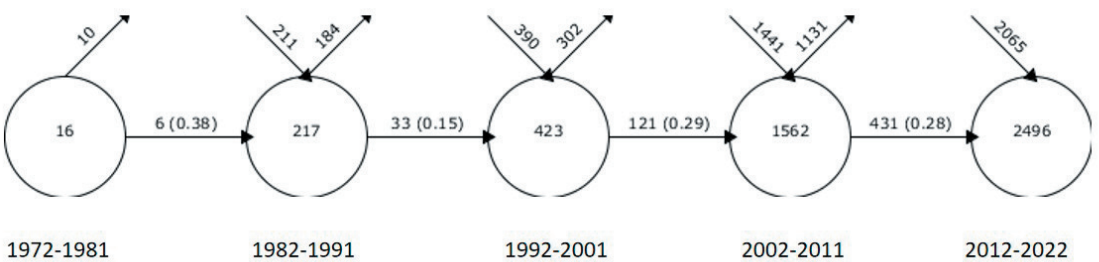

Figure 3. Diagram of stability between periods. The circles contain the author keywords in each subperiod. The horizontal arrows represent the shared keywords between subperiods and the similarity index, in parentheses. The number of new keywords in each subperiod is represented by the upper-incoming arrow, and keywords only used in one subperiod —but not in the following— are represented by the upper-outgoing arrow.

Figura 3. Diagrama de estabilidad entre períodos. Los círculos contienen las palabras clave del autor en cada subperíodo. Las flechas horizontales representan las palabras clave compartidas entre subperíodos y el índice de similitud, entre paréntesis. El número de palabras clave nuevas en cada subperíodo está representado por la flecha entrante superior, y las palabras clave que solo se usan en un subperíodo —pero no en el siguiente— están representadas por la flecha saliente superior.

