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Additional Information

Trends in funding research and international collaboration on greenhouse gas emissions: a bibliometric approach

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Abstract

The Web of Science Core Collection platform was used to withdraw the papers included in this study. The studied period comprised from inception till 2018. Trends in research, journals of publication, subject areas of research, keywords most frequently used, countries of publication, international collaboration and trends of funding research was also analysed. A total of 3,902 articles were published, most of them (52.5%) during the five-year period 2014-2018. The area with the highest number of papers was Environmental Sciences (41%), followed by Energy Fuels (16.6%) and Engineering Environmental (15.7%). "Nitrous oxide emissions" was the most frequent word, followed by "Carbon dioxide emissions" and "Methane emissions". Other words that stood out were "Life cycle assessment", "Climate change" and "Environmental impacts". United States was the country with the highest productivity (27.9%), followed by China (12.8%), and United Kingdom (9.6%). There was a concentration of research in recent years, as more than 80% of the papers were published in the last 10 years. The journals that published the largest number of publications were devoted mainly to environmental studies (sciences and engineering), sustainable and green science and technology, energy and fuels, economics, and agriculture. Half of the works were published in Europe, and the other half between North America and Asia. Two thirds of the works (67%) were financed compared to a third that were not financed. The percentage of funded works has been increasing over the last decade, which is seen as an indication of the importance of GHGE.

Key words: Greenhouse gas emissions; international collaboration; funded research; impact of research.

Introduction

Since the beginning of the Industrial Revolution (in 1750) human activity has caused a 45% increase in atmospheric CO2 concentration from 280 ppm to 400 ppm in 2016. Anthropogenic CO2 emissions (produced by human activities) come from combustion of fossils, mainly coal, oil and natural gas, in addition to deforestation, and animal production.

Greenhouse gases (GHGs) are atmosphere components with ability to absorb solar as well as re-emitted radiation (Lacis et al. 2010). GHG emissions are leading to global warming, increase of the sea levels (Meehl et al. 2005; Raper and Braithwaite 2006), extreme weather conditions and modification of agricultural patterns (Patz et al. 2014). The definition of greenhouse gases (GHGs) includes CO2, methane, nitrous oxide and fluoride gasses that are generated and emitted during the different stages of the goods production chains. These emissions are added together with GHGs emissions that take place during the uptake of the activities (Hertwich and Peters 2009). Burning of fossil fuels, solid waste degradation, biological respiration and agricultural soil, in this order, are the main sources of GHG emissions (McKain et al. 2012; Yang et al. 2015).

It has been estimated that if greenhouse gas emissions continue at the current rate, the terrestrial surface temperature could exceed the 2ºC limit of global warming with potentially damaging effects on ecosystems and biodiversity, potentially endangering the subsistence of the people on the planet (IPCC, 2014). For these reasons, the study of GHGs has become a hot topic of global research.

As human activities continue to cause an increase in GHG emissions, the temperature of the earth surface is expected to rise, causing the global climates to change. More and more countries/territories have joined the study of GHGs, but a clear gap between developing and developed countries on GHG research was observed (Yang et al. 2013). However, in the past few years many developing countries started to be more and more involved in GHG research.

Furthermore, increased scientific activity was observed from these countries on the following topics: reduction of GHG emission, carbon sequestration, biotechnology and energy applications (van Vuuren et al. 2009; Figueroa et al. 2008; Englade and Jin 2006).

The control of the GHGE is part of the Sustainable Development Goal 13 established by the United Nations in 2015, entitled "Take urgent action to combat climate change and its impacts" (The Paris Agreement, 2015). As early as 1992, the Earth Summit of Rio de Janeiro established a framework of action aimed at stabilizing atmospheric concentrations of greenhouse gases (GHGs) to avoid "dangerous anthropogenic interference with the climate system". Member states expressed their concern about the continued increase in GHGs and the vulnerability of all countries to the adverse effects of climate change, as well as the need for enhanced international collaboration to increase effectiveness in combating climate change (IPCC, 2014). Climate change is affecting the entire planet, and the levels of CO2 and other greenhouse gases in the atmosphere have increased dramatically. The Paris Agreement (2015) aimed to strengthen the global response to the threat of climate change by keeping the global temperature increase during this century below 2ºC. In addition, climate change affects the poorest in developing countries. However, developed countries are responsible for 85% of global warming. In contrast, 140 developing countries only generate 10% of the planet's warming. There is great inequity from the point of view of those who are contributing the most to the problem and those who suffer the most from the consequences (IPCC 2014).

