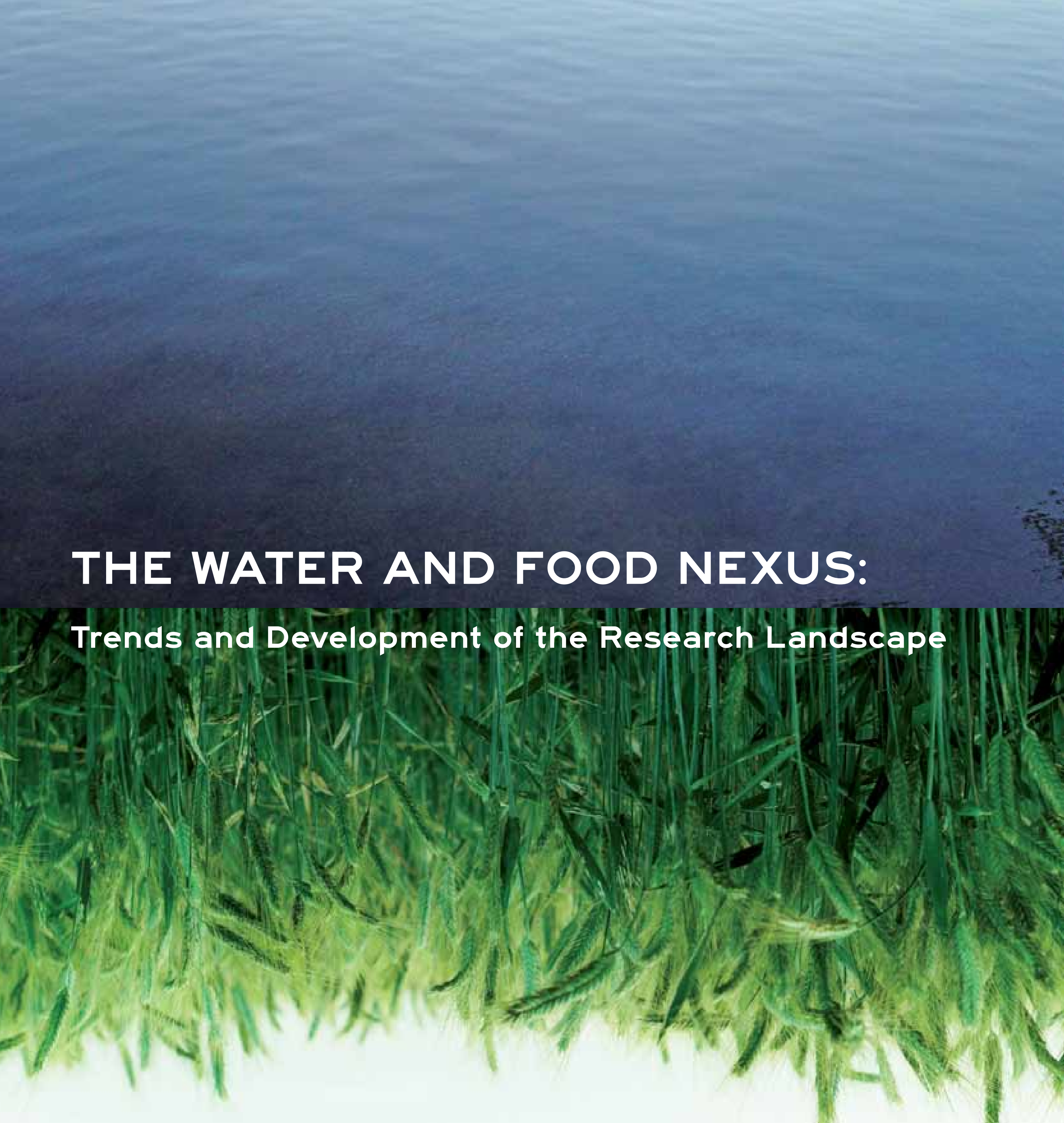

THE WATER AND FOOD NEXUS:

Trends and Development of the Research Landscape

SIWI

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THE WATER AND FOOD NEXUS:

Trends and Development of the Research Landscape

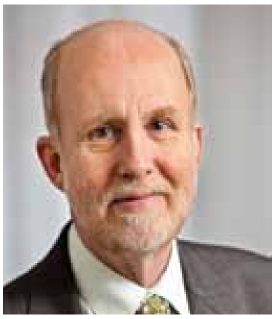
AUGUST 2012

A Report by

Stockholm International Water Institute and Elsevier

www.info.scival.com/waterfoodnexus

PREFACE



The world's water situation is becoming more challenging each year. In the last century, water use has grown at twice the rate of population increase. By 2025, two-thirds of the world's population could be facing water stress[1]. Growing demands for water arise in all sectors of society, while a warming planet places ever higher pressure on Earth's limited water resources.

In 2011, Elsevier published "Confronting the Global Water Crisis through Research," which analyzed trends in scientific publications on water sciences. The findings of the report provided crucial insights for the Stockholm International Water Institute (SIWI), both in strategic planning of SIWI's work as a policy institute and in establishing the scientific program for World Water Week in Stockholm. The report clearly showed that the field of water research and the knowledge base on water issues are growing in new places around the world while becoming increasingly multi-disciplinary. These are very positive developments. The entire water community has a great opportunity to better leverage the growing knowledge creation on water research that's emanating from new places and new partnerships. Still, there are many areas where more knowledge is needed. As the dominant global water user, food production has the greatest impact on water. There are huge opportunities to manage food and water more effectively; reducing loss and waste of food alone could save billions of dollars and trillions of liters of water.

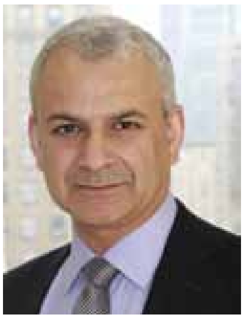
Achieving those benefits, of course, requires dedicated investment in research to inform action in local, national and global contexts. This is why international attention paid to water and food in 2012, through UN World Water Day, World Water Week in Stockholm and reports and public awareness campaigns initiated throughout the year, are so timely. This also is why SIWI partnered with Elsevier to produce this report to analyze the research landscape on the

1 Statistics come from a UNWATER.ORG fact sheet http://www.unwater.org/downloads/WWD2012_water_scarcity.pdf

water and food nexus. This research is critical, but equally important is the improved performance by the research community to disseminate this scientific understanding to policy makers and professionals in the right form at the right time, in order for the knowledge to be implemented in practice.

We hope that through this report, and the discussions brought forth during World Water Week, we can accelerate the process of transferring knowledge from research to informed decision-making and sustainable action.

Per Bertilsson
Deputy Executive Director at Stockholm International Water Institute



Water and food security are recognized as one the grand challenges of the 21st century. The knowledge needed to meet this challenge is already being created by researchers from a growing number of countries, often working together in international collaborations. However, transferring this science and technology so that it empowers sustainable solutions to the world's water situation is one of the most complex problems we face.

As a global provider of information solutions, our mission is to deliver superior tools and information to build insights and advance research. We deliver 26% of the scientific literature in the field of water resources research. But beyond our role as traditional publishers, we continuously seek new ways to develop water from a highly fragmented field of research to an integrated scientific discipline.

Some of the best innovations are created in partnerships. We collaborate closely with principal players in the generation, dissemination and policy applications of water, while working with scientific institutes, societies, industry and NGOs. We also organize conferences, webinars, innovation competitions and support nonprofit initiatives to provide developing countries with access to the latest and most important water research.

Elsevier is proud to collaborate with the Stockholm International Water Institute in this in depth and critical report. Our 2012 analysis and the ensuing industry discussion will provide a powerful tool to assess present and future trends in the nexus of water and food research. Like SIWI, we are committed to advancing and disseminating water science to those who need it most.

Ron Mobed
Chief Executive Officer Elsevier

ACKNOWLEDGEMENTS

This *WATER AND FOOD NEXUS: Trends and Development of the Research Landscape* report is jointly prepared by SIWI and Elsevier, and was motivated by a previous study whose findings were presented by Elsevier at the 2010 Government-University-Industry Research Roundtable (GUIRR)[2] meeting in Washington DC.

At Elsevier the study has been executed by the SciVal Analytics unit with guidance from experts in the field of water research from the Aquatic and Green Sciences portfolio and Stockholm International Water Institute (SIWI). Authors of this report are: Britt-Louise Anderson, Christiane Barranguet, Jens Berggren, Judith Kamalski, Iris Kisjes, and Alexander van Servellen.

Special thanks go to M'hamed Aisati, and Ylann Schemm for their support.

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2 GUIRR was created in 1984 in response to the report of the National Commission on Research, which called for an institutionalized forum to facilitate dialogue among the top leaders of government and non-government research organizations. The Roundtable is sponsored by the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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EXECUTIVE SUMMARY

THE WATER AND FOOD NEXUS: Trends and Development of the Research Landscape follows a related report also published by Elsevier, *Confronting the Global Water Crisis through Research*, which examined the dynamics of global water resources research from 2005-2008. This current report examines the field of water research from 2007-2011, expanded to include the increasingly critical interface of water and food research. Water resources research refers to natural and social science studies of water use, mostly freshwater use and technology. Water and food research is the natural and social science study of water consumption and recycling to produce food.

The criticality of water and food research can be discerned by a few statistics:

- 70% of all fresh water use is by irrigation
- About 20% of the world's cropland is irrigated, yet irrigated agriculture supports 40% of all food production
- Drought is the No.1 threat to food supply in high-population developing countries
- By 2050, the planet could have nearly 3 billion additional people to feed with virtually no new cropland and no new sources of water

The dramatic growth in publication of research papers on water resources and water and food research began in the 1980s, then spiraled upward in the mid-1990s. From 2007-2011, the compound annual growth rate (CAGR) for water resources research published articles was 9.2% a year, while food and water research articles grew at 4.7% a year. In 2011, water resources research articles surpassed 6,000 articles per year and water and food research topped 4,000 articles per year.