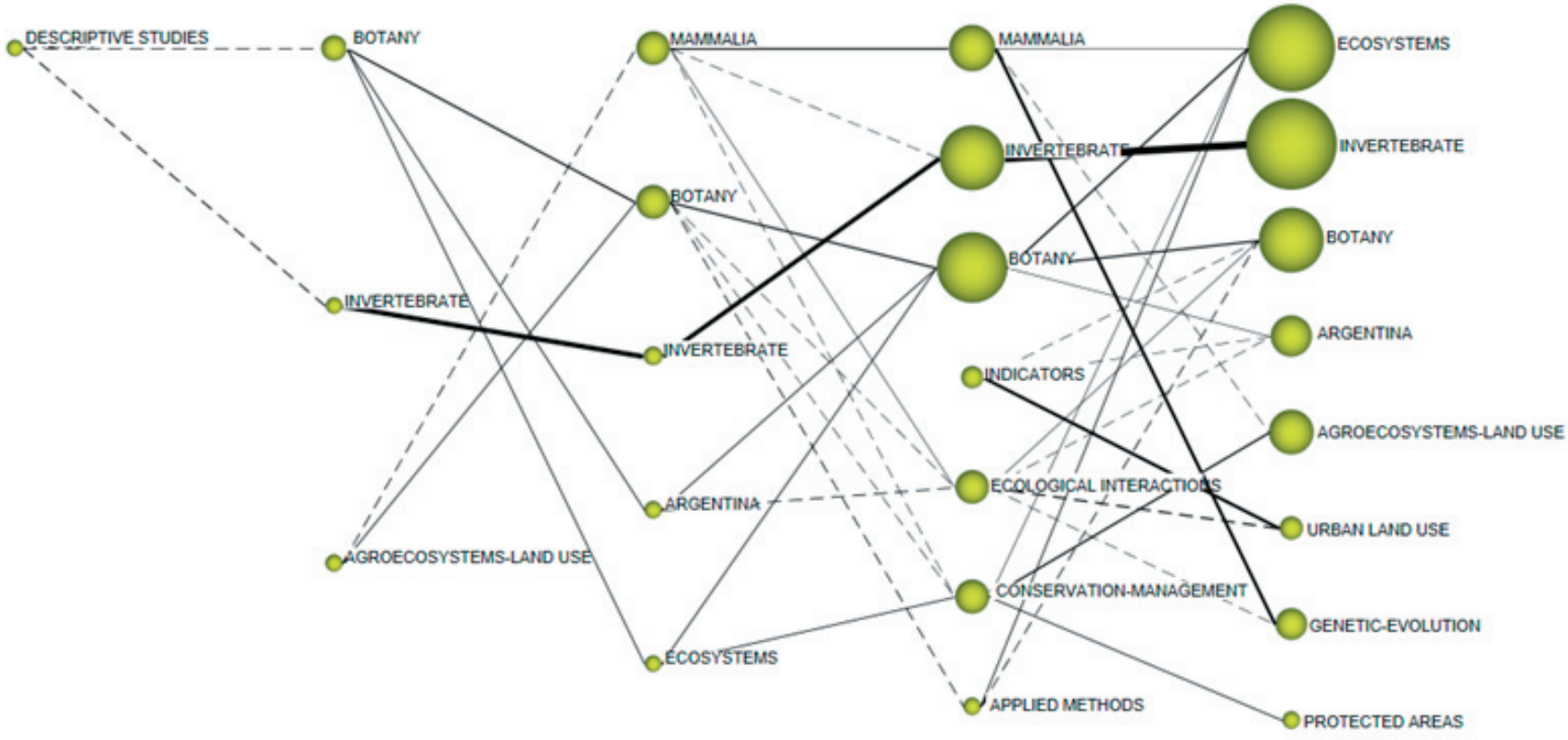

Figure 4. Evolution of research themes from 1972 to 2022. The spheres represent the number of published documents, the lines indicate the interconnection between the themes between periods. Solid lines connect themes with the same name, dotted lines connect themes that share some common elements (i.e., keywords) and give rise to new topics. The lines between themes represent the link between them based on common elements (e.g.. keywords) and whose thickness is proportional to the shared elements calculated by the inclusion index.

Figura 4. Evolución de los temas de investigación de 1972 a 2022. Las esferas representan el número de documentos publicados, las líneas indican la interconexión entre los temas entre períodos. Las líneas sólidas conectan temas con el mismo nombre, las líneas punteadas conectan temas que comparten algunos elementos comunes (i.e., palabras clave) y dan lugar a nuevos temas. Las líneas entre temas representan el nexo entre ellos a partir de elementos comunes (e.g., palabras clave) y cuyo grosor es proporcional a los elementos compartidos calculados por el índice de inclusión.

From 2002-2011 we observed an increase in the number of themes. Botanical studies have broadened to include studies on ecological interactions, conservation, and management and the application of novel methods and analyses. The study of mammals and invertebrates continued to develop, with a peak in scientific production. In this period, namely indicators of environmental degradation ("Indicators"). In the last subperiod (2012-2022), the study of invertebrates remained a topic of interest for research, with little connection with other topics. In turn, botany expanded to include studies on ecosystems of Argentina. Conservation and land management gave rise to the study of protected areas and land uses. New research interests also emerged at this stage, such as genetics and evolution, indicators of environmental degradation and the study of urban ecosystems.

Scientific production

Among the 1828 documents included in this synthesis, the most frequent type of document was scientific articles (1684 documents). The number of articles varied greatly through time (Figure 5). The first subperiod (1972-1981) included 89 articles published mostly in local, unindexed journals. The number of scientific articles published and the proportion of those articles published in indexed journals increased gradually from 1982 to 2022. We also recorded the same increasing trend for the number of people working at IADIZA. During the 50 years analyzed here, the main outlets for publication included the Journal of Arid Environments, Multequina, Revista de la Facultad de Ciencias Agrarias and Deserta. In contrast, if we weight publication frequency by the number of citations of articles published in different journals, the top journals become Journal of Arid Environments, Ecology Letters, Science, and Ecology (Supplementary Material 2-Figure S2).

