Global trends in nitrate leaching research in the 1960-2017 period

Francisco M. Padilla[1,3], Marisa Gallardo[1,3], Francisco Manzano-Agugliaro[2,3,*]

[1]Department of Agronomy, University of Almeria, Almeria, Spain

[2]Department of Engineering, University of Almeria, Almeria, Spain

[3]CIAIMBITAL Research Centre for Mediterranean Intensive Agrosystems and Agrifood Biotechnology, ceiA3 Agrifood Campus of International Excellence, University of Almeria, Almeria, Spain

*Corresponding author: fmanzano@ual.es, Universidad de Almería, Carretera de Sacramento s/n, 04120 La Cañada de San Urbano, Almeria, Spain

Running title: Trends in nitrate leaching research

Abstract

Nitrate leaching is the process whereby the nitrate (NO_3^-) anion moves downwards in the soil profile with soil water. Nitrate leaching is commonly associated with chemical nitrogen (N) fertilizers used in agriculture. Nitrate leaching from different sources and contamination of surface and groundwater is a global phenomenon that has prompted social and political pressure to reduce nitrate leaching and contamination of water bodies. This bibliometric study analyzed global trends in nitrate leaching research. The results showed a rising interest in the last decades on this topic; given the growth tendency over the last years, it was envisaged that the importance on nitrate leaching research will continue increasing in the future. Knowledge on nitrate leaching was mostly disseminated through scientific publications (90% of total documents recovered), both as journal articles and reviews, classified in the Scopus database in the Agricultural, Biological and Environmental Sciences areas. Most publications dealt with soil nitrogen losses from agroecosystems and farmlands and the associated impact on the environment; they were published in journals with a focus on the influence of anthropogenic and soil-crop-animal systems in the environment, and on how such changes in the environment impact agroecosystems. Most documents published on nitrate leaching were indisputably from the United States, followed by China, the United Kingdom and Germany. An analysis of the main keywords showed an overall dominance of the soil nitrogen cycle, fertilizer use in agriculture and water quality aspects. The evolution of main crop species involved in nitrate leaching research showed a rising relevance of research conducted on maize, wheat and grasses from 1990 onwards. The most productive institutions in terms of number of documents dealing with nitrate leaching research, h-index and total citations, were located in the United States, China and the Netherlands. The United States Department of Agriculture stood out, followed by the Chinese Academy of Sciences and Wageningen University and Research. There were clusters of institutions with intercontinental interaction, on nitrate leaching research, between institutions from Europe, Asia and South and North America. Overall, this study has highlighted, from a bibliometric perspective, the rising concern on nitrate leaching. Progress in this field has been made particularly on the impact of the soil-plant-animal system on the environment and agroecosystems, and on fundamental and applied aspects of plant-soil interactions with an emphasis in cropping systems.

Keywords: agriculture; drainage; environmental impact; fertilizer; groundwater; Scopus

Abbreviations: IF, impact factor; JCR, Journal Citation Report; N, nitrogen; N_2, dinitrogen gas; N_2O, nitrous oxide; NH_3, ammonia; NH_4^+, ammonium; NO_2^-, nitrite; NO_3^-, nitrate.

1. Introduction

Nitrogen (N) is an essential element for all life process in plants (Hester et al., 1996); it is a structural component of all proteins, including enzymes involved in photosynthesis, growth and development, and is an important component of nucleic acids and chlorophyll (Gianquinto et al., 2013; Lawlor et al., 2001). At the same time, N is one of the major limiting nutrients in most ecosystems and agricultural soils (Vitousek et al., 1997), which commonly contain between 0.1% and 0.6% N in the top 15 cm, depending on the soil type (Cameron et al., 2013). Soil N is present in four major forms: (a) organic matter, such as plant material, fungi and humus; (b) soil organisms and microorganisms; (c) ammonium ions (NH_4^+) held by clay minerals and organic matter, and (d) mineral N forms in soil solution, including NH_4^+, nitrate (NO_3^-) and low concentrations of nitrite (NO_2^-) (Cameron et al., 2013; Hester et al., 1996). However, any N in the soil that is available to plants is likely to be present as NO_3^-, or as NH_4^+, which microbes of the soil soon convert to NO_3^- (Hester et al., 1996). Mineral N forms are mainly prone to losses through: (a) ammonia (NH_3) volatilization (i.e., the loss of gaseous NH_3 from the soil surface), (b) denitrification and gaseous losses of nitrogen (mainly as dinitrogen gas (N_2) and nitrous oxide (N_2O)), and (c) leaching (i.e. removal in drainage water) (Cameron et al., 2013; Gillette et al., 2018). Nitrogen losses by leaching occur mainly in the NO_3^- form but some leaching of NH_4^+ may occur in sandy soils (Moreno et al., 1996). It is leaching of the NO_3^- anion that is analyzed in this article.

