The Journal of Agricultural Science

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Emerging topics in scientific research on global water-use efficiency

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Crops and Soils Research Paper

Cite this article: Aleixandre-Tudó J L, Castelló-Cogollos L, Aleixandre J L, Aleixandre-Benavent R (2019). Emerging topics in scientific research on global water-use efficiency. *The Journal of Agricultural Science* **157**, 480–492. https://doi.org/10.1017/S0021859619000789

Received: 28 January 2019
Revised: 31 July 2019
Accepted: 26 September 2019
First published online: 16 October 2019

Key words:
Bibliometrics; scientific journals; scientific research; water-use efficiency

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Abstract

A bibliometric analysis of research articles published on water-use efficiency was performed using the Web of Science database and evaluated. Journal titles, publication years, subject categories, keywords and countries publishing were obtained. A number of 2077 papers were retrieved, two-thirds of them published in the last decade. The articles were published in 439 journals, with *Agricultural Water Management*, *Agronomy Journal, Crop Science, Field Crops Research* and *Indian Journal of Agricultural Sciences* the most productive. Most of the leading productive journals have Impact Factors in the top quartiles of the Journal Citation Reports. Agronomy, Plant Sciences, Water Resources and Agriculture Multidisciplinary were the most common journal subject categories, indicating a wide diversity of research fields ascribed to this topic. The predominant key words and phrases used were growth, 'carbon isotope discrimination', yield, photosynthesis, 'gas exchange', evapotranspiration and 'stomatal conductance'. The productivity ranking for countries was headed by China (456 papers), followed by the USA (410), Australia (176) and India (165). A content analysis of the papers made identification of the key issues of greatest scientific concern possible, as well as their evolution over time. The most cited papers relate to physiological aspects, but also important studies on experimental biology, drought resistance, effects of climate, crop production and ecology, among others.

Introduction

Approximately three-quarters of the earth's surface is covered by water, mainly in the form of oceans (Rahmstorf, 2002). The vital nature of water is due to the imperative need for drinking and food for animals and humans. Water environments also provide habitats, not only to humans but also to a broad number of other species. In addition, water is involved in the most important ecological phenomena, from the carbon and nutrient cycles to hydrological processes (Moss, 2012; Zhang *et al*., 2017*a*). Water is thus used for a variety of purposes such as human and animal viability, industrial production of goods or crop production (Vidyasagar, 2007).

The main uses of water resources are crop irrigation or hydroelectricity production. However, very often the water is obtained after substantial alteration of the landscape and natural courses of rivers (Rosenberg *et al*., 2000). Currently, there is intense concern over water resource degradation and the unequal distribution of water resources has become a topic of interest for the research community (Alperovits and Shamir, 1977; Morgan and Goulter, 1985; Cunha and Sousa, 1999). Intense progress on water resources has been observed over the past years including a variety of topics such as water resources monitoring (Resh *et al*., 1995; Sawaya *et al*., 2003), water treatment technology (Gahr *et al*., 1994; Dossantos and Livingston, 1995; Oturan, 2000; Bhojwani *et al*., 2019) and management of water resources (Andreu *et al*., 1996; Le Maitre *et al*., 1996; Middelkoop *et al*., 2001; Al-Jawad *et al*., 2019).

Water availability is strongly linked to water security. Social and economic sustainable development depends on the security of the water sources. A large proportion of the world's population is exposed to severe water security threats (Vörösmarty *et al*., 2010; Allan *et al*., 2013; Huai and Chai, 2016). Population growth and climate change are identified as the main reasons responsible for increased water security challenges. This is due to increasing demand for the production of agricultural products, industrial goods and household demand (Launiainen *et al*., 2014). Water security is also a high-priority topic in both policy and research activities (Staddon and James, 2014).

In addition to irrigation and electricity production, fresh water is used for other purposes such as drinking, fish farming, transportation and even for recreational activities (Stendera

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et al., 2012; Carvalho *et al.*, 2013; Dörnhöfer and Oppelt, 2016). This usage endangers water ecology and the water environment through the production of contaminants, eutrophication, acidification or higher water temperatures, derived from climate change effects (Brönmark and Hansson, 2002; Dudgeon *et al.*, 2006; Adrian *et al.*, 2009; Zhang *et al.*, 2017*b*). In the past years, a considerable amount of research has been dedicated to research fields directly linked with fresh water availability. This includes pharmaceutical applications (Heberer, 2002), the treatment of heavy metals and arsenic (Berg *et al.*, 2001; Bolisetty *et al.*, 2019) or the removal of organic contaminants (Kolpin *et al.*, 2002).

The above highlights the presence of intense research interest on water resources, water safety and water management, and the importance of these research fields in human sustainability. Bibliometric studies interpret the main features of articles published in a given topic or field of study through statistical analysis of quantitative data (Fu *et al.*, 2013). The main aim of the current study is thus to provide a detailed evaluation of the publication outputs on water-use efficiency and to identify current research hotspots and future research directions (Zhi *et al.*, 2015), leading to a better understanding of this relevant research topic. Types of document, subject categories, most prolific journals and most cited articles will be evaluated at country, institution and author level.

Methods

Search strategy

A bibliometric analysis of the scientific articles included in Science Citation Index-Expanded (SCI-E) database from the Web of Science platform (Clarivate Analytics) on water-use efficiency was evaluated. The search was performed from inception (1964) to 28 February 2018. Web of Science is one of the preferred options for bibliometric studies and is seen as the world's leading database for evaluation of scientific research. 'Water-use efficiency' (quote marks were used to recover the exact phrase and to avoid inconsistencies) were the terms used in the search strategy. The bibliometric analysis was restricted to research articles, i.e. book chapters and reviews; therefore, proceeding papers, meeting abstracts, notes, news, editorials, corrections and retracted publications were excluded.