Global impact of scientific production

The frequency of keywords appearing in IADIZA's publications (Figure 1) differed strongly from the frequency of keywords weighted by citations (chi-square test: X^2=57830; P<<<0.0001) (Figure 6). Therefore, the emphasis of the institute's research topics did not match the interest raised by the institute's publications in the international scientific community citing those publications.

When we analyzed the global impact of IADIZA's publications, we found 29355 citations and 1806 collaborations associated with 159 and 84 countries, respectively

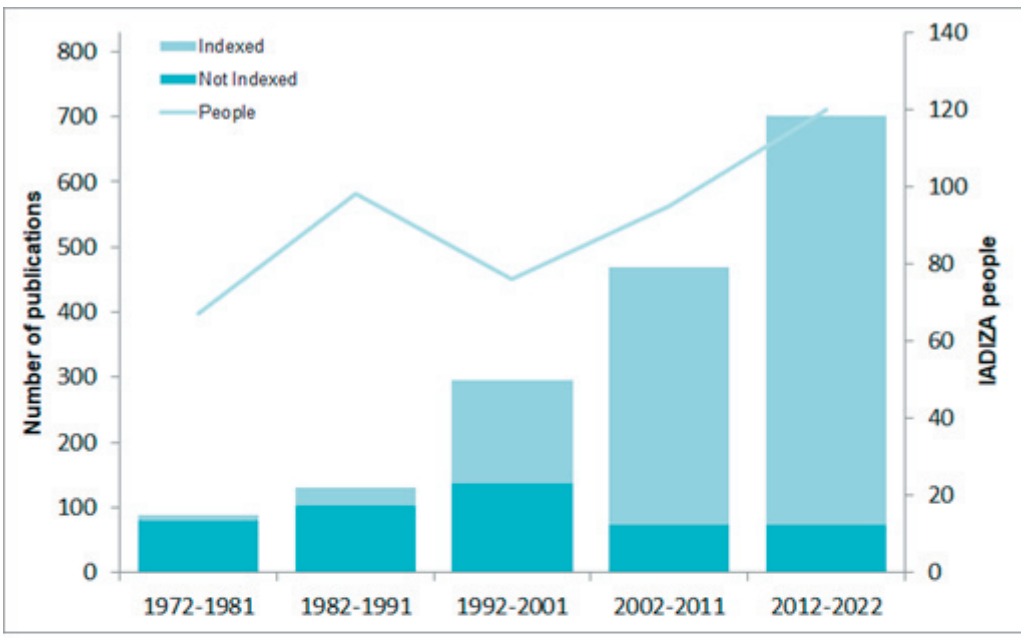

Figure 5. Number of scientific articles published and number of staff (researchers, technicians and graduate students and post-docs) in each sub period of the IADIZA in fifty years.

Figura 5. Número de artículos científicos publicados y número de personal (investigadores, técnicos y becarios) en cada subperíodo del IADIZA en cincuenta años.

Figure 6. Keyword frequency in IADIZA's publications weighted by citations of IADIZA's publications.

Figura 6. Frecuencia de palabras clave en las publicaciones del IADIZA ponderada por las citas de las publicaciones de IADIZA.

Table 2. Countries associated with the global impact of IADIZA publications. Citations: number of publications by country that cited IADIZA publications. Collaborations: number of publications that co-authored IADIZA publications. Relative values are given in percentage (%).

Tabla 2. Países asociados con el impacto global de las publicaciones del IADIZA. Citas: número de publicaciones por país que citan artículos del IADIZA. Colaboraciones: número de publicaciones en coautoría con autores del IADIZA. Los valores relativos están expresados en porcentaje (%).