An increase in the efforts made at institutional level in terms of carbon management and therefore GHG emission reduction (including carbon accounting) has been noticed in the scientific literature over the past years. Institutions such as private companies (Penela et al. 2009; Lee 2011) and universities (Parsons 2009) or entire regional and national economic and public sectors such as health care (Chung and Meltzer 2009), fisheries (Iribarren et al. 2010) or tourism (Dwyer et al. 2010) have been intensely investigated. A number of methodological options have been proposed, providing a wide variety of specific approaches towards carbon management.

The analysis of research trends through bibliometric studies provides valuable information of the scientific research and its development over time for a particular field of study. The aim of this study was to analyse the scientific productivity and impact of the research on GHG emissions, as well as the influence of funding on global research through bibliometric analysis of articles included in the Web of Science Core Collection (WoS) database. The joint analysis of productivity, collaboration, scientific impact of research and funding provides a global and integrated view of the research applying to this particular field.

2. Methods

The analyzed articles were withdrawn from the Web of Science Core Collection (Clarivate Analytics) platform. For more accurate results, the terms "Greenhouse gas emissions" OR "Green house gas emissions" OR "GHG" were used in the search, established in the "title" field. The studied period comprised from inception till 2018. Reading the titles and abstracts of the retrieved papers testified that all of them were relevant. Only research papers and reviews were analysed.

The records obtained were processed using an Access (Microsoft) relational database (Redmont, Washington, USA). The journals in which the articles were published, the thematic categories of the journals, the keywords most frequently associated with these topics, countries of publication of the journals and most cited articles were identified. Trends of funding research were also analyzed, information that WoS offers in indexed registers from 2008 (Paul-Hus et al. 2016).

In addition, the number of co-occurrences between countries was quantified through the social networks analysis (SNA), from which indicators of centrality and prestige in the network have been extracted. These indicators identify the countries in the network with the highest “degree” (i.e., the countries that have more collaborations with other countries and are therefore considered more

active), with the highest “closeness” (i.e., which countries have a shorter path when establishing contacts with other countries and account for the speed of contact) and finally the “betweenness” (which refers to which countries act as a bridge with other countries and therefore indicate their possibility to have a control over the contacts). The graphical representation of the networks of collaboration between countries was performed with Pajek software (Batagelj and Mrvar 2002). The VOSViewer software (Leiden, The Netherlands) was used to build the global collaboration maps. In these maps, the thickness of the lines connecting the countries and the number of articles published in collaboration is proportional. Impact factor data of the journals corresponds to the 2017 edition of the Journal Citation Reports (JCR). However, data on citations corresponds to the 12 of February 2019.

3. Results

3. 1. General data

During the period under review, 3,902 articles were published. Fig. 1 shows the evolution of the articles by five-year periods. As can be seen, most of the papers (2,048; 52.5%) were published during 2014-2018, and 1,207 (30.9%) during the five-year period 2009-2013, so that almost all the papers (3,255; 83.4%) were published in the decade 2009-2018.

3. 2. Journals of publication

The 18th most prolific journals, along with the number of citations, 5 years’ impact factor, subject areas, countries and funding are presented in Table 1. The journal that published the largest number of papers was the *Journal of Cleaner Production* (603), followed by *Energy Policy* (536) and, *Agriculture Ecosystems & Environment* (228) and *Environmental Science Technology* (222), with considerably fewer papers. The ranking by number of citations was headed by *Energy Policy* (15,604), followed by *Agriculture Ecosystems & Environment* (8,616), *Environmental Science Technology* (8,476) and *Journal of Cleaner Production* (8,445). However, the average citations per paper ranking