COLLABORATION

Since the flow of water respects no man-made boundaries, water problems are often international problems. And, as the water crisis touches nearly every corner of the globe, the search for solutions is a collaborative effort. More than half of all water resources and water and food research articles are produced by international collaboration among researchers. For water resources research, the rate of international collaboration is growing quickly. Collaboration between industry and academia ranges between 2% and 4% for both water subject areas.

SUBJECT AREA CHANGES

It appears that water and food research is intrinsically interdisciplinary, while water resources research is becoming more interdisciplinary. In water resources research, computer science and mathematics remain high-growth fields, while economics has significantly declined in the last two years. The increased publication production in computer science and mathematics likely reflects the growing use and sophistication of statistical modeling and quantitative measurement tools. Environmental science remains the mainstay of water resources research, accounting for nearly half the papers and reflecting the continued attention to human impact the natural environment. In water and food research, mathematics and social sciences are the fastest growing fields. Agriculture and biological sciences account for well over half of all water and food research articles.

PUBLICATION LANDSCAPE PER COUNTRY

Output is highest in the United States in both water resources and water for food research, but recent growth is very low. China is seeing the fruits of steadily increased investment in water research. If China's growth trajectory continues, it will surpass the United States in water research publication in a few years. Two countries in Asia – Iran and Malaysia – have seen mercurial growth in water resources research, while Iran, Malaysia and South Africa have undergone the same growth in water and food research.

COUNTRY IMPACT

For the purposes of this paper, impact is defined as average citations per paper. The average impact for water resources research is 4.9 citations per paper, while for water and food research it is 5.8 citations per paper. The highest performing countries in citations per paper are Sweden, Switzerland, the Netherlands, Belgium and United Kingdom, all of which are home to older, well-established universities with research strength in water science.

INTERNATIONAL COLLABORATION

When looking at international collaboration both percentage of internationally coauthored papers and impact of these papers are taken into account. The Netherlands, Belgium, Denmark and Switzerland have the highest levels of productive collaboration, with an average of 9-11 citations per paper and 60%-70% international collaborations among water research papers. These figures are very high, even among other European nations.

INSTITUTES

For water resources, the top three institutions are western US Universities, in a region where water issues are paramount in public policy. Two of the top universities are in the Netherlands, another region where water issues are all-important.

CONCLUSION

Despite progress in recent years, the continued expansion of water research is more critical than ever, as the worldwide population is projected to reach 9.2 billion people by mid-century. Developing and disseminating the science and technology to produce more food with less water is a global imperative. However, much of the expertise in water resources and water and food research resides in developed nations, while technological advancement is most needed in developing countries. The immense knowledge being developed must be translated into sustainable action. New information technology in data analytics and networking, along with advancements in bibliometric tools, can enhance the global sharing of data and information, bring researchers together and match water research to best practices in water development and management.

INTRODUCTION

Water resources are sources of water that are useful to human society, uses that include agricultural, environmental, household, industrial and recreational. For the most part, water resources research focuses on fresh water, which constitutes only 3% of the planet's water, although salt water is an important resource in relation to fisheries, marine habitat, desalinated drinking water and various beach and near-shore recreation.

Emerging from the field of water resources research is the subsidiary field of water and food research, which refers to all the uses of water for agriculture. The importance of the water and food nexus can be easily understood in the fact that while the daily drinking water requirement per person is 2-4 liters, it takes 2,000 to 5,000 liters of water to produce one person's daily food (FAO 2009). About 20 percent of the world's cropland is irrigated; the rest is watered by rainfall only. Yet, irrigated agriculture supports 40% of all food production. That's because irrigation increases the yields of most crops by 100% to 400% (FAO 2009). Water and food research is increasingly critical to human society because by 2050, the world must grow food to support an additional 2.7 billion people (FAO 2009). And this must be accomplished without major new amounts of water, crop and pasture land.

Already, drought remains the No. 1 threat to food supply in developing countries, particularly in Africa and Asia. More deaths were caused by drought than any other natural disaster in the last century (Below, R. Grover-Kopec, E. and Dilley, M. 2007). But deaths are not the only problem associated with drought and the resulting decrease in food supply. Other severe impacts include poverty, poor health, malnutrition and reduced productivity (Fuente, A de la. and Dercon, S. 2008).

The need for the advancement of water and food research grows greater every year. Simply put, countries must grow more food with less water. Many of the world's major food-producing regions already face serious water constraints. Today's water and food challenges include unsustainability of water resources, degradation of quality and supply, overuse and inefficient use, conflicts over distribution and mismanagement. These are the leading challenges that the multidisciplinary field of water and food research must help solve.

This report takes the first look at the state of water and food research within the larger field of water resources research, examining the state of research literature on both fields through the year 2011.

HISTORICAL PERSPECTIVE ON WATER RESEARCH PUBLICATIONS

Knowledge of water development – particularly related to food production – has shaped human communities throughout history (Tempelhoff, J. et al. 2009). One of the first wars ever documented was fought between the Mesopotamian city-states of Lagash and Umma more than 4,500 years ago because of a dispute over a canal and its use irrigating fields that produced staple crops for the two city-states (Cooper, J.S. 1983) Throughout antiquity, expertise in water use became integral to the success of empires. And the loss of knowledge about water development following the decline of the Roman Empire, along with the loss of much scientific and technological knowledge, ushered in the so-called Dark Ages.

It was not until the 17th century, that the science of hydrology was rediscovered in Europe, when a French author published a quantitative test to measure whether rainfall was sufficient to supply water to local rivers and springs (Dooge J.C.I., 1959). The science made slow progress until the early 19th century, when English natural philosopher and mathematician John Dalton published a paper about the relations of rainfall quantity to the flow of rivers minus evaporation (Dooge J.C.I., 1975). During the 19th century, water resources development and management became more organized by the creation of national institutions in several countries. This institutional framework allowed for a more consistent dissemination of the knowledge and scientific advances in the field (Rodda, J.C., 2006). In Britain, the Geological Survey was established in 1835, the British Meteorological Society in 1850, the Meteorological Department in 1854 and the British Rainfall Organisation in 1860, began recording and publishing data on water issues including groundwater and rainfall. Methods for predicting flood peaks and determining flow velocity in channels were developed. Published records of flows began for several rivers, and then in 1883, a project to continuously record the discharge of the Thames was launched (Rodda, J.C., 2006).

Old Aqueduct in de Provence in France
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Following the research of Louis Pasteur and the discovery of bacteria in the 1860s, the science and engineering of drinking water development led several major cities in the United States and Europe to begin disinfecting drinking water. Soon after, water treatment and the use of chlorine and other disinfectants resulted in the rapid decrease of waterborne diseases such as cholera and typhoid which rapidly decreased in the early 20th century (US Environmental Protection Agency, 2000). As the century progressed, water diversion for agriculture expanded, particularly in the American West with massive irrigation projects such as the Columbia Basin Project in Washington State and the Central Valley Project in California. Many mammoth dam projects for hydroelectric power got underway in the first half of the century.

At the same time, new water development scientific and engineering organizations and societies, including the International Association of Hydrological Sciences in 1922 and the International Association of Hydraulic Engineering and Research in 1935, promoted the publication of water research papers (Varady, R.G. Meehan, K. McGovern, E. 2009).

After World War II, research into water development for irrigation, power, flood control and drinking water began its rapid, global advancement, spurred by technological and scientific advances in developed countries. The entrance of the United Nations in 1945 launched a new era of human development in low- and middle-income countries that included many water development projects, along with the global

> *"During the 1950s and 1960s, UN agencies spearheaded the earliest global resources initiatives. The first of these to address water issues was the influential International Hydrological Decade (IHD), which drew together scientists and water managers from across the world, spanning the ideological divide created by the Cold War. IHD consolidated understanding of the hydrological cycle, compiled the first comprehensive water atlases and reference works, fostered programs to train new water researchers, established protocols for collecting and exchanging information, and perhaps most significantly, drew public attention to the importance of water."*
> (Varady 2009)

dissemination of information on water resources (Varady, R.G. Meehan, K. McGovern, E. 2009). Water-related research and publications multiplied and fructified in a dramatic way, initiating most of the advances in knowledge available today. It was also in this era that public awareness of water issues dawned in the global consciousness as information about water resources found its way into popular media.

The widespread dissemination of scientific advances began within the last few decades. While in the 1980s, the number of papers published per year on water resources and water and food research were counted in hundreds, by the turn of the century, thousands of papers were produced and published every year. A real explosion of research articles relating to water began in the mid-1990s, Figure 1.

This report focuses on the dynamics of both water resources research and water and food research from 2007 to 2011. Water resources research is a broad category that can range from water quality to flood control and from rainfall patterns to desalination. Water and food research is a more specialized and highly interdisciplinary field that may include agronomy, horticulture, civil engineering, economics, earth and atmospheric sciences, geography, geology, hydrology and other disciplines.

The criticality of water and food research is undeniable. A 2009 study of water and food issues in Asia by the UN Food and Agriculture Organisation (FAO) and the International Water Management Institute (IWMI) found that without dramatic improvements in irrigation, many high-population Asian nations will lack one-quarter of the grain they need to feed their people by 2050 (Mukherji, A. et al. 2009). At stake in the field of water and food research is the ability of nations to feed themselves.