Countries	Citations		Countries	Collaborations	
	Number	%		Number	%
United States	4639	15.8	Argentina	1011	56.0
Argentina	2971	10.1	United States	151	8.4
United Kingdom	1727	5.9	Chile	72	4.0
Brazil	1647	5.6	Spain	63	3.5
China	1588	5.4	Germany	56	3.1
Germany	1462	5.0	Brazil	41	2.3
Australia	1250	4.3	Canada	38	2.1
Spain	1140	3.9	United Kingdom	26	1.4
Canada	1049	3.6	Mexico	24	1.3
France	946	3.2	Australia	22	1.2
Mexico	730	2.5	Peru	20	1.1
Italy	667	2.3	Switzerland	20	1.1
Chile	607	2.1	France	19	1.1
Switzerland	560	1.9	Belgium	15	0.8
South Africa	459	1.6	Colombia	15	0.8
Netherlands	436	1.5	Italy	15	0.8
Czech Republic	391	1.3	New Zealand	12	0.7
New Zealand	377	1.3	China	9	0.5
Sweden	367	1.2	South Africa	9	0.5
India	319	1.1	Sweden	9	0.5
Denmark	297	1.0	Netherlands	8	0.4
Poland	283	1.0	Uruguay	8	0.4
Japan	273	0.9	Israel	7	0.4
Belgium	259	0.9	Ecuador	6	0.3
Portugal	254	0.9	Russian Federation	6	0.3
Colombia	239	0.8	Czech Republic	5	0.3
Russian Federation	214	0.7	Denmark	5	0.3
Austria	210	0.7	Portugal	5	0.3
Israel	188	0.6	Austria	4	0.2
Others	3854	13.1	Others	105	5.8
Total	29403	100	Total	1806	100

(Supplementary Material 3-Table S3). We found 30 countries that cited the publications at least 100 times and collaborated with IADIZA at least 4 times (e.g., Austria) (Table 2). For both citations and collaborations, we observed that larger buffers or influence areas were mainly associated with particular regions (e.g., North America, Europe and parts of Oceania). In addition, the collaboration map included countries with coauthors not observed in the citations map, such as other countries in South America (e.g., Ecuador, Colombia) (Supplementary Material 4-Figure S4).

Discussion

Here, we applied science mapping tools to quantify the evolution of themes and their impact arising from IADIZA, a pioneering institution in dryland research. We detected that IADIZA's scientific production and impact increased throughout the 50 years since the creation of the institute, currently covering several disciplinary fields. Knowledge about the structure and functioning of arid lands has motivated much interest to address many research questions at least since the 1950s (Hutchinson and Herrmann 2007). In this context, mapping the evolution of scientific knowledge in the face of the growing production of literature has become one of the main current challenges (Azoulay et al. 2018; Enserink 2018). We note that bibliometric analysis in dry ecosystems has been synthesized to a greater extent on specific topics (Xie et al. 2020; Hu et al. 2021) or particular regions (Armas et al. 2016; Shi et al. 2021). However, beyond the expected pattern of evolution of a scientific institution, the development of knowledge in drylands has been influenced by multiple local and global factors.

We found that the temporal evolution of IADIZA's research through subperiods is characterized by the emergence of research themes, either new or originating from the fusion or transformation of themes from previous periods of time. Only two themes, Invertebrates and Botany, have been maintained consistently in almost all subperiods, playing a role as motor themes in most of the subperiods. We suggest that globally important paradigms and conceptual frameworks constituted a key driver in the emergence and reconversion of thematic lines observed in our results. Therefore, knowledge on biodiversity, which constituted the main institutional goal during the founding period of IADIZA, responded to the need to obtain primary data on local dryland environments and their biodiversity, but gradually merged in subsequent periods with other topics of broader international relevance. For example, in 2007 dryland degradation and the search for early warning indicators of degradation became one of the key global issues for the 21st century identified by the United Nations (Sivakumar and Stefanski 2007). Our findings about the thematic structure of the subperiod 2002-2011 match this global concern, suggesting that it triggered in our institution the emergence of several themes, including ecological interactions, conservation, and management and applied methods linked to remote sensors and indicators of environmental degradation.