was led by *Climatic Change* (42.15). The three journals with the highest 5-years impact factor were *Renewable & Sustainable Energy Reviews* (10.093), *Applied Energy* (7.888) and *Journal of Cleaner Production* (6.352). The list of journals included in Table 1 were included in the first quartiles of their respective subject areas, except for the journal Sustainability, which was included in three subject areas in the third quartile. With respect to the most prolific countries in these journals, the United States was the most productive country in 10 of the journals included in the table, followed by China with 8 and Germany with one. Other countries that stand out were France, The Netherlands, Finland, Japan, Canada, Australia, United Kingdom, Switzerland, South Korea, Austria, Sri Lanka, India and Spain. The journals in which the greatest number of funded works were published were *Science of the Total Environment* (64; 82.1%), followed by *Environmental Science Technology* (92; 41.4%) and *Environmental Research Letters* (44; 40%), and the journals in which the fewest funded papers were published were *Energy Conversion and Management* (6; 93.5%), followed by *Ecological Economics* (92.2%) and *Energy Policy* (49; 90.9%).

3.3. Subject content and topics

Table 2 shows the thematic areas the journals belong to. The area with the highest number of papers was Environmental Sciences (1,629; 41%), followed by Energy Fuels (647; 16.6%) and Engineering Environmental (614; 15.7%). The number and percentage of works funded was almost three quarters in the areas of Agronomy (103; 72%) and Ecology (167; 71.7%) and somewhat less in Soil Science (144; 69.9%). Conversely, the areas whose work was least funded were Economics (129; 75%), Environmental Studies (236; 56.9%) and Thermodynamics (72; 56.7%).

Most frequent key words included in the analysed papers and grouped according to continents can be seen in Table 3. "Nitrous oxide emissions" was the most frequent word in the works published in all continents. The second place was for "Carbon dioxide emissions" in Europe, North America and South America, while in Africa, Asia and Oceania it was "Methane emissions". Other words that stood out with a frequency greater than 500 appearances were "Life

cycle assessment", "Climate change" and "Environmental impacts". Fig. 2 shows a world map with the clouds containing the most frequent words in each continent.

3. 4. Research by countries

Twelve countries published more than 100 papers (Table 4). United States was the most productive country (n=1,076; 27.9%), followed by China (n=492; 12.8%), United Kingdom (n=368; 9.6%), Canada (n=343; 8. 9%) and Australia (n=286; 7.4%). By citations, United States was the leading country (n=29,167; 35.9%), followed by United Kingdom (n=11,713; 14.4%) and Canada (8615; 10.6%), occupying China the fourth position (n=8,224; 10.1%). Taking into account the ratio citations per paper, the ranking was headed by Austria (C/A=48.3), followed by Switzerland (C/A=39.2), Ireland (C/A=36.1) and Norway (C/A=35.6). Fig. 3 shows the world map of countries' productivity. Again it highlights Canada, United States and Brazil in America; United Kingdom, Germany, The Netherlands, Spain, Sweden and France in Europe; China and Japan in Asia and Australia in Oceania. Fig. 4 shows a graphical evolution of papers and citations by continents according to 5-years' periods.

3.5. International collaboration

United States was the country that has published more works in collaboration with other countries (Fig. 5). The country with the largest number of collaborative papers was China (78 papers), followed by United Kingdom (58), Canada (55), Australia (29), The Netherlands (29), Japan (29) and Germany (26). China also collaborated intensively with Canada (34), United Kingdom (34) and Australia (26). Moreover a more marked triangle of collaboration between the United States, China and the United Kingdom can be seen in the collaboration network (Fig. 6). At European level, United Kingdom is the country with more intense, followed by Germany. Considering the centrality indicators, the most active countries with the highest degree of centrality and closeness in the network are United States (degree =52, closeness = 0.861) and United Kingdom (degree = 40, closeness = 0.738). However, the countries that bridge

the gap with other countries (betweenness) are Australia (betweenness = 6,656) and Switzerland (betweenness = 3,584) (Table 5).

3.6. Funded research

The percentage of works funded during de 2009-2018 decade can be seen in Table 6. Two thirds of the works (67%) were financed compared to a third that was not financed (33%). This percentage increased from 46.3% in 2009 to 71.6% in 2018. 2017 was the year with the highest percentage of funded work (76%). Trends in funded and unfunded research can be seen graphically in Fig. 6, as well as the evolution of citations received.