> *"There is no new land or water to develop so we have to make more use of what we have... That is the only way we are going to feed everyone... If nothing is done, you are going to get an increase in social unrest, migration and a fertile ground for terrorism."*
> Colin Chartres
> Director General
> International Water Management Institute

One roadblock has been that while in recent decades the development of scientific knowledge in water-related disciplines has been significant, the transfer of this knowledge into realistic scenarios that can propel sustainable water management has advanced but slowly. The UN World Water Development Report 2012 stated: "Even when the appropriate knowledge is available, it does not always get readily disseminated and shared – and translated-into proper planning or effective action" (UN Educational, Scientific and Cultural Organization, 2012).

Advancements in data analytics, accelerated computing power, and mega-networking now available can help solve the frustrating fragmentation of scientific information in the field of water resources. In particular, bibliometric tools will support the information-sharing and national, regional and global strategizing that will be necessary to solve water challenges. Clearly, today's global water situation calls for opening the flow and dissemination of information about water resources and water and food that will allow the crafting of new policies and better environmental management and governance. Translating knowledge into action is imperative.

METHODOLOGY

To construct the initial data pool, the keywords "water resources*" were used to search titles, abstracts, and keywords of original articles and reviews published in the Scopus™ database (http://www.info.sciverse.com/scopus) from Elsevier between January 1, 2007 and Dec 31, 2011.
Scopus is the largest global abstract and citation database of peer reviewed research information with more than 19,500 active titles from over 5,000 publishers.
The second data pool that was used for the analysis for the water and food nexus resulted from a search of keywords "water" and "food" with the subdomains: Agricultural and Biological Sciences, or Environmental Science, or Earth and Planetary Sciences or Engineering or General from the same data source and time frame.

The resulting pools of research papers related to water resources and the water and food research, also known as the water and food nexus, was then analyzed by the SciVal Analytics team. The data pools were used to investigate trends on subject categories, institutions, and national rankings in three ways: according to the total number of papers, total cites, and average citations per paper. Subsequently the international collaboration trends were investigated.

BIBLIOMETRIC PROFILE

OVERVIEW

A common refrain in reports about the present global water challenge is that solutions based in science and technology could reduce the human impact in the coming decades, particularly if those solutions address water for food. A report by the U.S. National Intelligence Council on global water security concluded: "Because agriculture uses approximately 70 percent of the global fresh water supply, the greatest potential for relief from water scarcity will be through technology that reduces the amount of water needed for agriculture" (National Intelligence Council. 2012).

Growing more food with less water will require continued investment in agricultural research, and depend on the ability of the agriculture industry and government institutions to adopt the latest technologies. Innovation and sustained agricultural productivity depend on robust research and development. According to data from the Organisation for Economic Co-operation and Development (OECD), public research and development expenditures on agriculture in OECD countries have increased over the last decade from about 1% to 4% (OECD-FAO, 2012). However, in developing countries, where increased agricultural productivity is most needed, public research and development expenditures on agriculture are increasing in real terms at a lower rate than in the past and declining as a percentage of agricultural GDP (Beintema, N. M. and G.J. Stads 2008). Agricultural research funding in lower income countries often comes from foreign aid for individual projects, which may impede the development of countries' research capacity. Agricultural research in developed countries can benefit developing countries, but only with effective technology transfer

Water use for agriculture

1 kilo of rice requires 3,000 litres of water
1 kilo of beef requires 15,000 litres of water
1 cup of coffee requires 140 litres of water
Source: UN Food and Agriculture Organization

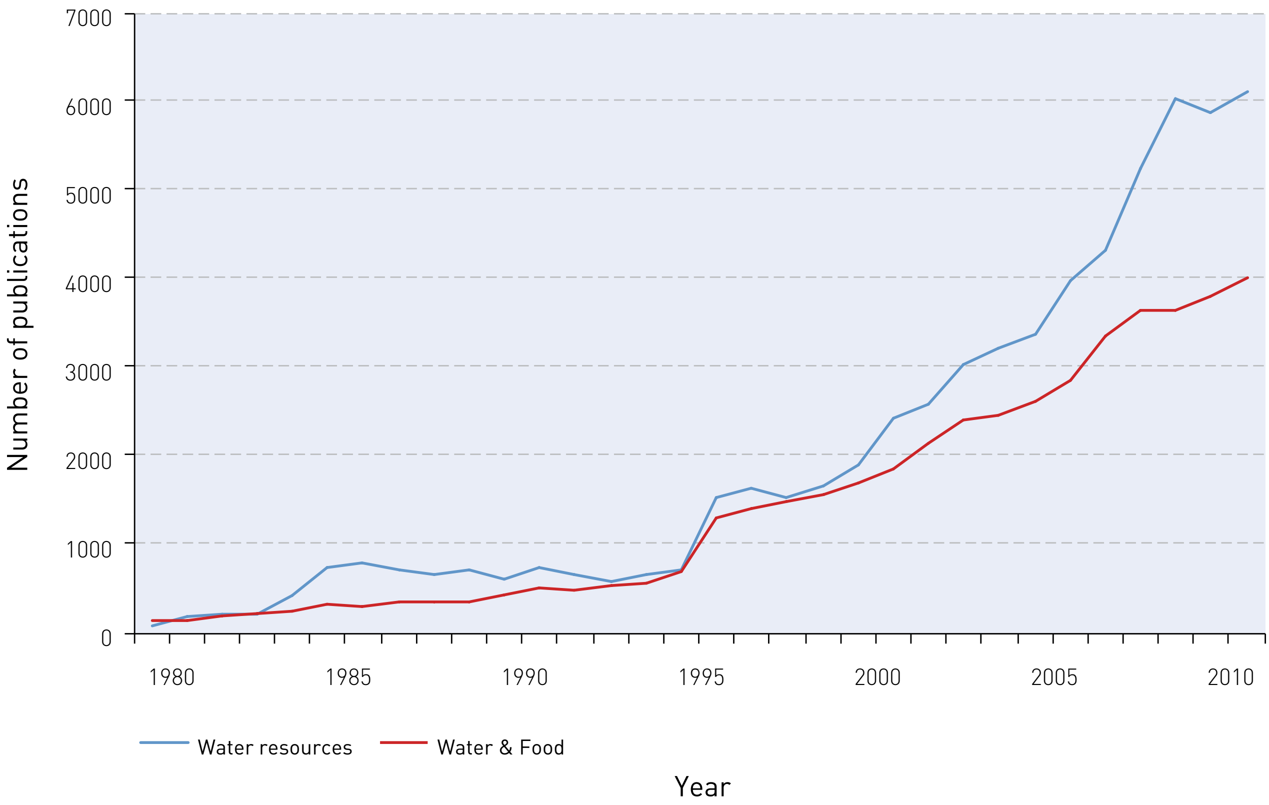

Figure 1 Number of papers published in the fields of water resources and water for food between 1980 and 2011

and adaption of research results to local conditions (OECD-FAO, 2012).

This report examines the growth in water resources research and water and food research between the years of 2007 to 2011. Overall, research output into the water and food nexus grew at 4.7% in compound annual growth rate (CAGR). But research into water resources showed a much stronger growth of 9.2% per year between 2007 and 2011. In 2011, research on water resources surpassed 6,000 articles a year, while research into water and food topped 4,000 articles, Figure 1.

Future productivity gains will depend on protecting the resource base and investments in research and development, as well as on the agriculture industry's ability to adopt the latest technologies. Agricultural research and development is the main source of innovation, which is needed to sustain agricultural productivity growth in the long-term. Also, according to data from the OECD, public research and development expenditures on agriculture across OECD countries has increased over the last decade, from about 1% to 4%, both in real terms and as a share of agricultural GDP (OECD-FAO, 2012).

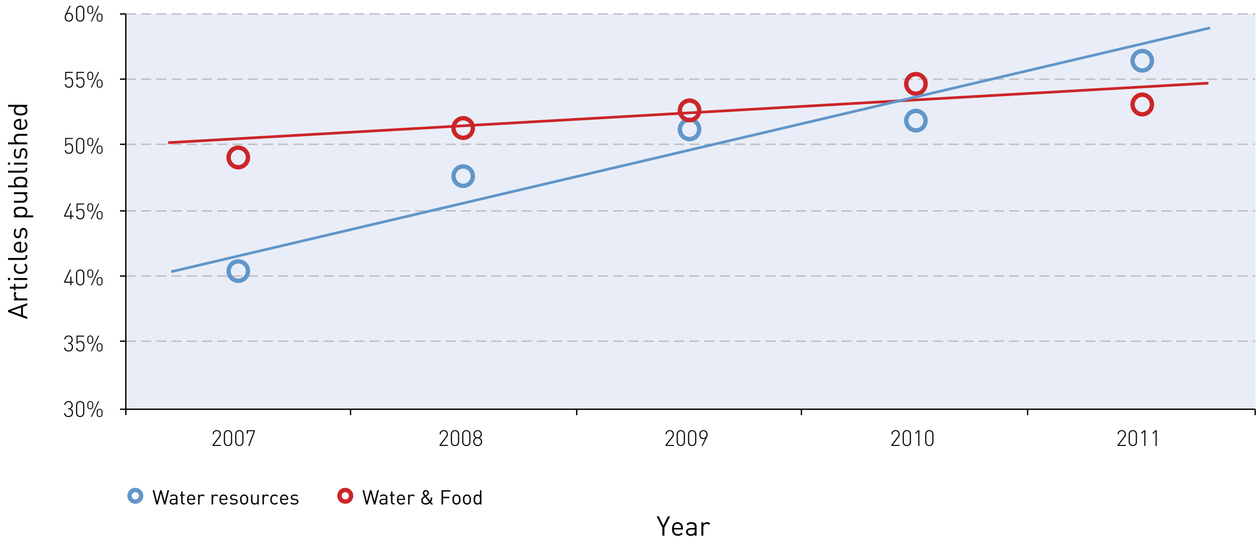

Figure 2 Percentage of scientific articles co-authored internationally for the fields of water resources research and water and food, published between 2007 and 2011

Most studies argue that the estimated benefits of agricultural research and development generally far exceed costs. Public research and development expenditures on agriculture in developing countries are increasing in real terms at a lower rate of growth than in the past and declining as a percentage of agricultural GDP (Beintema, N. M. and G.J. Stads 2008). Moreover, funding is often dependent on foreign aid, granted for time-limited projects, which may hamper the development of national research and development institutions and capacity building. However, research in some developed and emerging economies have spill-over effects, leading to technology transfer to developing countries. An important challenge is to better adapt research results to local conditions and to foster the adoption of technologies able to improve sustainable productivity growth in diverse conditions (OECD-FAO, 2012).