The importance of promoting interaction among researchers, disciplines and international institutions is a healthy process for the growth of an institution (Chen and Chen 2016; Hackett et al. 2021). This process of internationalization of science that we observe in our temporal analysis is consistent with the challenges faced by research institutions in developing countries throughout the world. Since the 1980s, Latin American institutions have implemented policies to stimulate visibility and impact of their research output in Latin America, an adaptation to often unrealistic international standards (Vesuri et al. 2014). The results of the institute's performance analysis agree with this view, showing that the visibility and impact of research has increased since 1982, exhibiting a growing trend of publication in indexed journals and an increased citation rate. We also assessed the impact and the growing production of IADIZA research articles, determined by the increase in the number of researchers affiliated with the institution and the increased dominance of teamwork overtime. In fact, teamwork has increased over time in all research fields, with articles produced by teams cited more frequently than those produced by solo authors (Wuchty et al. 2007). This fact, together with greater access to information and the speed of communication, made it possible to increase collaborations with authors and research groups from the region and globally, as reflected in our data.

We also found that international collaborations in IADIZA's publications are dispersed across approximately 84 countries and are not evenly distributed among them. Conversely, a substantial number of

collaborations are clustered within specific countries or regions, primarily in North America and Europe, represented with smaller numbers in South America, Africa, Oceania and Asia. The global pattern of international collaborations in scientific organizations can be interpreted considering different factors such as geographical proximity, cultural backgrounds and economic considerations. For instance, Chen and Chen (2016) suggest that scientists from geographically proximate countries tend to share similar cultural backgrounds, interests and strengths, facilitating more frequent interactions. This could facilitate the exchange of ideas and methodologies, fostering a culture of innovation and intellectual growth within the center (Katz and Martin 1997). This could explain collaborations between IADIZA and countries in Latin America. Furthermore, the economic status and the level of development of the research and innovation system of the collaborating countries may also influence their shared research (Chen and Chen 2016; Vieira 2023). Collaborations enable researchers to combine their expertise, resources and data, which can lead to more extensive and impactful research projects (Wuchty et al. 2007). In fact, scientists and academic institutions have historically established collaborative ties with the United States and Europe, which facilitate access to the economic resources and equipment required for high-quality scientific research, among other benefits (Vieira 2023). Moreover, co-authoring papers with researchers from other institutions can also lead to more citations (Vieira 2023). Highly cited papers are seen as influential and this can reflect positively on the scientific impact of the center (Wutchy et al. 2007). This partly accounts for the numerous collaborations between IADIZA and various institutions in Europe and North America.

The growth of the number of publications observed in our analysis matches the trends observed by other bibliometric studies. At least 1346000 articles are published per year worldwide in all scientific disciplines (Björk et al. 2008), most of which stop being cited quickly after publication (Evans 2008). Our results on the temporal stability of research themes indicate that many keywords have been abandoned in recent periods, suggesting obsolescence of themes and, therefore, of the articles that include them. Furthermore, as we have shown, the frequency of different keywords in the institute's publications does not match the frequency of citation of publications with those keywords (cf. Figure 1 and Figure 6). Therefore, it is clear that the snapshot of the relative frequency of the research topics does not match their influence on the broader research community and suggests that the institute may need to reassess its research priorities. In our study we have measured the impact and visibility of research with citation metrics, which represent only one among many ways of quantifying the societal impact of research. Because quantifying such impact with other approaches may be difficult due to the lack of data, citation measures remain useful as tools to define future research institutional goals and resource allocation.

Our study offers an overview of the evolution of the research process, from an institutional focus, in the study of dryland ecosystems over 50 years. An analysis of the last decade (2012-2022) allows predicting future dryland research challenges aligned with global demands such as land degradation and biodiversity conservation, driven by the application of new technologies and tools. The current research themes constitute a thematic network based on international and interdisciplinary cooperation that seeks to understand the interaction of human societies with dryland ecosystems.