More than half of the works were published in Europe (n=2,019; 52.4%), just over a third in North America (n=1,468; 38.1%) and almost a third in Asia (n=1,165; 30.3%) (Table 7). The other continents published percentages ranging from 9% in Oceania, 4.5% in South America and 2.8% in Africa. The number of citations received was almost similar between Europe and North America, with a small advantage for Europe (45.3% versus 44.7%). However, the ratios citations/article were higher in North American works (24.7) than in the other continents, where it was around 18 citations per article, except in Asia, that was 14.6. The production of BRIC countries (Brazil, Russia, India, China and South Africa) was of 767 papers (19.7% of the total), while global citations of these countries represented 11%.

The percentage of works funded was highest in Asia (61.7%) and South America (61%), followed by North America and Oceania with a similar percentage close to 56%. Europe was the continent with the lowest percentage of funded works (43.5%).

The citations per paper ratio was somewhat higher in funded papers than in non-funded papers (19.9 versus 18.1). The ratio of citations per paper was higher than 20 points in North America, Europe, Oceania and Africa. In non-funded work, the ratio was higher in North America (29.3) and South America (23).

3.7. Most cited papers

Table 8 shows the 25 most cited papers. The paper with the highest number of citations was published in *Science* in 2008 and received 2.414 citations, with an average of 241 citations per year. The paper was entitled “Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change” and was published by US researchers from several institutions. No information about possible funding was found for this paper. The second most cited paper entitled “Greenhouse-gas emission targets for limiting global warming to 2 degrees C” was published in 2009 in *Nature*. This paper received 1.063 citations, 118 per year, and was published by a team of researchers from Germany, Switzerland and United Kingdom. In the paper, the authors acknowledge the German Ministry of Environment for financial support, the German Academic Exchange Service (DAAD) and The Natural Environment Research Council as the UK's leading public funder of environmental science. Two papers with about 750 citations followed, one signed by US researchers and published in *Nutrient Cycling in Agroecosystems* and the next signed by Austrian researchers and published in *Climatic Change*. As can be seen in the table, some papers obtain an average of annual citations that would place them in different positions than they occupy according to the total number of citations received. Only one third of the published works have received funding.

4. Concluding remarks

This work contributes to the development of scientific knowledge about GHGE because it identifies important characteristics of research in this field integrating bibliometric and social network analysis. It has allowed for the identification of the relevant characteristics of the world-wide research on GHGE, among them, the evolution of the research on the subject, the journals of publication and its impact, the geographical distribution, the main topics of research and the assigned funding. The data was sourced from the Web of Science Core Collection database, usually chosen as preferential in this type of studies as it includes the journals with the greatest international impact (Mongeon 2016;

Martin-Martin et al. 2018; Chavarro et al. 2018). The dissemination of this kind of information concerning GHGE may contribute to stimulate an advanced level of collaboration within the researchers and to generate a favourable atmosphere for discussion. On the other hand, these discussions would be of noteworthy relevance and would act as a first step to supervise forthcoming advances in this important field (Husain and Mushtaq 2015).

One of the most striking results of the study is the growing number of articles published and their concentration in recent years, as more than 80% were published in the last decade. This growth appears to be in line with the great interest and concerns observed worldwide about GHGE and a big body of research to achieve its reduction was observed. The growth of publications in recent years has also occurred in other areas and in other topics considered trending topics because of their social or economic relevance at a global level. This was the case for: climate change (Haunnschild et al. 2016; Aleixandre et al. 2017), biotechnology (Dalpe 2002), global warming (Aleixandre-Tudo et al. 2019), renewable energies (Hache and Palle 2019; Aleixandre-Tudo et al. 2019), forest ecology (Song and Zhao 2013) or water use efficiency (Aznar-Sanchez et al. 2018), among others.

As noted, the most prolific journals were devoted mainly to several scientific areas, including environmental studies (sciences and engineering), green and sustainable science and technology, energy and fuels, economics, agriculture and ecology. These are journals that tend to have a high impact factor which places them in the top quartiles of the JCR thematic category rankings. The diversity of the thematic categories found in the journals where the articles were published contributes to an understanding of the complexity of the GHGE problem.

Regarding the thematic categories in which the journals were classified, it is not surprising that the areas related to the environment and fuels have been the ones that monopolized a greater number of works, given the close relationship that GHGE has with these areas. On the other hand, the thematic analysis that was deduced from the keyword ‘evaluation’ revealed which were the gas

emissions to which a greater research effort was dedicated, as well as the aspects related to these emissions. The main emissions were nitrous oxide, carbon dioxide and methane, which correspond to the current emission figures for these gases worldwide (United States Environmental Protection Agency 2019). Research on these emissions was linked to phenomena and aspects such as life cycle assessment, climate change, environmental impact, global warming, carbon footprint, land use change, management and mitigation.