Data extraction

For each record obtained, the article title, journal name, publication year, subject category, keywords and country were retrieved by one researcher (LC-C) in February 2018. To minimize possible data inaccuracies, the data was verified by a second researcher (RA-B). The number of times a publication was cited by other subsequent publications (times cited) was also retrieved. In addition to 'author keywords', 'keywords plus' were used to evaluate the scientific content of the articles. 'Keywords plus' are populated by the Web of Science using information contained in the titles of references included in each article. Incorporation of keywords plus and author keywords provides an improved representation of the scientific content covered in the published articles (Fu *et al.*, 2013). To guarantee consistency in the count of keyword frequency, one researcher (JL-A) corrected the list of keywords, unifying synonyms (e.g. 'atmospheric carbon-dioxide' and 'atmospheric CO_2') and grammatical variants (e.g. 'climate change' and 'climatic change'), and using only one keyword for the same concept. In addition, typographical and indexing errors were removed (researcher JL-A), with the data finally verified by a second researcher (LC-C). Discrepancies observed during the process were resolved though discussion involving all researchers. The registries downloaded were recorded into a Microsoft Access® database (Microsoft, Seattle, WA, USA). The 5-year Impact Factors and quartile were extracted from the 2016 edition of Journal Citation Reports (JCR) from Clarivate Analytics.

Data analysis

The current paper analysed the annual evolution of published papers and citations, journals, subject categories, countries and keywords. In the case of journals, the information obtained included number of articles, number of citations, ratio citations per paper and 5-year Impact Factor. The Impact Factor and the 5-year impact factor were provided by JCR, Web of Science platform (Clarivate Analytics). The Impact Factor of a journal is calculated by dividing the number of the current year's citations by the papers published in the journal during the previous 2 years. The 5-year Impact Factor is calculated as follows: sum of citations in the edition year to papers published in each of the previous 5 years, divided by the number of papers published in the previous 5 years. The 5-year Impact Factor was chosen because it better shows the long-term citation trend for the journals. The quartile indicates each of four equal groups into which journals of a subject category are divided according to the distribution of Impact Factor values. The journals included in the first quartile are considered to be of higher quality and prestige. Scientific output of the most productive countries has been relativized, taking into account the number of universities and the number of researchers (per million inhabitants) in each country.

A world map representing the status of the most prolific scientific collaboration between countries was used, considering a collaboration threshold of 50 papers. A 'co-words network' of keywords representing the co-occurrence of very frequent keywords was also performed and evaluated. The network of co-words provides a map constructed using the most frequent keywords and the relationships between the terms and, consequently, between the papers (Batagelj and Mrvar, 2002). The free software package Pajek was used to construct network graphs (Mrvar and Batagelj, 2019). The most cited papers (>1000 citations) are also presented.

Results

Publication trend

A total of 2077 papers were obtained and included in the current study. Increasing numbers of papers have been published during the period under evaluation (Fig. 1), with approximately two-thirds of all articles being published in the last decade. The oldest article was published in 1964 by Slatyer and Bierhuizen in *Australian Journal of Biological Sciences*, entitled 'Influence of several transpiration suppressants on transpiration photosynthesis and water-use efficiency of cotton leaves'. Moreover, the number of citations has also increased, especially since the 1990s. The percentage of works financed has increased progressively over the last decade, from 67.5% in 2009 to 83.6% in 2017. Web of Science only began to record financing data in 2008 and the data for that year are incomplete, so it was not taken into account in this calculation (Fig. 2).

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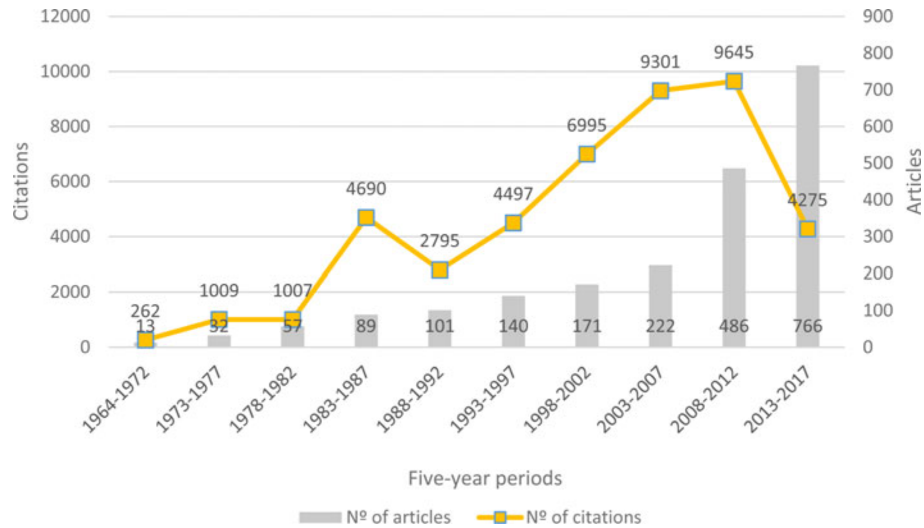

Fig. 1. Evolution of published papers and citations. Colour online.

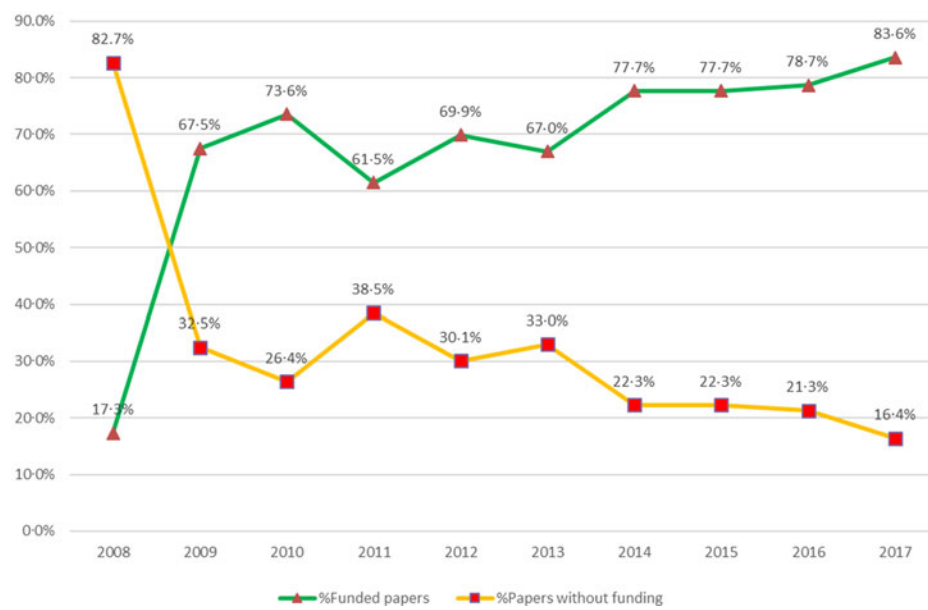

Fig. 2. Evolution of the percentage of funded and unfunded papers during the 2008–2017 period. Colour online.