While some water supply issues are local problems, many others are regional, as watersheds and water courses traverse international borders. Upstream development can create downstream water quality and flooding problems in other countries. Therefore collaborative solutions are a necessity, and not just on regional levels. The challenges and solutions for water resources and water and food problems may be complex and extensive, but they also are very similar the world over. To some extent, the water crisis touches nearly every corner of the globe. Therefore, it is natural for the world's water experts to join forces in examining problems and developing solutions. In fact, that's exactly what's happening.

Today, more than half of all articles published on both water resources and water and food are international collaborations.

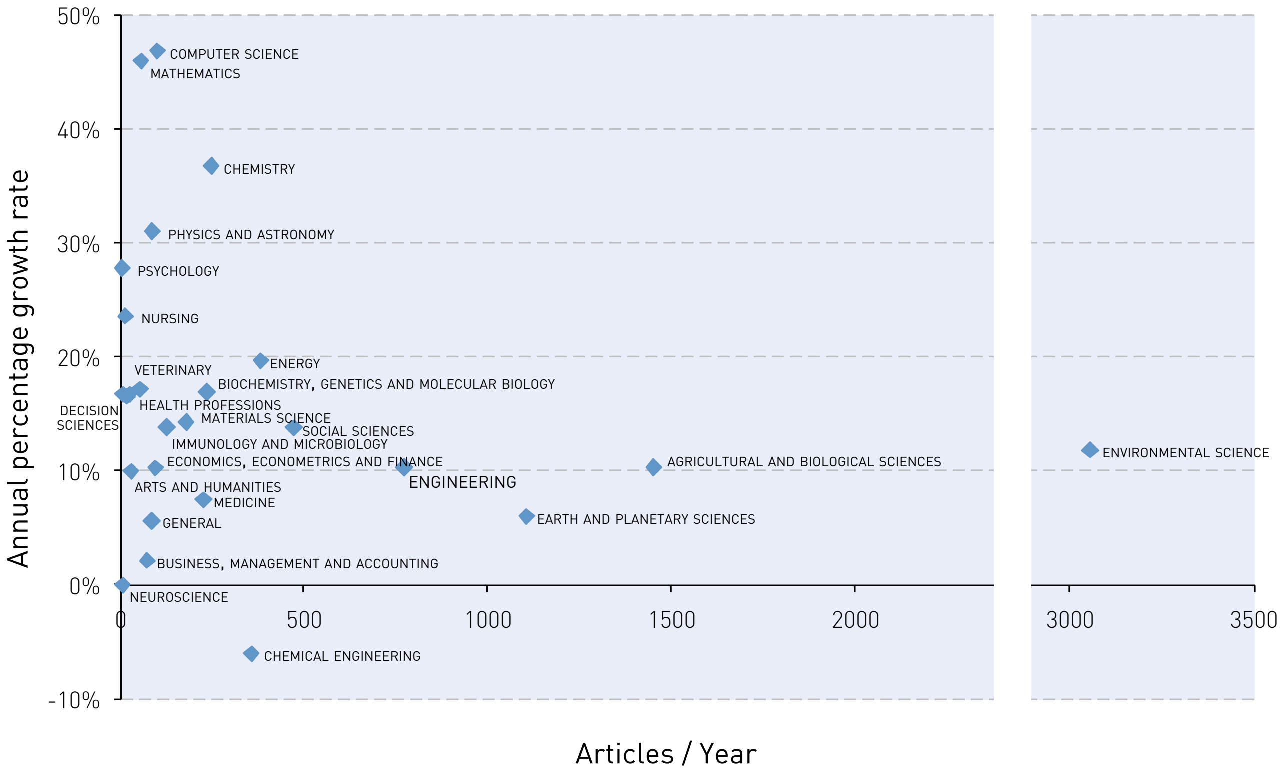

Figure 3a Annual growth rate of papers published relative to papers published per year in the diverse disciplines within the field of water resources research during the period 2007-2011

Figure 2 shows that 53% of water and food publications in 2011 have at least one co-author from another country. An examination of the percentage of internationally coauthored papers in each of these fields shows that the percentage of international water resources articles has been growing quickly over the last several years and has surpassed the percentage of internationally coauthored papers in water and food research. Water and food international collaboration shows a more stable trend over time, Figure 2. In addition, collaboration between industry and academia fluctuates between 2% and 4% for both subject areas.

The growth in international water resources research could be due to the steady growth of a wide variety of transboundary water issues, or that funding for water research is becoming more international than national.

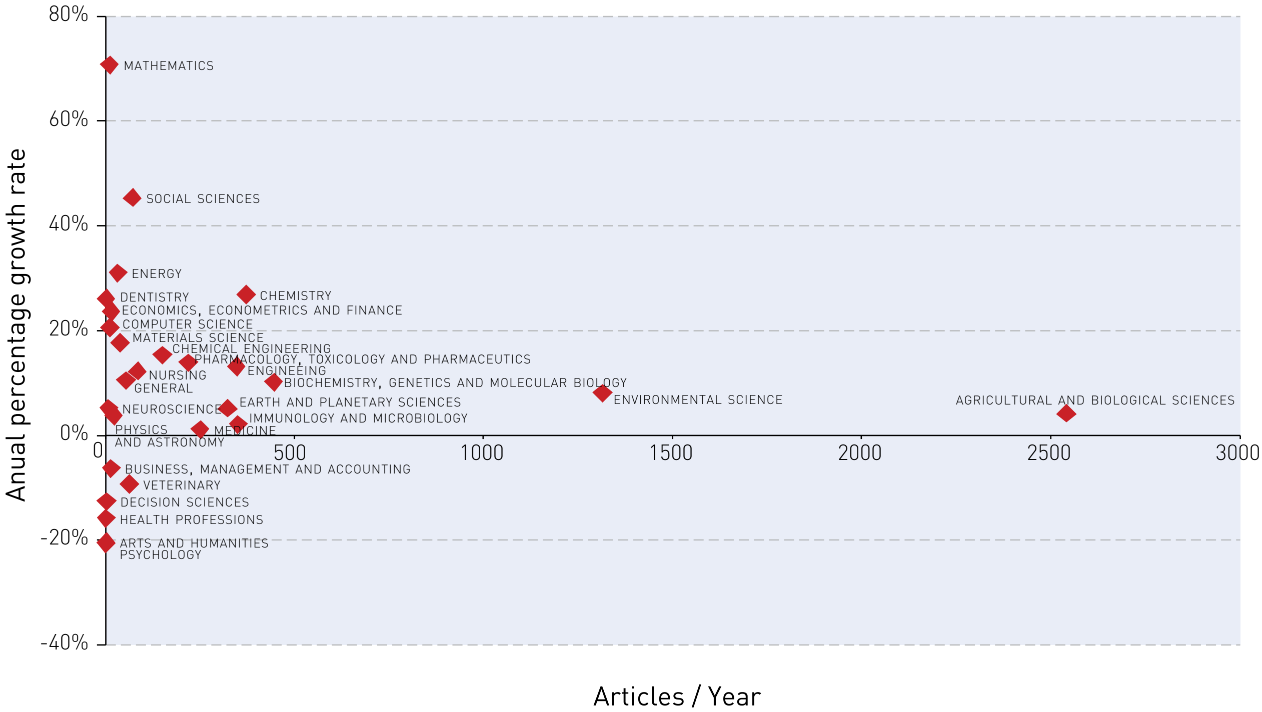

Figure 3b Annual growth rate of papers published relative to papers published per year in the diverse disciplines within the fields of water and food research during the period 2007-2011

SUBJECT AREA SHIFTS

In this section, articles in the water resources and water and food field respectively are analyzed in more detail by investigating the disciplines of origin of these articles. For this analysis, the standard Scopus subject classification was used.

When compared to the 2011 report "Confronting the Global Water Crisis Through Research (www.info.scival.com/resource-library), the contribution of economics to water resources research has stabilized, relenting its dramatic annual growth rate of 100%. Within water resources, computer science and mathematics have remained as high-growth fields, Figure 3a. This may reflect the continuing growth in statistical modeling and quantitative measurement to help address a range of questions around water resources. The growth in chemistry and the decline in chemical engineering in water resources research also stand out. This may be attributed to the importance of basic chemistry research in discerning the nature of water quality problems, before chemical engineering solutions can build upon these findings. The most highly cited papers in this area are focused on climate prediction and water purification. Meanwhile, agricultural and biological sciences, earth and planetary sciences and particularly environmental sciences continue to be the most prominent fields for water resources, although their growth rates are relatively slow, hovering around 5-10%. Environmental sciences account for nearly half the papers in water resources in recent years, as the global, regional and local impacts of development on the natural environment continue to be a major subject of scientific research. The significance of agricultural and biological sciences in water resources research, at nearly 1,500 papers a year, is likely due in part to the impact of agriculture on water supply and quality, and to the overlap of water resources and water and food research.