As we have seen, half of the works were published in Europe, just over a third in North America and almost a third in Asia, but the number of citations is similar in Europe and North America, which means that publications from North America have greater impact in terms of citations than the European ones. This phenomenon, which has been called "citation advantage", could be due to the bias of US publications in the WoS database (Gingras and Khelfaoui 2018), but as suggested it could also be due to the consequences for the European Union of the integration of new Eastern European countries whose publications have a lower impact than those of Western Europe (Leydesdorff et al. 2014). With regards to international collaboration, it is not surprising that United States, the country that collaborates the most with other countries in the world, collaborates above all with China, since these two countries produce the greatest emissions of greenhouse gases, especially carbon dioxide (Boden et al. 2017).

The extent of funding for GHGE works can be considered high, as two thirds have received it. In addition, the percentage of funded works has been increasing over the last decade, which can be seen as an indication of the importance of GHGE. Funding benefits most thematic areas almost equally. As seen, the citations per paper ratio was somewhat higher in funded papers than in non-funded papers. Although in our work this relationship has not stood out strikingly, a direct relationship between funding and impact of the papers have been reported in other studies (Jacob and Lefgren 2011; Goek et al. 2016; Yan et al. 2018).

The topics specifically dealt with in the most frequently cited works make it possible to find out which issues attract the most interest in research. As can be

seen, the most relevant topics were: the increase in greenhouse gases produced by the change in the use of cultivated land (land use change) to produce biofuels (Searchinger et al. 2008); greenhouse-gas emission targets for limiting global warming (Meinshausen et al. 2009); Intergovernmental Panel on Climate Change from the United Nations guidelines for national GHGE inventory methodology (Mosier et al. 2009); Representative Concentration Pathways (a set of pathways on GHG concentration and emissions designed to support research on impact and potential policy responses to climate change scenarios) (Riahi et al. 2011); GHGE from crop production systems (Snyder et al. 2009); public health benefits of strategies to reduce GHGE such as urban land transport, hybrid vehicles and food chain (Woodcock et al. 2009; Samaras and Meisterling 2008); inventories and databases (Dodman 2009; Zhang et al. 2000); climate impacts of emissions (Shine et al. 2005) or global warming (Fearnside 2000; Shine et al. 2005). The fact that six of the 25 papers were published in high-impact multidisciplinary journals such as *Science*, *Nature* and *Lancet* shows evidence of the current importance of greenhouse gas emissions. Probably the authors of these papers chose these journals to try to communicate their message to a wider audience than the more narrowly focused specialized journals. In this way their findings potentially influence scientists in multiple areas of research as the high citation rates of these journals provide a potentially wider dissemination and greater visibility.

International cooperation involving technology transfer between rich and poor countries and the provision of funds that contribute to sustainable development is essential to enhance the reduction of GHGE. In parallel, there is a need to increase investment in research on environmentally safe technologies and the use of renewable energy, as well as basic, applied and experimental agricultural research to help farmers and trade adapt to change. Appropriate training of scientific and technical workforces in these technologies and the renewal and modernization of equipment and facilities are also of vital importance. In addition, there is a need to invest in public education to promote efficient energy use in households, particularly renewable energy, and to use public transportation. Independent global bodies such as the United Nations

can advise and help develop plans and policies to reduce GHGE to appropriate levels.

5. Limitations and future work

This paper contains some limitations that must be considered during the interpretation of the results. First of all, the papers were extracted from the Web of Science platform and although it is possible that other databases such as Scopus include some relevant work, it should be borne in mind that WoS is one of the most important sources for the analysis of scientific literature and that it indexes the world's highest quality journals. Second, WoS only includes funding information that has been published in English. It is therefore possible that articles published in languages other than English may not have collected this information. However, most of the works indexed in WoS are in English.

Future work in this line should analyse the evolution of the indicators obtained in this work in future periods and contrast them. On the other hand, it could identify the groups that are at the forefront of research in this field and their collaborative relationships on specific GHGE issues.

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