Journals, key words and subject categories

The papers obtained were published in 439 different journals. *Agricultural Water Management* ($n = 75$) was the most prolific journal, followed by four journals with 55 papers, respectively: *Agronomy Journal*, *Crop Science*, *Field Crops Research* and *Indian Journal of Agricultural Sciences* (Table 1). Taking into account the number of papers published per year, since journals were indexed in SCIE, this ranking was also led by *Agricultural Water Management* (4.22), followed by *PLoS ONE* (1.91), *Field Crops Research* (1.41) and *Indian Journal of Agricultural Sciences* (1.38). *Agricultural Water Management* is also the most cited journal ($n = 4605$), followed by *Crop Science* ($n = 2352$) and *Agronomy Journal* ($n = 1943$). The number citations per paper (C/P) is highest for *Australian Journal of Agricultural Research* (C/P = 86), followed by *Global Change Biology* (C/P = 54.18) and *Oecologia* (C/P = 53.26). If the 5-year impact factor (IF) is analysed, *Global Change Biology* (IF = 9.455) stands out, followed by *Plant Cell and Environment* (IF = 6.555) and *Agricultural and Forest Meteorology* (IF = 4.753). Most papers were classified in one or two of Web of Science's journal subject categories. A diverse range of journal subject categories was observed, with the inclusion of articles in Agronomy, Plant Sciences, Water Resources and Agriculture Multidisciplinary subject categories. Most of the journals in Table 1 are classified in the first quartile of JCR (11 of 19), five in the second quartile and one in the fourth quartile. *Indian Journal of Agronomy* ceased to be covered by JCR in 2004 and *Australian Journal of Agricultural Research* in 2010.

The evolution of keywords and phrases assigned to articles in 5-year periods was examined (Fig. 3). In the first three 5-year periods, the predominant words/phrases were photosynthesis and 'carbon isotope discrimination'. In the 2003–2007 period, the most frequent terms were growth, 'carbon isotope discrimination' and yield. In the last two periods, the same three terms predominated but the order had changed to growth, yield and 'carbon isotope discrimination'. In the last decade, evapotranspiration, photosynthesis, 'carbon dioxide', 'stomatal conductance' and 'gas exchange' were identified as the most frequent keywords.

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Table 1. Most productive journals, citations, Impact Factor, subject categories and quartile

Journal	Country	Papers	First year indexed in SCIE	Years from indexation in SCIE to 2017	No. papers per year indexed in SCIE	Citations	Citations/ paper	5-year impact factor	Subject categories	Quartile
Agricultural Water Management	The Netherlands	173	1976	41	4.22	4605	26.62	3.366	Water Resources	Q1
									Agronomy	Q1
Agronomy Journal	USA	55	1949	68	0.81	1943	35.33	1.838	Agronomy	Q2
Crop Science	USA	55	1966	51	1.08	2352	42.76	1.787	Agronomy	Q2
Field Crops Research	The Netherlands	55	1978	39	1.41	1446	26.29	3.839	Agronomy	Q1
Indian Journal of Agricultural Sciences	India	55	1977	40	1.38	150	2.73	0.254	Agriculture, Multidisciplinary	Q4
Indian Journal of Agronomy[a]		53	1977	40	1.33	71	1.34		Agronomy	
Photosynthetica	Czech Republic	42	1969	48	0.88	477	11.36	1.81	Plant Sciences	Q2
Agricultural and Forest Meteorology	The Netherlands	33	1984	33	1	915	27.73	4.753	Meteorology and Atmospheric Sciences	Q1
									Forestry	Q1
									Agronomy	Q1
Scientia Horticulturae	The Netherlands	33	1976	41	0.8	624	18.91	1.883	Horticulture	Q1
Oecologia	Germany	31	1969	48	0.65	1651	53.26	3.407	Ecology	Q2
Plant Cell and Environment	England	31	1980	37	0.84	1186	38.26	6.555	Plant Sciences	Q1
Irrigation Science	USA	30	1978	39	0.77	838	27.93	2.492	Water Resources	Q2
Plant and Soil	The Netherlands	30	1948	69	0.43	826	27.53	3.736	Agronomy	Q1
									Plant Sciences	Q1
									Soil Science	Q1
Tree Physiology	Canada	24	1986	31	0.77	1035	43.13	4.148	Forestry	Q1
Australian Journal of Agricultural Research[a]		23	1950	67	0.34	1978	86		Agriculture	
									Multidisciplinary	
									Agronomy	
Environmental and Experimental Botany	England	22	1976	41	0.54	811	36.86	4.218	Environmental Sciences	Q1
									Plant Sciences	Q1
Global Change Biology	England	22	1995	22	1	1192	54.18	9.455	Ecology	Q1
									Environmental Sciences	Q1
									Biodiversity Conservation	Q1
Forest Ecology and Management	The Netherlands	21	1976	41	0.51	439	20.9	3.387	Forestry	Q1
PLoS ONE	USA	21	2006	11	1.91	163	7.76	3.394	Multidisciplinary Sciences	Q1

[a]*Indian Journal of Agronomy* ceased to be covered by the JCR in 2004 and *Australian Journal of Agricultural Research* in 2010.

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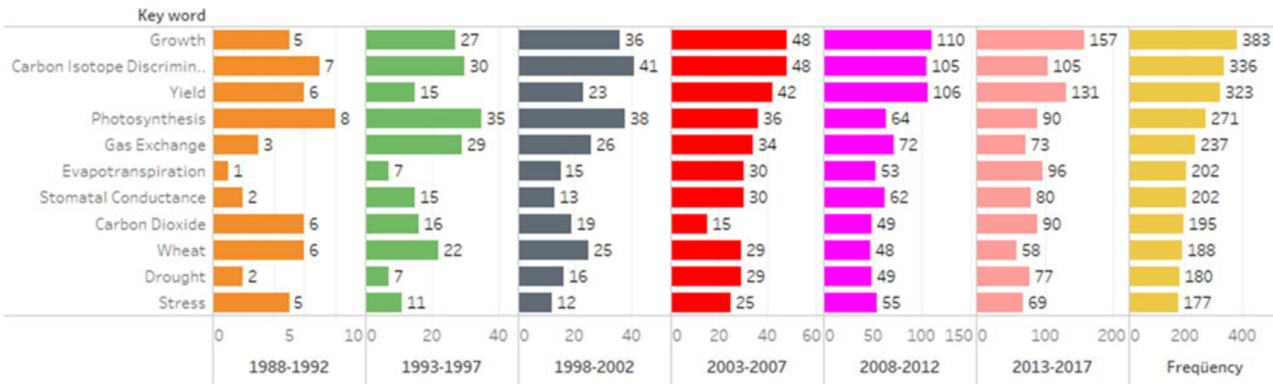

Fig. 3. Most frequent keywords in each 5-year period. Colour online.