Acknowledgements. We thank O. Estévez for providing the institute's annual reports and J. M. López for collaborating in the development of the database of publications. Special thanks to M. J. Cobo for assistance with the SciMAT software and to the anonymous reviewers for their valuable contributions.

References

Armas, C., J. R. Gutiérrez, D. A. Kelt and P. L. Meserve. 2016. Twenty-five years of research in the north-central Chilean semiarid zone: the Fray Jorge Long-Term Socio-Ecological Research (LTSER) site and Norte Chico. Journal of Arid Environments 126:1-6. https://doi.org/10.1016/j.jaridenv.2015.12.008.

Azoulay, P., J. Graff-Zivin, B. Uzzi, D. Wang, H. Williams, J. A. Evans, et al. 2018. Toward a more scientific science. Science 361(6408):1194-1197. https://doi.org/10.1126/science.aav2484.

Behnke, R. H., and M. Mortimore (eds.). 2016. The End of Desertification? Disputing Environmental Change in the Drylands. Springer Earth System Sciences. Springer-Verlag Berlin Heidelberg. Pp. 560. https://doi.org/10.1007/978-3-642-16014-1.

Björk, B. C., A. Roos, and M. Lauri. 2008. Global annual volume of peer reviewed scholarly articles and the share available via different Open Access options. Proceedings of ELPUB.

Callon, M., J. Courtial, and F. Laville. 1991. Co-word analysis as a tool for describing the network of interactions between basic and technological research - The case of polymer chemistry. Scientometrics 22(1):155-205. https://doi.org/10.1007/BF02019280.

Castro, A. J., C. Quintas-Soriano, and B. N. Egoh. 2018. Ecosystem services in dryland systems of the world. Journal of Arid Environments 159:1-3. https://doi.org/10.1016/j.jaridenv.2018.09.006.

Chen, C. 2017. Science mapping: a systematic review of the literature. Journal of data and information science 2(2): 1-40. https://doi.org/10.1515/jdis-2017-0006.

Chen, R. H. G., and C. M. Chen. 2016. Visualizing the world's scientific publications. Journal of the Association for Information Science and Technology 67(10):2477-2488. https://doi.org/10.1002/asi.23591.

Chen, W., Y. Geng, S. Zhong, M. Zhuang, and H. Pan. 2020. A bibliometric analysis of ecosystem services evaluation from 1997 to 2016. Environmental Science and Pollution Research 27(19):23503-23513. https://doi.org/10.1007/s11356-020-08760-x.

Coban, O., G. B. De Deyn, and M. van der Ploeg. 2022. Soil microbiota as game-changers in restoration of degraded lands. Science 375(6584):abe0725. https://doi.org/10.1126/science.abe0725.

Cobo, M. J., A. G. López-Herrera, E. Herrera-Viedma, and F. Herrera. 2011. Science mapping software tools: Review, analysis, and cooperative study among tools. Journal of the American Society for Information Science and Technology 62(7):1382-1402. https://doi.org/10.1002/asi.21525.

Cobo, M. J., A. G. López-Herrera, E. Herrera-Viedma, and F. Herrera. 2012. SciMAT: A new science mapping analysis software tool. Journal of the American Society for Information Science and Technology 63(8):1609-1630. https://doi.org/10.1002/asi.22688.

Davis, D. K. 2016. Deserts and Drylands Before the Age of Desertification. Pp. 203-223 *in* R. Behnke and M. Mortimore (eds.). The End of Desertification? Springer Earth System Sciences. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-16014-1_8.

Enserink, M. 2018. Research on research. Science 1178-1179. https://doi.org/10.1126/science.361.6408.117.

Evans, J. A. 2008. Electronic publication and the narrowing of science and scholarship. Science 321(5887):395-399. http://doi.org/10.1126/science.1150473.

Fortunato, S., C. T. Bergstrom, K. Börner, J. A. Evans, D. Helbing, S. Milojević, et al. 2018. Science of science. Science 359(6379):eaao0185. https://doi.org/10.1126/science.aao018.