Figure 1 summarizes the nitrogen cycle and the nitrate leaching process, whereby the NO_3^- anion moves downwards in the soil profile with soil water (Gianquinto et al., 2013; Hester et al., 1996). Nitrate is completely soluble in water and is prone to be leached, because the negatively-charged NO_3^- anion is repelled by negatively charged surfaces of clay minerals and soil organic matter. This keeps nitrate dissolved in the soil solution and moves freely in the soil by percolating rainfall or irrigation (Gianquinto et al., 2013; Hester et al., 1996).

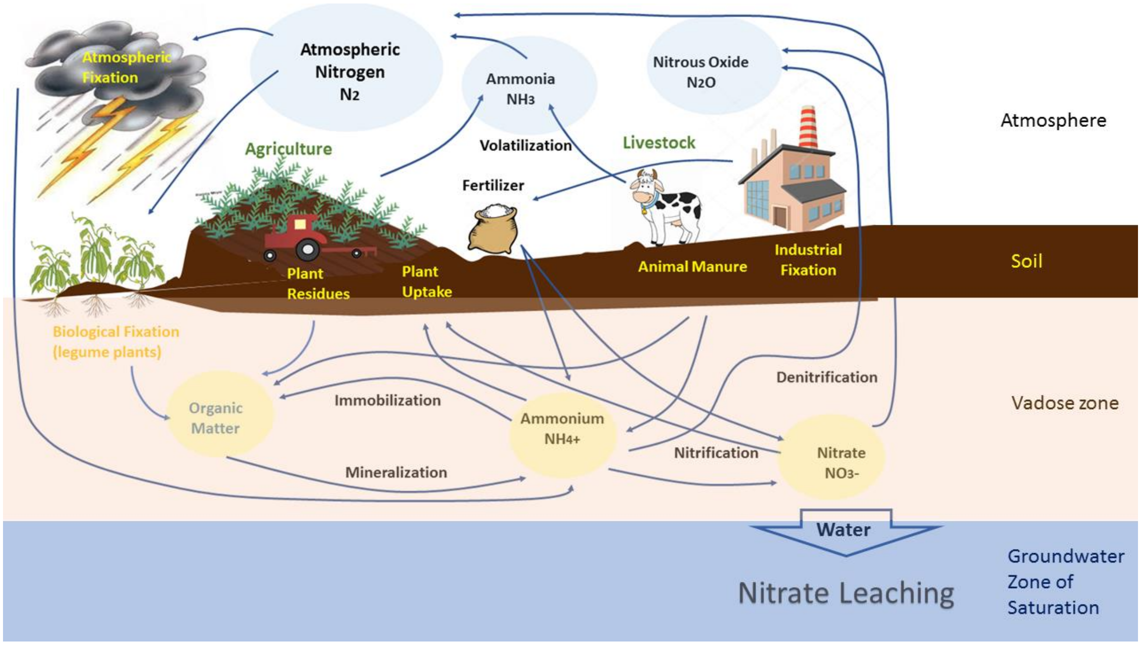

Figure 1. The nitrogen cycle and the nitrate leaching process.