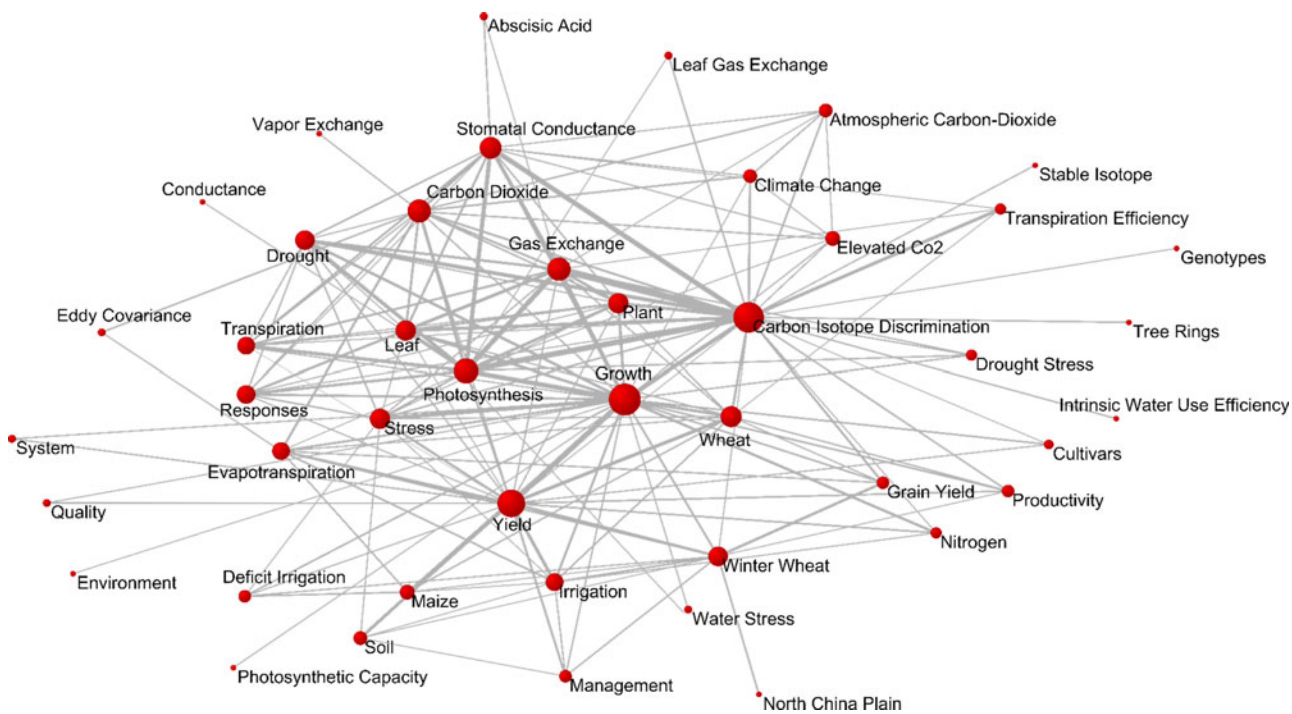

Fig. 4. Network of co-words. Colour online.

The network of co-words (Fig. 4) evaluates the relationships between terms that coincide in the same work. This network has been constructed with a threshold of >20 co-occurrences between keywords. The keywords co-occurrences are proportional to the size of the circles. The width of the connecting lines between two keywords represents the number of times those two keywords co-occur in the articles. The strongest relationships are ‘carbon isotope discrimination’ with: ‘gas exchange’ ($n = 110$), photosynthesis ($n = 92$) and ‘stomatal conductance’ ($n = 81$); growth with yield ($n = 91$) and with photosynthesis ($n = 76$). A strong co-occurrence was also observed for the pair ‘gas exchange’ and photosynthesis ($n = 81$).

The most frequent subject categories including the most frequent key words and most productive journals in each category were examined (Table 2). The subject category with the most published articles was Agronomy ($n = 653$). The most frequent keywords in this subject category were yield ($n = 156$), growth ($n = 147$) and evapotranspiration ($n = 100$), and the most productive journals were *Agricultural Water Management* ($n = 173$), *Crop Science* ($n = 55$) and *Field Crops Research* ($n = 55$). In the second most prolific subject category (Plant Sciences ($n = 405$)), the prevailing keywords were ‘gas exchange’ ($n = 110$), ‘carbon isotope discrimination’ and photosynthesis ($n = 100$). In this category, the most productive journals have been *Photosynthetica* (42), *Plant Cell and Environment* ($n = 31$) and *Plant and Soil* ($n = 30$). The third area was Water Resources ($n = 295$), with yield ($n = 62$), evapotranspiration ($n = 59$) and growth ($n = 59$) as most frequent key words and *Agricultural Water Management* ($n = 173$), *Irrigation Science* ($n = 30$) and *Irrigation and Drainage* ($n = 10$) as most frequent journals of publication. Other outstanding areas with >100 works have been Agriculture Multidisciplinary ($n = 170$), Environmental Sciences ($n = 167$), Ecology ($n = 140$), Forestry ($n = 135$) and Soil Science ($n = 117$).