Gonçalves, P. H. S., T. Gonçalves-Souza, and U. P. Albuquerque. 2020. Chronic anthropogenic disturbances in ecology: a bibliometric approach. Scientometrics 123(2):1103-1117. https://doi.org/10.1007/s11192-020-03403-x.

Guan, Y., R. Kang, and J. Liu. 2019. Evolution of the field of ecological restoration over the last three decades: a bibliometric analysis. Restoration Ecology 27(3):647-660. https://doi.org/10.1111/rec.12899.

Hackett, E. J., E. Leahey, J. N. Parker, I. Rafols, S. E. Hampton, U. Corte, et al. 2021. Do synthesis centers synthesize? A semantic analysis of topical diversity in research. Research Policy 50(1):104069. https://doi.org/10.1016/j.respol.2020.104069.

Hanan, N. P., E. Milne, E. Aynekulu, Q. Yu, and J. Anchang. A Role for Drylands in a Carbon

Neutral World? 2021. Front Environ Sci 9: 786087. https://doi: 10.3389/fenvs.2021.786087.

Hu, H., J. Dai, Y. Jin, and X. Liu. 2021. Bibliometric analysis on desertification restoration based on CiteSpace. Arabian Journal of Geosciences 14:1-10. https://doi.org/10.1007/s12517-020-06309-3.

Hulme, P. E. 2022. Importance of greater interdisciplinarity and geographic scope when tackling the driving forces behind biological invasions. Conservation Biology 36(2):e13817. https://doi.org/10.1111/cobi.13817.

Hutchinson, C. F., and S. M. Herrmann. 2007. The future of arid lands-revisited: a review of 50 years of drylands research (Vol. 32). Springer Science and Business Media.

Jinha, A. E. 2010. Article 50 million: An estimate of the number of scholarly articles in existence. Learned Publishing 23(3):258-263. https://doi.org/10.1087/20100308.

Katz, J. S., and B. R. Martin. 1997. What is research collaboration? Research Policy 26(1):1-18. https://doi.org/10.1016/S0048-7333(96)00917-1.

Kennedy, C. M., J. R. Oakleaf, D. M. Theobald, S. Baruch-Mordo, and J. Kiesecker. 2019. Managing the middle: a shift in conservation priorities based on the global human modification gradient. Global Change Biology 25(3):811-826. https://doi.org/10.1111/gcb.14549.

Lang, D., and G. Chien. 2018. wordcloud2: Create Word Cloud by 'htmlwidget'. R package version 0.2.1. URL: CRAN.R-project.org/package=wordcloud2.

Liu, X., L. Zhang, and S. Hong. 2011. Global biodiversity research during 1900-2009: a bibliometric analysis. Biodiversity and Conservation 20(4):807-826. https://doi.org/10.1007/s10531-010-9981-z.

QGIS Development Team 2022. QGIS Geographic Information System. Open Source Geospatial Foundation Project. URL: qgis.osgeo.org.

Maestre, F. T., B. M. Benito, M. Berdugo, L. Concostrina-Zubiri, M. Delgado-Baquerizo, D. J. Eldridge, et al. 2021. Biogeography of global drylands. New Phytologist 231(2):540-558.https://doi.org/10.1111/nph.17395.

Miguel, M. F., H. S. Butterfield, and C. J. Lortie. 2020. A meta-analysis contrasting active versus passive restoration practices in dryland agricultural ecosystems. PeerJ 8:e10428. https://doi.org/10.7717/peerj.10428.

Meyer, D., A. Zeileis, and K. Hornik. 2020. vcd: Visualizing Categorical Data. R package version 1.4-8.

Noyons, E., H. Moed, and A. Van Raan.1999. Integrating research performance analysis and science mapping. Scientometrics 46(3):591-604. https://doi.org/10.1007/bf02459614.

R Core Team. 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: R-project.org.