In the water and food nexus, mathematics and social sciences are growing fields, Figure 3b. Again, the growth in mathematics may be linked to an increase in statistical modeling and quantitative measurement tools used to examine current and future problems. Mathematics papers in water resources grew from 65 to 121 papers per year, totaling 492 papers over the period. The social sciences' contribution to the field grew from 84 to 230 papers per year, with a total of 802 papers, which may reflect the interdisciplinary nature of water and food research. The study of economics has critical bearing on agricultural production and food supply and consumption, while both human and physical geography impact greatly on issues of water use for food supply on global, regional and national scales. A sub-discipline of food geography – concerned with production, consumption and supply chains of food – has matured within the field of human geography over the last several decades. The many tools related to spatial analysis within geography and other social sciences are readily applied to water and food research. Water and food challenges and solutions are also impacted by public policy, such as governmental decisions on major irrigation projects, so political science is an important area of study. At the same time, traditional agricultural patterns and methods, sometimes dating back thousands of years, and the history of land that has been under cultivation for just as long, can be examined through social science disciplines of sociology and anthropology.

The study of environmental science also accounts for a large number of papers – approximately 1,300 per year – in water and food research, again related to the enormous impact of development on the natural environment, which can have a deep effect on agricultural land, irrigation and water runoff. The most highly cited papers in the water and food nexus investigate long-term observations and predictions related to environmental conditions of the biosphere, focusing on climate and system change.

PUBLICATION LANDSCAPE PER COUNTRY

An interesting comparison can be made between the United States and China, the most productive countries in terms of publication output. The United States produces approximately 1,400 papers annually in water resources research and 850 in water and food research. China produces nearly 800 water resources research articles a year at a growth rate of 15%, and approximately 300 articles on water and food research a year at a nearly 20% growth rate. US growth in research papers in these

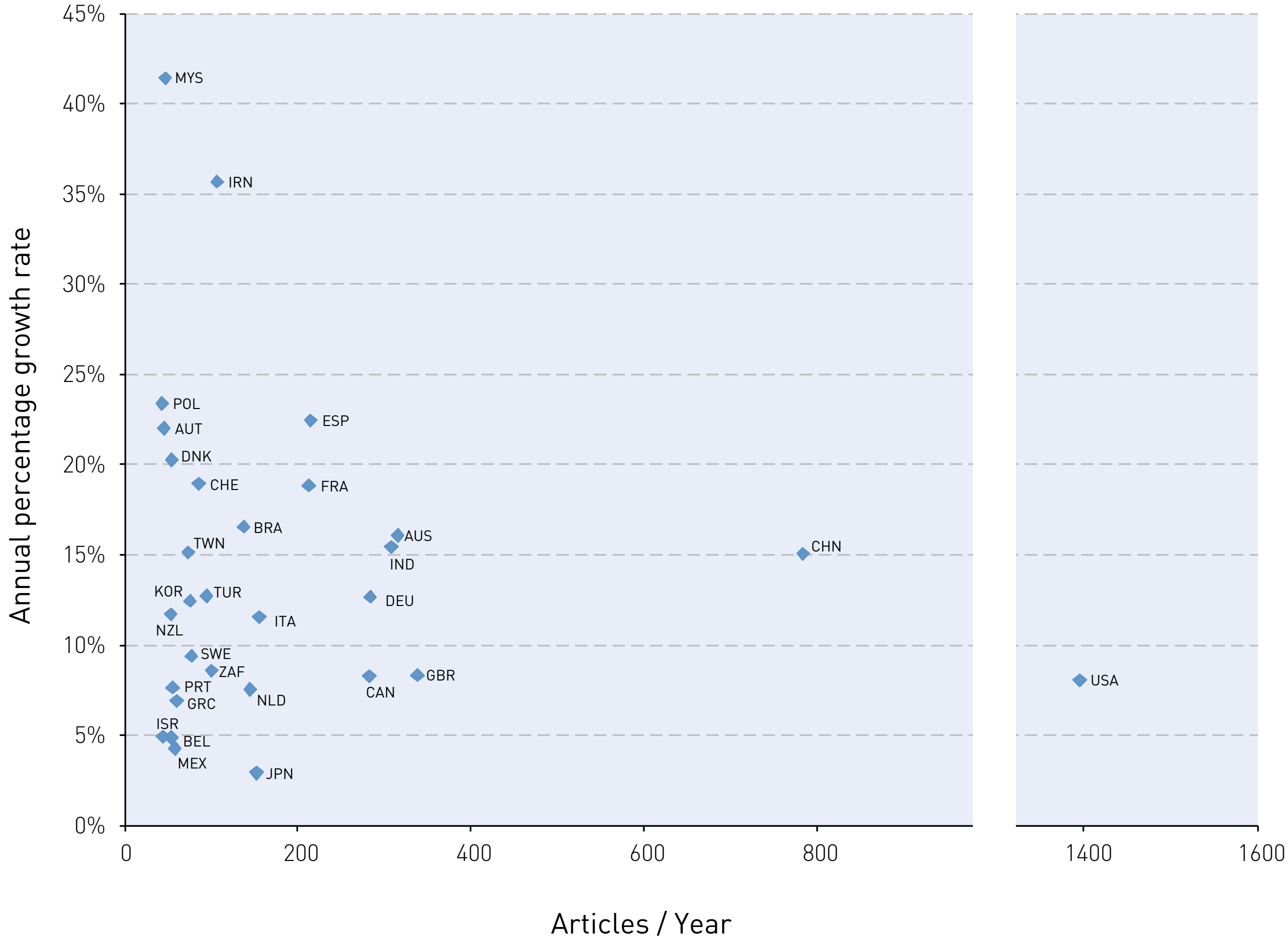

Figure 4a Annual growth rate of scientific publications (%) and the total number of papers per year during the fields of water resources for the period 2007-2011

areas is much lower, at approximately 8% and 1% respectively. The United States has a history of robust funding for scientific research, but China's investment in science has been escalating rapidly in recent years. With the urgency to improve food production in the most populous country in the world, and the growing impact of urban development on both natural and human environment, China's growing investment in both water and food and water resources research is a matter of exigency, Figure 4a and b.

Spain shows an increasing interest in water resources issues, with approximately 200 research articles published each year and growing at a pace of about 23% each year, which may be consistent with the growing problem of desertification affecting Mediterranean countries. However, Spain's research output is currently hampered by

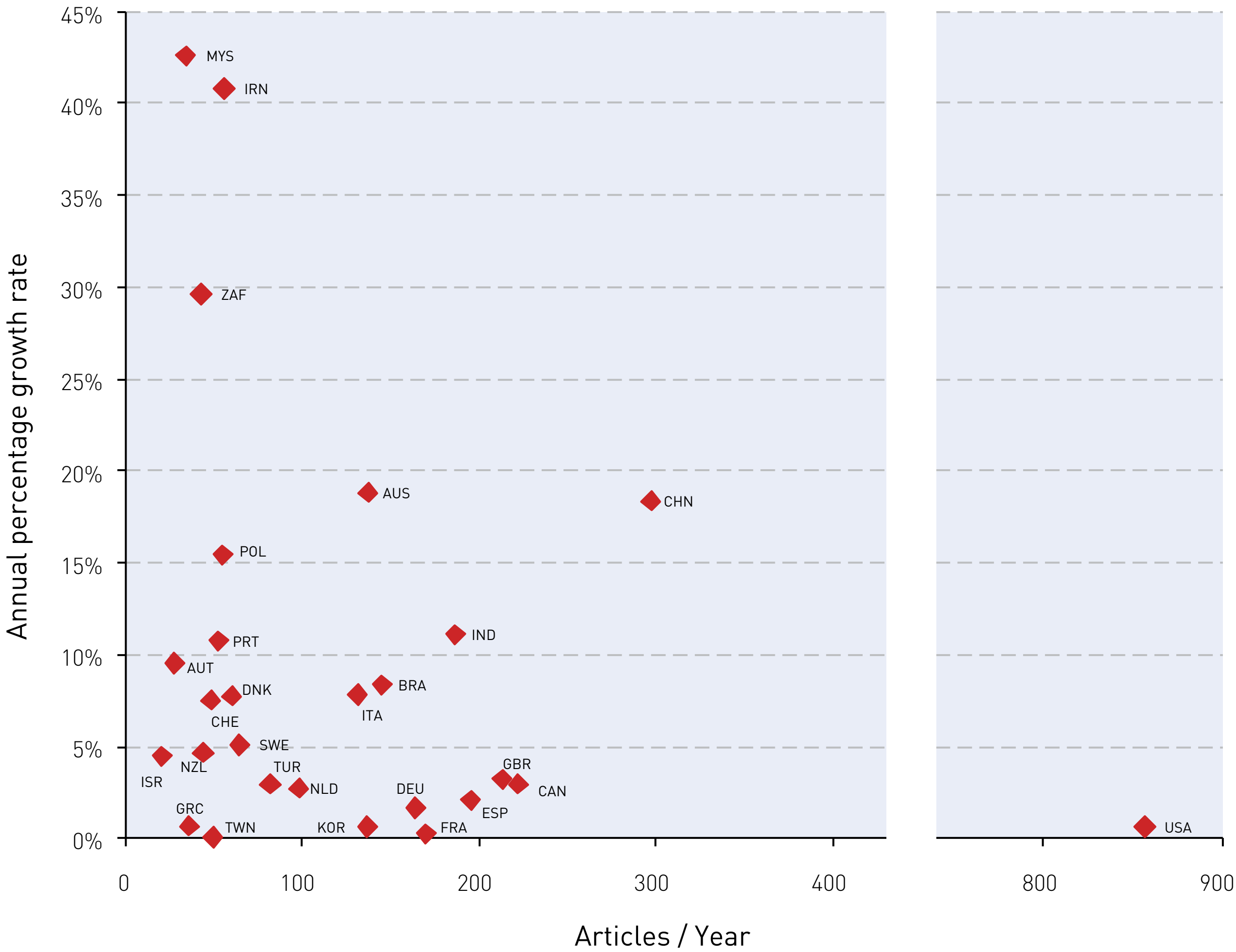

Figure 4b Annual growth rate of scientific publications (%) and the total number of papers per year during the fields of water for food for the period 2007-2011

the country's severe economic problems; research sustained a 22.5% budget cut in the first half of 2012 (Vela, C. 2012).