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Table 2. Most frequent subject categories, most frequent key words and most productive journals in each category

		Most frequent key words						Most productive journals					
Subject category	*N*	Key word 1	*n*	Key word 2	*n*	Key word 3	*n*	Journal 1	*n*	Journal 2	*n*	Journal 3	*n*
Agronomy	653	Yield	156	Growth	147	Evapotranspiration	100	*Agricultural Water Management*	173	*Crop Science*	55	*Field Crops Research*	55
Plant Sciences	405	Gas Exchange	110	Carbon Isotope Discrimination	110	Photosynthesis	100	*Photosynthetica*	42	*Plant Cell and Environment*	31	*Plant and Soil*	30
Water Resources	295	Yield	62	Evapotranspiration	59	Growth	59	*Agricultural Water Management*	173	*Irrigation Science*	30	*Irrigation and Drainage*	10
Agriculture, Multidisciplinary	170	Yield	37	Growth	30	Irrigation	27	*Indian Journal of Agricultural Sciences*	55	*Agriculture Ecosystems & Environment*	11	*Journal of Integrative Agriculture*	11
Environmental Sciences	167	Climate Change	40	Carbon Dioxide	40	Photosynthesis	35	*Environmental and Experimental Botany*	22	*Global Change Biology*	22	*Agriculture Ecosystems & Environment*	11
Ecology	140	Carbon Isotope Discrimination	48	Carbon Dioxide	39	Climate Change	31	*Oecologia*	31	*Global Change Biology*	22	*Agriculture Ecosystems & Environment*	11
Forestry	135	Carbon Isotope Discrimination	58	Stomatal Conductance	29	Gas Exchange	26	*Agricultural and Forest Meteorology*	33	*Tree Physiology*	24	*Forest Ecology and Management*	21
Soil Science	117	Yield	29	Growth	25	Carbon Isotope Discrimination	21	*Plant and Soil*	30	*Soil & Tillage Research*	16	*Communications in Soil Science and Plant Analysis*	14
Horticulture	97	Growth	24	Gas Exchange	20	Photosynthesis	17	*Scientia Horticulturae*	33	*Hortscience*	14	*Journal of the American Society For Horticultural Science*	11
Meteorology & Atmospheric Sciences	67	Carbon Dioxide	18	Evapotranspiration	18	Climate Change	16	*Agricultural and Forest Meteorology*	33	*Journal of Agrometeorology*	6	*International Journal of Biometeorology*	4
Multidisciplinary Sciences	58	Growth	14	Photosynthesis	11	Carbon Isotope Discrimination	10	*PLoS ONE*	21	*Scientific Reports*	13	*Proceedings of the National Academy of Sciences of the USA*	4

Table 3. Country of publication, citations, number of research centres and number of researchers

Country	Papers	Citations	Citations/articles	N° Universities[a]	Articles/universities	N° researchers[b] (per million people)	Articles/researchers (per million people)
China	456	7235	15.87	942	0.48	1159	0.39
USA	410	11 312	27.59	1810	0.23	4313	0.10
Australia	176	7758	44.08	40	4.40	4539	0.04
India	165	1339	8.12	878	0.19	216	0.76
Spain	93	2243	24.12	75	1.24	2639	0.04
Italy	88	2200	25.00	82	1.07	2115	0.04
Germany	87	2288	26.30	368	0.24	4748	0.02
Canada	81	1758	21.70	101	0.80	4552	0.02
France	76	2171	28.57	214	0.36	4307	0.02
UK	63	1725	27.38	161	0.39	4350	0.01
Brazil	60	594	9.90	198	0.30	881	0.07
Iran	57	419	7.35	309	0.18	671	0.08
Japan	43	796	18.51	717	0.06	5173	0.01
Pakistan	37	203	5.49	179	0.21	294	0.13
Turkey	36	584	16.22	175	0.21	1216	0.03
Switzerland	33	979	29.67	23	1.43	5257	0.01
Egypt	32	443	13.84	49	0.65	663	0.05
The Netherlands	32	965	30.16	55	0.58	4673	0.01
Israel	24	1186	49.42	35	0.69	8250	0.00
Denmark	24	815	33.96	26	0.92	7458	0.00
Belgium	22	518	23.55	63	0.35	4711	0.00

[a]Source for data on universities source: UniRank (https://www.4icu.org/).
[b]Source for data on researchers: The World Bank (https://www.worldbank.org/).

Countries

Overall, 92 countries were identified in the papers obtained from the search strategy. The distribution of papers and citations by countries, number of research centres, number of papers per research centre, number of researchers and number of papers per researcher were investigated (Table 3). China (456 papers) appeared as the most prolific country in terms of the number of publications, followed by the USA (410 papers), Australia (176 papers) and India (165 papers). Citation ranking is headed by the USA (11 312), followed by Australia (7758) and China (7.235). In the number of citations per paper, Australia ranks first (44.08), followed by Israel (49.42) and Denmark (33.96). If the number of papers published per university in each country is taken into account, Australia is also first here (4.4), followed by Switzerland (1.43) and Spain (1.24). Finally, if the number of researchers (per million inhabitants in each country) is considered, India is in first place (0.76), followed by China (0.39) and Pakistan (0.13).

A world map representation of the 22 most productive countries (with a threshold of >20 papers) was produced (Fig. 5). Within the European Union countries, Spain ($n = 93$), Italy ($n = 88$) and Germany ($n = 87$) were the most prolific countries.

There was variability in the distribution of keywords according to the papers' countries of origin (Table 4). For example, the keyword 'carbon dioxide' attracted more attention in China, the USA and Germany; 'carbon isotope discrimination' was highlighted in the USA, followed by China and France; drought was more frequent in China, the USA and Spain; evapotranspiration prevailed in China, the USA and Australia; 'gas exchange' in China, the USA and Italy; and irrigation was the second most important keyword for India.

Most cited papers

A list of papers with >200 citations received was developed (Table 5). Interestingly, one publication stood out with >1000 citations. This leading paper was published in 1984 by Farquhar and Richards from the Department of Environmental Biology of the Australian National University, in *Australian Journal of Plant Physiology* ($n = 1301$). The paper describes the correlation observed between the variation in carbon-isotope composition in different wheat genotypes and the water-use efficiency in pot experiments. Two other papers with nearly 500 citations stood out. The first ($n = 497$) was published in *Journal of Experimental Botany* in 2004 by Condon *et al.*, a research team from the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia, and the Department of Environmental Biology located in the Australian National University. The paper reviewed recent advances in the breeding of rain-fed wheat for enhanced water-use efficiency with the