Nitrate leaching is commonly associated with chemical fertilizers used in agricultural crops (Cameron et al., 2013; Fowler et al., 2013; Lemaire and Gastal, 1997; Pratt, 1984), but some of the soil nitrate that is vulnerable to leaching is produced by microbes that break down plant residues and other nitrogen-containing residues in the soil (Hester et al., 1996). Localized sources of nitrate leaching can be animal organic waste effluents; some of these being dairy shed effluent, dairy pond sludge, pig slurry or sewage sludge (Di and Cameron, 2002; Power and Schepers, 1989). Published data indicate that nitrate leaching losses typically would follow the order: forests < cut grassland < grazed pastures < arable cropping < ploughing of pastures < horticultural and vegetable crops (Cameron et al., 2013; Di and Cameron, 2002). Nitrate leaching losses are generally lowest from forest systems because there is usually zero or only low rates of N fertilizer applied, and the N is cycled efficiently through the forest ecosystem (Di and Cameron, 2002). However, logging and burning of forests can release large amounts of N that can be leached or washed off slopes through soil erosion (Cameron et al., 2013). In grassland systems, NO_3^- comes from fertilizers (i.e., mineral or urea-based fertilizers) or from mineralization of soil organic N. Grasslands that are mown or cut for hay or silage have very low nitrate leaching losses, because grass and pasture plants are usually very efficient at taking up the N applied in fertilizer or N fixed by legumes such as clovers that are grown in the pasture sward (Cameron et al., 2013). The nitrate leaching potential increases when grassland is grazed rather than harvested. This is because a large proportion of the N ingested by the grazing animals is excreted back to the soil in the small concentrated areas of urine and dung patches (Minet et al., 2018). However, the low animal stocking density of extensive systems means that the whole of the grazed field is not covered by urine patches (Cichota et al., 2018). The overall nitrate leaching loss is thus somewhat diluted by the lower leaching loss from the inter-urine patch areas (Cameron et al., 2013). Nitrate leaching losses are generally greatest from horticultural crops because of the higher rates of N fertilizer that are used in these crops, the shallow root systems of horticultural plants and the low nutrient use efficiency (Fereres and Goldhamer, 2003; Goulding, 2006; Meisinger et al., 2008; Pratt, 1984; Thompson et al., 2007b). Indeed, intensive vegetable production systems are commonly associated with significant nitrate leaching loss worldwide (Goulding, 2006; Min et al., 2011; Ramos et al., 2002; Thompson et al., 2017; Zotarelli et al., 2007).

Nitrate leaching losses from soil into water not only represent a loss of soil fertility but also represent a threat to the environment and to human health (Cameron et al., 2013; Hester et al., 1996; Watanabe et al., 2018). Nitrate leaching from different sources and contamination of surface and ground water is a global phenomenon (Ju et al., 2006; Prakasa Rao and Puttanna, 2006; Pulido-Bosch et al., 2000). Nitrate that enters rivers or lakes can contribute to eutrophication, which may result in algae blooms and loss of fish (Cameron et al., 2013). A critical factor related to nitrate leaching from irrigated lands is the subsequent use of drainage waters or waters composed significantly of drainage waters. The problem of nitrate leaching to groundwaters is naturally more crucial in areas where high-value crops with high water and high N demands are grown and where municipalities and irrigation districts are both using the underground supplies (Pratt, 1984). In addition, there is a public concern about nitrate as a health hazard (Hester et al., 1996). This arises from two medical conditions that have been linked to nitrate: methaemoglobinaemia (or the 'blue-baby syndrome') in infants, and stomach cancer in adults. Both are serious conditions that are not caused by NO_3^- itself, but by the reduction of NO_3^- to NO_2^-; nitrate itself seems to be harmless (Hester et al., 1996).

Methaemoglobinaernia or the 'blue-baby syndrome' can occur when an infant ingests too much NO_3^- in drinking water. Microbes in the stomach convert NO_3^- to NO_2^- and when this reaches the blood-stream it reacts with the haemoglobin. Normal oxyhaemoglobin becomes methaemoglobin, greatly lessening the capacity of the blood to carry oxygen (Hester et al., 1996). A link between stomach cancer and NO_3^- consumption in drinking water has been suggested (Hester et al., 1996). Nitrite produced from reduction of NO_3^- could react in the stomach with a secondary amine coming from the breakdown of meat or other protein, to produce an N-nitroso compound. The N-nitroso compounds are carcinogenic, so the reaction could result in stomach cancer (Hester et al., 1996).