A striking change between this report and the 2011 water report is that Mexico and Russia do not exhibit a high growth rate any longer in their publication output, showing the fast rate of change in the field. Australia's double-digit growth in both water resources and water and food research reflect that country's commitment to funding earth and atmospheric sciences, along with its emphasis on greater research collaboration, particularly with Chinese researchers (Australian Department of Industry, Innovation, Science, Research and Tertiary Education, 2011).

Figure 5a Average number of citations per paper per country, relative to the total production of scientific publications per country in the field of water resources. Period considered: 2007-2011

COUNTRY IMPACT

The impact of a country's research in this study is measured by average citations per paper. The impact for water resources research is 4.9 citations per paper while for water and food research it is 5.8 citations per paper.

The United States has a high citation rate considering the vast number of papers it produces, with an average of seven citations per paper and 1,400 papers per year. China is very prolific but just below average in terms of citations per paper; India is similar in impact to China but less prolific. High performing countries in terms of impact are Sweden, Switzerland and the United Kingdom for water and food research, and the Netherlands, Switzerland and Belgium for water resources research,

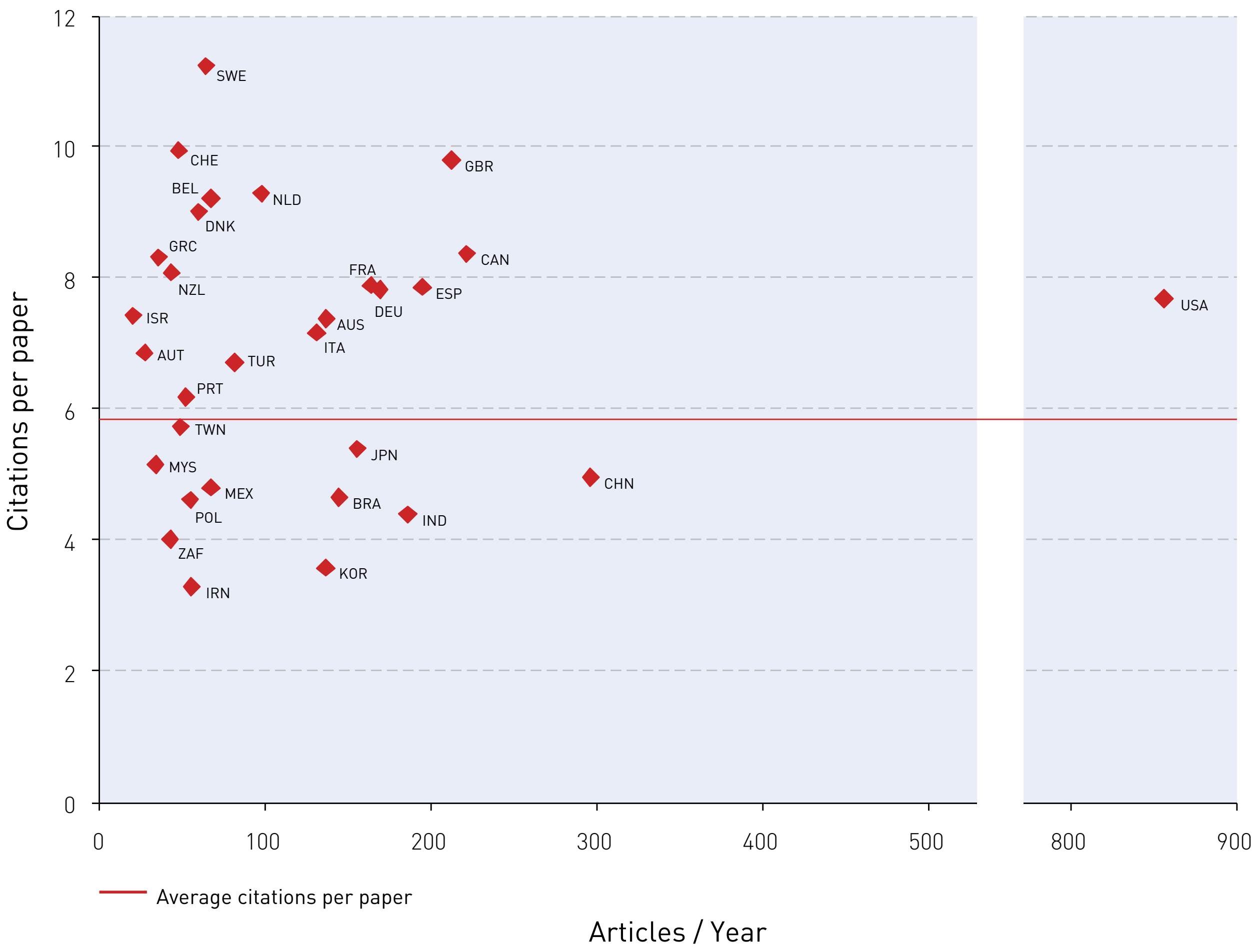

Figure 5b Average number of citations per paper per country, relative to the total production of scientific publications per country in the fields of water and food. Period considered: 2007-2011

Figure 5a and b. The fact that the impact of water resources research is so high in the Netherlands is not surprising, considering the country's historic struggle against the sea and that 20% of its area and 21% of its population are below sea level. The Netherlands also has the lowest per capita water usage and lowest leakage losses in its water systems of any other country in the world (Vewin, 2010).

With the highest number of citations per paper, Sweden published 79 papers in the water and food nexus in 2011. Sweden's most cited water and food research papers are related to human health and food and water contamination.

IMPACT OF INTERNATIONAL COLLABORATION

In order to investigate international collaboration two aspects are important: the percentage of papers in a specific country that are the result of international cooperation, and the impact of those papers. Generally, there will be greater need for cross-border collaboration in smaller countries compared to larger countries such as the United States, which mainly collaborates across state boundaries rather than national borders. Waterways that cross national borders or form national borders often engender problems that become the subject of bi-national or international water resources research.

For water resource research, countries with the highest levels of international collaboration are the Netherlands, Belgium, Denmark and Switzerland, averaging between 9-11 citations per paper and 60%-70% international collaborative papers, Figure 6a. These figures are very high compared to the average level of international collaboration at 44% across the Scientific, Technical and Medical (STM) publication history for countries such as Germany and France. Several other Western European countries also score comparatively high on international collaboration. These countries are notable for long-established academic and research institutions with high levels of scholarship where researchers have long-standing relationships with their peers at other regional institutions. Though the country may have a high-level of scholarship, there are not many institutions in these small countries, so top researchers naturally seek out their peers across borders.

Another notable country in water resources research is Mexico, with more than half of its research papers in this field resulting from international collaboration. This may be due to the significant work on transboundary water resource issues between institutions in Mexico and the United States, including on the Rio Grande, which forms 1,900 miles (3058 km) of the border between those two countries.

INTERNATIONAL COLLABORATION VS. CITATIONS PER PAPER FOR COUNTRIES

We found a significant correlation between international publication share (percentage) and citations per paper (0.769; $p<0.001$) when examining publication output per country; confirming the relationship between international collaboration and the impact (in terms of cites) of research, Figure 6a.

For water and food research, a similar pattern of impact in collaboration among Northern and Western European nations can be discerned, with Sweden standing out among others at more than 11 citations per paper and nearly 70% of its papers the result of international cooperation.

For the field of water and food the correlation between international publication share (percentage) and citations per paper is also significant, though the graph shows a somewhat wider scattering when plotting publication output per country (0.5228; $p<0.005$), Figure 6b.