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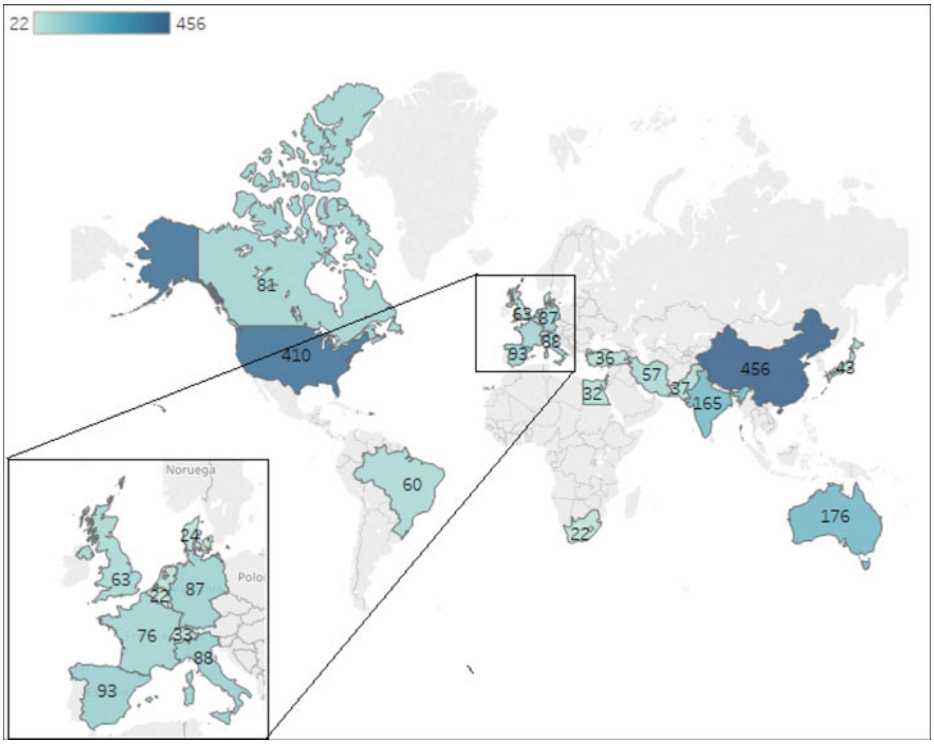

Fig. 5. World map representing the most productive countries. Colour online.

aim of providing insights into some of the occurring interactions and to highlight the opportunities and pitfalls potentially applicable to other crops. The second ($n = 461$) was published in 2005 by Blum in *Australian Journal of Agricultural Research*. It evaluated the compatibility, dissonance and/or mutual exclusion of the topics drought resistance, water-use efficiency and yield potential. If the number of years since publication is taken into account, the highest number of citations (69) corresponded to an article entitled: 'Increase in Forest Water-Use Efficiency as Atmospheric Carbon Dioxide Concentrations Rise', published in 2013 in *Nature*. In summary, the most cited papers identified provide studies including physiological aspects, but also relevant contributions on experimental biology, drought resistance and effects of climate, crop production and ecology, among others.

Discussion

In the current study, global scientific research in the water-use efficiency field based on publications provided by the Science Citation Index from the Web of Science database was investigated. The annual evolution of research on the topic, most productive countries, most common keywords and subjects, most prolific journals and 'citation classics' were evaluated. To the best of our knowledge, this appears to be the first comprehensive global mapping evaluation of scientific publications in water-use efficiency.

Publication trend

One of the most noticeable results was the increasing number of published articles observed in recent years, with approximately two-thirds of the articles appearing in the last decade, in accordance with similar research studies conducted in other areas, such as water research based on MODIS images (Zhang *et al*., 2017*a*), drinking water research (Fu *et al*., 2013), climate change (Bjurström and Polk, 2011; Aleixandre-Benavent *et al*., 2017) and deforestation (Aleixandre-Benavent *et al*., 2018). Other works that have analysed scientific production related to water are those of water security research (Huai and Chai, 2016); papers published in water resources journals (Wang *et al*., 2011); water transfer (Zhang *et al*., 2015); water environment (Zhang *et al*., 2017*b*); groundwater (Niu *et al*., 2014). The percentage of works financed has also increased gradually over the last decade, which reflects the growing interest of nations and research funding organizations in this area. Funding of projects is very important as it helps researchers to create large collaborative teams that are more likely to produce and publish high-impact research.

Journals, key words and subject categories

The importance of the water-use efficiency topic is reflected in the type and quality of the journals in which research on the subject is published. As noted, most have Impact Factors that place them in the top quartiles of the JCR categories. Journal Impact Factor is considered an indicator of the quality of journals and its position in the first quartiles indicates leading positions in the rankings of each subject category.

The current great social and economic impact of water use and its multidisciplinary nature results in the research being published in a vast variety of journals in numerous subject areas, particularly Agronomy, Plant Sciences, Water Resources, Agriculture, Environmental Sciences, but also in others such as Ecology, Forestry, Soil Sciences, Horticulture and Meteorology and Atmospheric Sciences. In fact, only two of the most productive journals belong to the specific area of Water Resources: *Agricultural Water Management* (which is also the most frequently cited) and *Irrigation Science*.

The analysis of paper content, carried out on the basis of the analysis of keyword frequency and co-word analysis, made it

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Table 4. Most frequent key words and countries

Country	Keywords															Total
	Carbon dioxide	Carbon isotope discrimination	Drought	Evapotranspiration	Gas exchange	Growth	Irrigation	Leaf	Photosynthesis	Plant	Stomatal conductance	Stress	Wheat	Winter wheat	Yield	
China	68	60	43	79	37	99	48	32	56	31	38	36	49	96	103	875
USA	62	82	37	50	50	72	20	35	63	34	48	27	31	25	47	683
Australia	20	29	8	30	19	30	13	11	15	10	22	13	19	18	32	289
Spain	7	41	26	7	26	20	8	8	21	9	23	15	4	1	14	230
Italy	8	12	12	11	30	24	6	10	21	16	13	15	6	1	14	199
Germany	22	38	9	7	16	16	1	15	20	8	17	9	4	1	3	186
France	14	40	5	6	20	15	2	11	17	5	24	6	6		8	179
India	1	12	4	13	3	23	30	3	5	2	1	7	18	4	36	162
Canada	6	21	13	14	10	9	5	10	11	3	11	9	9	7	16	154
UK	20	19	6	1	13	7	5	9	17	7	17	2	6	1	6	136
Iran	2	5	6	2	3	15	7	3	4	8	4	10	16	5	10	100
Japan	5	9	2	6	3	13	2	7	9	5	8	4	4	2	7	86
Brazil	1	5	3	4	3	11	7	5	12	5	9	5			11	81
Denmark	8	5	4	1	6	8		5	11	6	10	3	3	1	5	76
Pakistan	2	1		4	3	12	5	2	4	3	1	5	15	5	10	72
Switzerland	12	12	3	6	7	4		2	3	5	13				2	69
The Netherlands	5	8	5	1	2	2	1	5	7	5	4	1	8	5	2	61
Turkey	1	6	4	5	1	6	6	3	4	3	2	3	6	1	8	59
Egypt			3	3	3	10	5	1	1	3		7	1		4	41
South Africa	5	4	1	2	3	6	3	1	1	1			3		6	36
Belgium	3	3	6	1		4	2	2	1	2	5	2	1	2	1	35
Israel	2	2	4	2	3	3	1	2	4	2	4		1		3	33