Ramankutty, N., A. T. Evan, C. Monfreda, and J. A. Foley. 2008. Farming the planet: 1. geographic distribution of global agricultural lands in the year 2000. Global Biogeochemical Cycles 22:1-19. https://doi.org/10.1029/2007GB002952.

Reynolds, J. F. 2021. Desertification is a prisoner of history: An essay on why young scientists should care. Ecosistemas 30(3):2302. https://doi.org/10.7818/ECOS.2302.

Roig, V. 1991. Desertification and distribution of mammals in the Southern Cone of South America. Parte III Conservation policy and management. Pp. 239-279 *in* M. A. Mares and D. J. Schmidly (eds.). Latin American Mammalogy. History, biodiversity and conservation. University of Oklahoma Press.

Samoylenko, I., T. C. Chao, W. C. Liu, and C. M. Chen. 2006. Visualizing the scientific world and its evolution. Journal of the American Society for Information Science and Technology 57(11):1461-1469. https://doi.org/10.1002/asi.20450.

Schimel, D. S. 2010. Drylands in the earth system. Science 327(5964):418-419. https://doi.org/10.1126/science.1184946.

Shi, Y. F., F. F. Huang, S. H. Shi, Y. S. Jiang, and X. M. Huang. 2021. Research trends and focus on the deserts of Northern China: A bibliometric analysis during 1986-2020. Frontiers in Earth Science 9:1064. https://doi.org/10.3389/feart.2021.777626.

Shiffrin, R. M., and K. Börner. 2004. Mapping knowledge domains. Proceedings of the National Academy of Sciences 101(suppl_1):5183-5185. https://doi.org/10.1073/pnas.0307852100.

Silcock, J. L., and R. J. Fensham. 2019. Degraded or just dusty? Examining ecological change in arid lands. Bioscience 69(7):508-522. https://doi.org/10.1093/biosci/biz054.

Sivakumar, M. V., and R. Stefanski. 2007. Climate and land degradation—an overview. Pp. 105-135 *in* M. V. Sivakumar and R. Stefanski (eds.). Climate and land degradation. Springer Berlin Heidelberg.

Stork, H., and J. J. Astrin. 2014. Trends in biodiversity research—a bibliometric assessment. Open Journal of Ecology 4(07):354. https://doi.org/10.4236/oje.2014.47033.

Veth, P. 2005. Between the desert and the sea: Archaeologies of the Western Desert and Pilbara regions, Australia. Pp. 132-141 *in* M. A. Smith and P. Hesse (eds.). 23 Degrees South: The Archaeology and Environmental History of Southern Hemisphere Deserts. National Museum of Australia Press.

Vieira, E. S. 2023. The influence of research collaboration on citation impact: the countries in the European Innovation Scoreboard. Scientometrics 128:3555-3579. https://doi.org/10.1007/s11192-023-04715-4.

Wickham, H. 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.

Whitford, W. G. 2002. Ecology of desert systems. Page xvi. Pp. 343. Framework. Academic Press. URL: books.google.com/books.

Wuchty, S., B. F. Jones, and B. Uzzi. 2007. The increasing dominance of teams in production of knowledge. Science 316(5827):1036-1039. https://doi.org/10.1126/science.1136099.

Xie, H., Y. Zhang, Z. Wu, and T. Lv. 2020. A bibliometric analysis on land degradation: Current status, development, and future directions. Land 9(1):28. https://doi.org/10.3390/land9010028.

Zhang, Y., and Y. Chen. 2020. Research trends and areas of focus on the Chinese Loess Plateau: A bibliometric analysis during 1991-2018. Catena 194:104798. https://doi.org/10.1016/j.catena.2020.104798.

Zhang, X., R. C. Estoque, H. Xie, Y. Murayama, and M. Ranagalage. 2019. Bibliometric analysis of highly cited articles on ecosystem services. PloS One 14(2):e0210707. https://doi.org/10.1371/journal.pone.0210707.