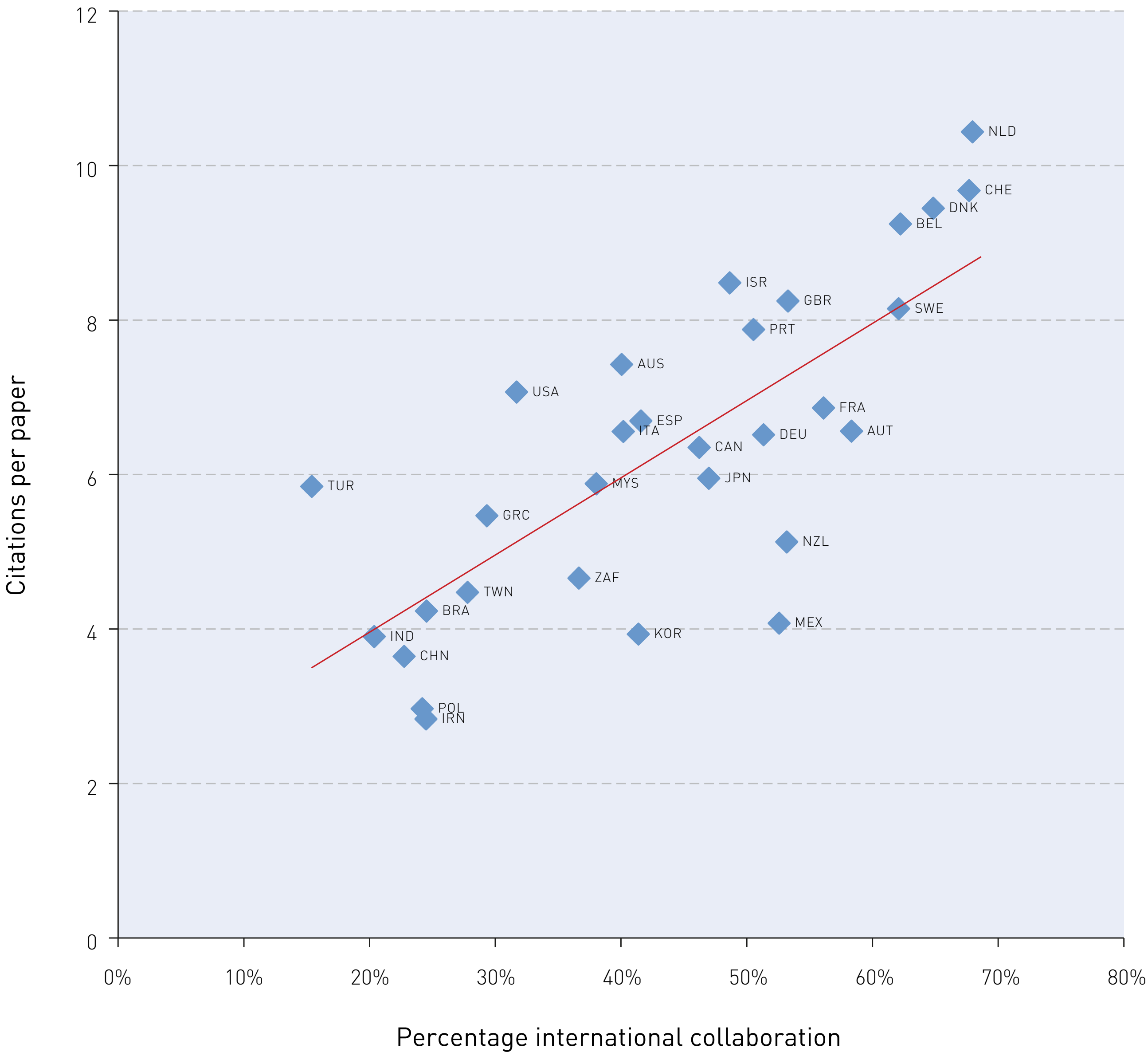

Figure 6a Water resources: average number of citations per paper per country, against percentage of papers co authored internationally per country. Period considered: 2007-2011.

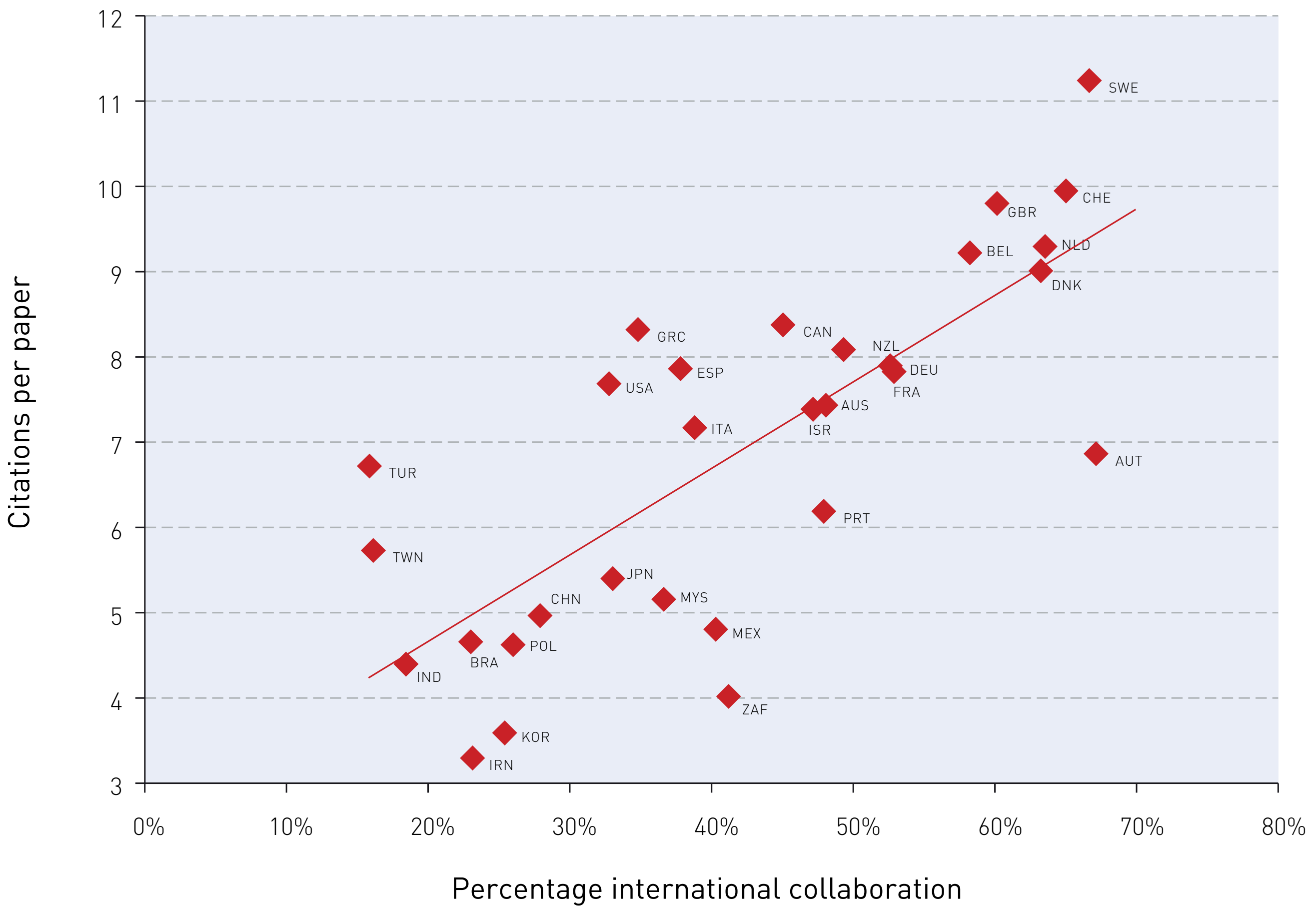

Figure 6b Water and food: average number of citations per paper per country, against percentage of papers co authored internationally per country. Period considered: 2007-2011

ACADEMIC-CORPORATE COLLABORATION

A specific form of collaboration, often beneficial in terms of citation impact, is that between academic and industry. In this study, we look at percentage of papers resulting from academic and corporate collaboration, as well as impact in terms of citations per paper. In both water resources research and the water and food nexus, more than 13% of Switzerland's research papers are collaborations with industry. The highest rate in any other country is 8%. Switzerland is home to several large food industries, and an association of these industries is dedicated to advancing food research. The Swiss Agency for Development and Cooperation sponsors global research projects related to water and food problems.

Table 1 Top twenty institutions ranked on citations per paper (cpp) in the field of water resources research during the period 2007-2011

	Affiliations	Av. no. of articles per year	CPP
1	University of Washington	24	15
2	Arizona State University	26	14
3	University of California, Berkeley	26	13
4	Delft University of Technology	27	12
5	Eidgenössische Technische Hochschule Zürich	23	11
6	University of Wisconsin Madison	23	10
7	Wageningen University	46	10
8	Centre National de la Recherche Scientifique (CNRS)	25	10
9	USDA Agricultural Research Service	30	10
10	Oregon State University	24	8
11	University of California, Davis	37	7
12	Colorado State University	26	7
13	University of Arizona	34	6
14	CSIRO Land and Water	33	6
15	University of Florida	25	6
16	US Geological Survey	57	6
17	Texas A & M University	33	6
18	US Environmental Protection Agency	22	6
19	University of British Columbia	27	6
20	University of Waterloo	22	6

INSTITUTES

Water Resources Research

An institute-level analysis shows the Top 20 most prolific institutes in water resources and water and food research, Tables 1 and 2.

The impact of each institute's research in these two fields is gauged by the average citations per article. In water resources research, the top 20 institutions with the most highly cited papers and prolific production of research stem from four countries: United States, Switzerland, the Netherlands and Australia, Table 1 and 2.

Three US universities – University of Washington, Arizona State University and University of California Berkeley – have the highest numbers of citations per paper with an average of 14. All three of these research universities are in the western United States, a region with some of the nation's and world's largest water projects and where water resources, whether for irrigation, urban use or hydropower, are critical to economic stability.

In Switzerland, Eidgenössische Technische Hochschule Zürich contributes highly to the field. From the Netherlands, Delft University of Technology and Wageningen University, and from Australia, CSIRO, are also among the top impactful contributors to the field. As the very existence of much of the Netherlands' land is dependent on keeping out the sea, the water resources expertise at Delft University of Technology and Wageningen University serve its country well.

The Chinese Academy of Sciences also has a sizeable output of water resources research articles. Headquartered in Beijing, the Chinese Academy of Sciences has more than 100 institutes throughout the country, plus a university and graduate school, each with numerous campuses. Membership in the Academy is the highest national honor for Chinese scientists. The size and academic strength of this institution explains its approximately 85 papers published each year on water resources research, which is critically important for the world's largest nation where development moves forward at a rapid pace. In water resources research, the Chinese Academy of Sciences has about four citations per paper, which is lower than most other institutions surveyed for this study.

Water and Food Research

In the field of water and food research, the number of countries contributing to this research nexus is more varied, with the United States, Spain, Canada, Brazil, China, Belgium, Finland, the Netherlands and Argentina all housing one or more of the top 20 most highly cited institutes.

Wageningen University is by far the most prolific institute in publishing research, with an average citation per paper count of over five, in the field of water and food research with approximately 39 papers each year.