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Table 5. Papers with more than 200 citations

Authors	Title	Source	Citations	Citations per year
Farquhar, GD; Richards, RA	Isotopic composition of plant carbon correlates with water-use efficiency of wheat genotypes	*Australian Journal of Plant Physiology* 1984; 11(6): 539–552	1301	39.42
Condon, AG; Richards, RA; Rebetzke, GJ; Farquhar, GD	Breeding for high water-use efficiency	*Journal of Experimental Botany* 2004; 55(407): 2447–2460	497	38.23
Blum, A	Drought resistance, water-use efficiency, and yield potential - are they compatible, dissonant, or mutually exclusive?	*Australian Journal of Agricultural Research* 2005; 56(11): 1159–1168	461	38.42
French, RJ; Schultz, JE	Water-use efficiency of wheat in a Mediterranean-type environment .1. The relation between yield, water-use and climate	*Australian Journal of Agricultural Research* 1984; 35(6): 743–764	396	12
Condon, AG; Richards, RA; Rebetzke, GJ; Farquhar, GD	Improving intrinsic water-use efficiency and crop yield	*Crop Science* 2002; 42(1): 122–131	340	22.67
Hubick, KT; Farquhar, GD; Shorter, R	Correlation between water-use efficiency and carbon isotope discrimination in diverse peanut (Arachis) germplasm	*Australian Journal of Plant Physiology* 1986; 13(6): 803–816	316	10.19
Field, C; Merino, J; Mooney, HA	Compromises between water-use efficiency and nitrogen-use efficiency in 5 species of California evergreens	*Oecologia* 1983; 60(3): 384–389	292	8.59
Keenan, TF; Hollinger, DY; Bohrer, G; Dragoni, D; Munger, JW; Schmid, HP; *et al.*	Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise	*Nature* 2013; 499(7458): 324+	276	69
Howell, TA; Tolk, JA; Schneider, AD; Evett, SR	Enhancing water use efficiency in irrigated agriculture	*Agronomy Journal* 2001; 93(2): 281–289	274	17.13
Sinclair, TR; Tanner, CB; Bennett, JM	Water-use efficiency in crop production	*Bioscience* 1984; 34(1): 36–40	269	8.15
Deng, XP; Shan, L; Zhang, HP; Turner, NC	Improving agricultural water use efficiency in arid and semiarid areas of China	*Agricultural Water Management* 2006; 80(1–3): 23–40	269	24.45
Hatfield, JL; Sauer, TJ; Prueger, JH	Managing soils to achieve greater water use efficiency: a review	*Agronomy Journal* 2001; 93(2): 271–280	244	15.25
Hsiao, TC; Acevedo, E	Plant responses to water deficits, water-use efficiency, and drought resistance	*Agricultural Meteorology* 1974; 14(1–2): 59–84	242	5.63
Polley, HW; Johnson, HB; Marino, BD; Mayeux, HS	Increase in C3 plant water-use efficiency and biomass over glacial to present CO_2 concentrations	*Nature* 1993; 361(6407): 61–64	242	10.08
Sivamani, E; Bahieldin, A; Wraith, JM; Al-Niemi, T; Dyer, WE; Ho, THD; *et al.*	Improved biomass productivity and water use efficiency under water-deficit conditions in transgenic wheat constitutively expressing the barley Hva1 gene	*Plant Science* 2000; 155(1): 1–9	220	12.94
Wallace, JS	Increasing agricultural water use efficiency to meet future food production	*Agriculture Ecosystems & Environment* 2000; 82(1–3): 105–119	218	12.82
Monclus, R; Dreyer, E; Villar, M; Delmotte, FM; Delay, D; Petit, JM; *et al.*	Impact of drought on productivity and Water Use Efficiency in 29 Genotypes of *Populus deltoides* × *Populus nigra*	*New Phytologist* 2006; 169(4): 765–777	212	19.27
Karaba, A; Dixit, S; Greco, R; Aharoni, A; Trijatmiko, KR; Marsch-Martinez, N; *et al.*	Improvement of water use efficiency in rice by expression of HARDY, an arabidopsis drought and salt tolerance gene	*Proceedings of The National Academy of Sciences of The United States of America* 2007; 104(39): 15 270– 15 275	201	20.1

possible to identify the key issues of greatest scientific concern, as well as their evolution over time. One of the most frequent keywords was 'carbon isotope discrimination', a technique used to evaluate water-use efficiency in plants to precisely select those with enhanced tolerance to water-deficit conditions (Moghaddam *et al.*, 2013). Other relevant key words were photosynthesis, evapotranspiration and 'stomatal conductance'. The basic process of production of new biomass (photosynthesis) and that of water consumption (transpiration) take place at the same time, and the entry of carbon dioxide and the exit of water use the same route, stomata in the leaves. The more open they are, the easier it is for CO_2 to enter but also the faster the water escapes. The price, the water used for biomass production, is therefore inevitable and high. The production of biomass without water is impossible for plants (Medrano Gil *et al.*, 2007). The most efficient use of water is directly correlated with stomatal

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conductance, a very important variable to evaluate the water status of plants, the energy balance and the photosynthetic relationships. Evapotranspiration is a keyword especially relevant in the areas of Agronomy, Water Resources and Meteorology, and Atmospheric Sciences. Although some of the irrigation water is returned to groundwater by filtering through the soil, the consumption through plant growth and evapotranspiration accounts for approximately 70% of the water withdrawn, i.e. it does not return to the groundwater (Molle and Berkoff, 2007; Tang *et al*., 2014). 'Gas exchange' is one of the tools traditionally used to assess the water needs of trees, both in optimal conditions and under water stress. Another word that stands out, especially in the area of agriculture, is irrigation. Indeed, improving irrigation efficiency, both in terms of transport and field application, is of vital importance to achieve maximum water savings (Howell, 2001).