Table 2 Top twenty institutions ranked on citations per paper (cpp) in water for food research during the period 2007-2011

	Affiliations	Av. no. of articles per year	CPP
1	University of Wisconsin Madison	16	11
2	Centre National de la Recherche Scientifique (CNRS)	19	10
3	US Environmental Protection Agency	17	10
4	CSIC - Instituto de Ciencias del Mar (ICM)	14	10
5	University of Massachusetts Amherst	16	10
6	Environment Canada	14	10
7	University of British Columbia	15	10
8	University of California, Davis	28	9
9	Katholieke Universiteit Leuven	14	9
10	Universidade de Sao Paulo	26	9
11	Cornell University	17	9
12	Chinese Academy of Sciences	22	9
13	Universiteit Gent	28	8
14	Oregon State University	14	8
15	Helsingin Yliopisto	15	7
16	Michigan State University	16	7
17	North Carolina State University	19	7
18	USDA Agricultural Research Service	28	7
19	Ohio State University	19	7
20	Texas A & M University	20	7
21	Wageningen University	39	7
22	University of Georgia	16	7
23	US Geological Survey	19	6
24	Consejo Nacional de Investigaciones Cientificas y Tecnicas	13	5
25	University of Guelph	19	5

CONCLUSIONS

- **General landscape:** Research into water resources and the critical water and food nexus is growing faster than the average 4% annual rate for all research disciplines. For both disciplines, more than half of all articles published are the result of international collaboration, which is merited for disciplines that seek solutions for global, regional and local problems. Both water resources and water and food research have increased their collaborative and interdisciplinary nature. In water resources research, the need for plausible scenarios that will enable the creation of sustainable environmental policies is reflected in the dramatic publication growth rate of computer science and mathematics in the discipline of water resources research. For water and food research, social sciences have also become one of the fastest growing fields, integrating the human factor more prominently in the picture, as most rural communities earn their living through some connection with agriculture.

- **Countries:** The scientific output shows a high pace of change, with the traditionally most productive country, US, exhibiting less growth on the number of papers published per year than China, the second most productive country. The fastest increases in research publication output are found in Malaysia and Iran for water resources and Malaysia, Iran and South Africa for water and food.

- **Impact:** Remarkably the research with the most impact did not come either from the most productive countries or from those exhibiting the highest growth rate in publication output. The most influential scientific papers originated from the Netherlands, Switzerland, Denmark and Belgium for water resources research, and Sweden, Switzerland, Great Britain, the Netherlands and Denmark for water and food research. Citations per paper are low in nations where growth in output is high but the level of international collaboration has remained low. Developing countries that face the most severe water problems need to be the focus of capacity development for research and technology in a collaborative and integrative manner.

- **Future trends:** Water research will not help solve the world's water challenges – particularly how to produce more food with less water – unless this research is translated into informed leadership decisions and sustainable action. Building capacity for action can be supported by improved knowledge exchange of research findings and technological best practices. To this end, advanced data analytics fueled by expanding computer power, and the growth in networking that's creating new horizons in sharing data and information, can facilitate global action in addition to global research. Bibliometric tools can reveal and interpret trends on the flow of information about water resources and the water and food nexus, bringing together researchers from around the world and matching water research to best practices in water development management by industry and government.

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APPENDIX

OFFICIALLY ASSIGNED CODE ELEMENTS

The following is a complete list of the current officially assigned ISO 3166-1 alpha-3 codes, using the English short country names officially used by the ISO 3166 Maintenance Agency (ISO 3166/MA):[4]

ABW	Aruba
AFG	Afghanistan
AGO	Angola
AIA	Anguilla
ALA	Åland Islands
ALB	Albania
AND	Andorra
ARE	United Arab Emirates
ARG	Argentina
ARM	Armenia
ASM	American Samoa
ATA	Antarctica
ATF	French Southern Territories
ATG	Antigua and Barbuda
AUS	Australia
AUT	Austria
AZE	Azerbaijan
BDI	Burundi
BEL	Belgium
BEN	Benin
BES	Bonaire, Sint Eustatius and Saba
BFA	Burkina Faso
BGD	Bangladesh
BGR	Bulgaria
BHR	Bahrain
BHS	Bahamas
BIH	Bosnia and Herzegovina
BLM	Saint Barthélemy
BLR	Belarus
BLZ	Belize
GIB	Gibraltar
GIN	Guinea
GLP	Guadeloupe
GMB	Gambia
GNB	Guinea-Bissau
GNQ	Equatorial Guinea
GRC	Greece
GRD	Grenada
GRL	Greenland
GTM	Guatemala
GUF	French Guiana
GUM	Guam
GUY	Guyana
HKG	Hong Kong
HMD	Heard Island and McDonald Islands
HND	Honduras
HRV	Croatia
HTI	Haiti
HUN	Hungary
IDN	Indonesia
IMN	Isle of Man
IND	India
IOT	British Indian Ocean Territory
IRL	Ireland
IRN	Iran, Islamic Republic of
IRQ	Iraq
ISL	Iceland
ISR	Israel
ITA	Italy
JAM	Jamaica
NLD	Netherlands
NOR	Norway
NPL	Nepal
NRU	Nauru
NZL	New Zealand
OMN	Oman
PAK	Pakistan
PAN	Panama
PCN	Pitcairn
PER	Peru
PHL	Philippines
PLW	Palau
PNG	Papua New Guinea
POL	Poland
PRI	Puerto Rico
PRK	Korea, Democratic People's Republic of
PRT	Portugal
PRY	Paraguay
PSE	Palestinian Territory, Occupied
PYF	French Polynesia
QAT	Qatar
REU	Réunion
ROU	Romania
RUS	Russian Federation
RWA	Rwanda
SAU	Saudi Arabia
SDN	Sudan
SEN	Senegal
SGP	Singapore
SGS	South Georgia and the South Sandwich Islands

BMU	Bermuda
BOL	Bolivia, Plurinational State of
BRA	Brazil
BRB	Barbados
BRN	Brunei Darussalam
BTN	Bhutan
BVT	Bouvet Island
BWA	Botswana
CAF	Central African Republic
CAN	Canada
CCK	Cocos (Keeling) Islands
CHE	Switzerland
CHL	Chile
CHN	China
CIV	Côte d'Ivoire
CMR	Cameroon
COD	Congo, the Democratic Republic of the
COG	Congo
COK	Cook Islands
COL	Colombia
COM	Comoros
CPV	Cape Verde
CRI	Costa Rica
CUB	Cuba
CUW	Curaçao
CXR	Christmas Island
CYM	Cayman Islands
CYP	Cyprus
CZE	Czech Republic
DEU	Germany
DJI	Djibouti
DMA	Dominica
DNK	Denmark
DOM	Dominican Republic
DZA	Algeria
ECU	Ecuador
EGY	Egypt
ERI	Eritrea
ESH	Western Sahara
ESP	Spain
EST	Estonia
ETH	Ethiopia
FIN	Finland
FJI	Fiji
FLK	Falkland Islands (Malvinas)
FRA	France
FRO	Faroe Islands
FSM	Micronesia, Federated States of
GAB	Gabon
GBR	United Kingdom
GEO	Georgia
GGY	Guernsey
GHA	Ghana
JEY	Jersey
JOR	Jordan
JPN	Japan
KAZ	Kazakhstan
KEN	Kenya
KGZ	Kyrgyzstan
KHM	Cambodia
KIR	Kiribati
KNA	Saint Kitts and Nevis
KOR	Korea, Republic of
KWT	Kuwait
LAO	Lao People's Democratic Republic
LBN	Lebanon
LBR	Liberia
LBY	Libya
LCA	Saint Lucia
LIE	Liechtenstein
LKA	Sri Lanka
LSO	Lesotho
LTU	Lithuania
LUX	Luxembourg
LVA	Latvia
MAC	Macao
MAF	Saint Martin (French part)
MAR	Morocco
MCO	Monaco
MDA	Moldova, Republic of
MDG	Madagascar
MDV	Maldives
MEX	Mexico
MHL	Marshall Islands
MKD	Macedonia, the former Yugoslav Republic of
MLI	Mali
MLT	Malta
MMR	Myanmar
MNE	Montenegro
MNG	Mongolia
MNP	Northern Mariana Islands
MOZ	Mozambique
MRT	Mauritania
MSR	Montserrat
MTQ	Martinique
MUS	Mauritius
MWI	Malawi
MYS	Malaysia
MYT	Mayotte
NAM	Namibia
NCL	New Caledonia
NER	Niger
NFK	Norfolk Island
NGA	Nigeria
NIC	Nicaragua
NIU	Niue
SHN	Saint Helena, Ascension and Tristan da Cunha
SJM	Svalbard and Jan Mayen
SLB	Solomon Islands
SLE	Sierra Leone
SLV	El Salvador
SMR	San Marino
SOM	Somalia
SPM	Saint Pierre and Miquelon
SRB	Serbia
SSD	South Sudan
STP	Sao Tome and Principe
SUR	Suriname
SVK	Slovakia
SVN	Slovenia
SWE	Sweden
SWZ	Swaziland
SXM	Sint Maarten (Dutch part)
SYC	Seychelles
SYR	Syrian Arab Republic
TCA	Turks and Caicos Islands
TCD	Chad
TGO	Togo
THA	Thailand
TJK	Tajikistan
TKL	Tokelau
TKM	Turkmenistan
TLS	Timor-Leste
TON	Tonga
TTO	Trinidad and Tobago
TUN	Tunisia
TUR	Turkey
TUV	Tuvalu
TWN	Taiwan, Province of China
TZA	Tanzania, United Republic of
UGA	Uganda
UKR	Ukraine
UMI	United States Minor Outlying Islands
URY	Uruguay
USA	United States
UZB	Uzbekistan
VAT	Holy See (Vatican City State)
VCT	Saint Vincent and the Grenadines
VEN	Venezuela, Bolivarian Republic of
VGB	Virgin Islands, British
VIR	Virgin Islands, U.S.
VNM	Viet Nam
VUT	Vanuatu
WLF	Wallis and Futuna
WSM	Samoa
YEM	Yemen
ZAF	South Africa
ZMB	Zambia
ZWE	Zimbabwe

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