These keywords are not too closely related to those identified in other studies that also have water as a central topic, with the exception of 'climate change'. For example, in the study on water security research, the most frequent keyword in addition to the search terms 'water safety' and 'water security' was 'climate change', followed by 'drinking water', 'water quality', 'risk assessment' and 'water resources' (Huai and Chai, 2016), while in the study on water resources journals, they were model, flow, soil, river and analysis (Wang *et al*., 2011). 'Climate change' was also the most frequent key word in a paper on water transfers (Zhang *et al*., 2015), followed by irrigation. In a study on integrated water assessment and modelling research, management, environment, groundwater and 'decision support system' were the most frequent keywords (Zare *et al*., 2017).

Countries

The fact that China appeared as the most prolific country in terms of published articles may be related to the magnitude of some projects such as the South to North Water Diversion Project. This is one of the most notable water transfer projects in the world and has led to numerous multidisciplinary studies, some of them covering all aspects of water management (conservation, purification, efficient use, etc.) (Yang *et al*., 2014; Chen *et al*., 2013*a*, 2013*b*; Zhang *et al*., 2015). It should also not be forgotten that China is the fastest growing economy in the world. The approval of the National Basic Research Program (also called 973 Program) in 1997 is likely to have contributed to the growth of publications in China in many areas of science (Wang *et al*., 2010).

The distribution of articles published by country in the current study differs from that found in the work of Wang *et al.* (2011), where the most productive countries were the USA, the UK, Canada and China. Although China was fourth in Wang *et al.* (2011), it has shown a rapidly ascending trend in recent years. In another paper on water footprint, the most productive countries were the USA, China, the Netherlands and Australia (Zhang *et al*., 2017*b*). Something similar occurred in the study on integrated water assessment and modelling research (Zare *et al*., 2017), with the USA, China, the UK and Australia as leading countries. The leadership of the USA and China in drinking water research is also similar, with the USA, Japan, China and Germany as countries with a higher production of articles (Fu *et al*., 2013). Drought is currently one of the most important ecological problems, which affects many countries and has been the subject of numerous studies, especially in China, the USA and Spain, the latter being the European country with the highest drought conditions and where improving the performance of water policies is especially important (Kahil *et al*., 2016).

The inclusion of relative indicators, such as the number of citations per article, has made it possible to relativize the absolute scientific production of countries and the emergence of small countries, such as Israel and Denmark. On the other hand, if other sociodemographic indicators of the countries are considered, such as the number of research centres and researchers, small countries such as Switzerland also emerge, as well as others that are not usually in the 'scientific elite', such as India and Pakistan.

International organizations play a very important role in the efficient management of water resources. One of these is the United Nations Water, whose objectives include increasing efficient use of water resources in all sectors significantly by 2030, as well as ensuring the sustainability of freshwater extraction, addressing water scarcity and significantly reducing the number of people suffering from water shortages. To achieve this, methodologies to measure changes in water-use efficiency over time, definitions, statistical procedures and recommendations, as well as harmonized indicators based on international standards on Water-Use Efficiency have been developed under the supervision of the Food and Agriculture Organization (FAO) (United Nations Water, 2018).

In the USA, the Alliance for Water Efficiency (http://www.allianceforwaterefficiency.org), a non-profit organization whose main purpose is the efficient and sustainable use of water, provides information, products, programmes and assistance on water conservation efforts, among other institutions.

In Europe, the European Environment Agency provides environmental information, studies and assessments in close cooperation with the European Environment Information and Observation Network (Eionet) (https://www.eea.europa.eu). Moreover, improving water productivity is part of the 'Europe 2020' strategy on economic growth, resource efficiency and the notion of green growth, called 'Towards efficient use of water resources in Europe' (http://www.enorasis.eu/uploads/files/Water%20Governance/2.EEAreport.pdf).

Most cited papers

The most cited documents are those that have had the most influence on subsequent studies, sometimes constituting themselves as pioneers in the field. They also reveal which topics receive the most attention, through the citations they receive from other researchers. In the case of water-use efficiency, the most frequently cited issues relate, among others, to the correlation between carbon-isotope composition and water-use efficiency of wheat genotypes; the progress in breeding for improved water-use efficiency of rain-fed wheat; the breeding water-use efficiency for relationships between drought resistance, water-use efficiency and yield potential; the relationship between water-use efficiency and climate; and the improvement of water-use efficiency in crop yield.

Conclusions

The current paper presents a synopsis of existing research in water-use efficiency, including an intense evaluation of annual publications, journals, subject categories, countries and keywords. A better understanding of the information on water-use efficiency may assist in the improvement of the ecosystem management for mitigation as well as adaption to global hydrological changes. Research on water-use efficiency increased significantly in recent years, with approximately two-thirds of the articles appearing in the last decade. Many studies in the categories of Agronomy and Agriculture, Plant Sciences, Water Resources, Environmental Sciences, Ecology, Forestry and Soil Sciences have been performed to investigate water-use efficiency. China, the USA, Australia, Spain, Italy and Germany had high productivity in publishing research papers. The most productive and cited journals were *Agricultural Water Management*, *Agronomy Journal* and *Crop Science*. Keyword analysis provided clues about the hot topics. Growth, 'carbon isotope discrimination', yield, photosynthesis, 'gas exchange', evapotranspiration and 'stomatal conductance' were the most frequently used keywords. Water-use efficiency is widely related to several research areas such as Environment, Energy, Society and Economy, providing relevant information on population growth, climate change, food safety and urbanization. Bibliometric techniques can provide us with a quantitative perspective on the status, features and trends of water-use efficiency research, which has proven to be an emerging and rapidly developing new area of research. Finally, future efforts in the field should contain the research progression in the coming years, with the inclusion of new topics and major players that will become an essential part of this research field.

Financial support. None.

Conflicts of interest. None.

Ethical standards. Not applicable.

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