Nitrogen fertilizers are commonly required in large amounts in modern agriculture to guarantee high crop yields (Fowler et al., 2013; Lemaire and Gastal, 1997). However, only part of the N applied is recovered by crops (Ter Steege et al., 2001; Vitousek et al., 2009), and much of the excess is lost as nitrate leaching beyond the rooting zone. Traditionally, a secure fertilization strategy, based on application of N quantities larger than those strictly required for maximum yield, was used to ensure profit (Thompson et al., 2007b). However, this secure fertilization strategy cannot be longer used (Lawlor et al., 2001). Protection of the environment and improved N management become a necessary constraint for sustainable agriculture (Ter Steege et al., 2001). Solving the problem of nitrate leaching starts with the optimization of N fertilization with respect to the plant demand and the soil supply capacity (Agostini et al., 2010; Ju et al., 2009; Neeteson et al., 1999; Ter Steege et al., 2001). The surest way of avoiding nitrate leaching is to ensure that as little NO_3^- as possible is in the soil at any time (Hester et al., 1996). However, nitrate leaching is not only related to N inputs but also to the interaction between N processes and the water balance in the soil (Moreno et al., 1996; Pratt, 1984; Ter Steege et al., 2001). In fact, nitrate leaching is mainly determined by NO_3^- concentration in the soil during the drainage period (Cameron et al., 2013; Ter Steege et al., 2001) and the amount of water that moves through the soil (Cameron et al., 2013; Pratt, 1984). With the exception of a few areas where irrigation waters are almost salt-free, irrigated lands must be leached periodically to maintain the rooting zone free of excessive soluble salts (Moreno et al., 1996; Pratt, 1984). In many areas leaching takes place as a result of rains; in some areas the rainfall is so small or so erratic that management must provide sufficient irrigation water to leach the soil profile. In irrigated lands, the leaching process is a result of the combination of relatively large inputs of N and ample irrigation that move drainage waters beyond the root zone (Pratt, 1984).

In addition to soil NO_3^- concentration and drainage volume, many other factors such as the nature of the crops, the type of soils or the cropping techniques are also responsible for the nitrate leaching potential (Di and Cameron, 2002; Pratt, 1984; Ter Steege et al., 2001). Soil properties have an influence on the nitrate leaching because they affect how the water is moved. The nitrate leaching losses are usually less from fine-textured soils than from coarse-textured soils, because of slower drainage and greater potential for denitrification (Di and Cameron, 2002). The depth of the vadose zone, i.e. the part of the soil that comprises the unsaturated zone beyond the roots and above the groundwater or zone of saturation, is also an important factor, with nitrate reaching the groundwater quicker in shallow soils than in deep soils (Di and Cameron, 2002).

Concerns over human health and environmental impact associated with nitrate leaching have prompted social and political pressure to reduce contamination of water bodies with nitrate originating from agriculture. For example, in the European Union (EU), two pieces of legislation, the Nitrate Directive 91/676/EEC (Council of the European Communities, 1991) and the Water Framework Directive 2000/60/EC (Council of the European Communities, 2000), require all farmers in areas sensitive to nitrate leaching, to adopt improved N management practices. Several organizations have set NO_3^- concentration limits for drinkable water: the World Health Organization and the EU imposes a limit of 50 mg L^{-1} (Council of the European Communities, 1991; World Health Organization, 2011), the United States Environmental Protection Agency (EPA, 2007) and the Water and Air Quality Bureau of Canada (Health Canada, 2013) set the limit at 45 mg L^{-1}.

Scientific publication is the end product of research activity. The scientific productivity of researchers can be assessed by a quantitative and qualitative description of their production. This in turn can be extended to the institutions and countries to which they belong. For bibliometric analysis, extensive bibliographic information is required (Hood and Wilson, 2001; King, 1987). A bibliographic database is usually used for this purpose (Rojas-Sola and Aguilera-García, 2015). These databases are made up of a set of records with bibliographic information (author, title, name of the source, date of publication, keywords, citations). Bibliometric studies consists of the use of tools and methodologies aiming at analyzing scientific production and trends in a research area (Cobo et al., 2015). Thanks to these tools it is possible to identify trending topics since the development of the research field and assess the current state of research, as well as the contributions of institutions and countries in the given field.

The present bibliometric study aims to analyze global perspectives in nitrate leaching research in the 1960-2017 period using the Scopus database. The existence of two major databases, Web of Science (Clarivate Analytics, Philadelphia, PA, USA) and Scopus (Elsevier B.V., Amsterdam, The Netherlands), poses the important question of the comparison and stability of statistics compiled from different data sources (Salmerón-Manzano and Manzano-Agugliaro, 2017). The overlap between databases and the impact of using different data sources for specific fields of research on bibliometric indicators has been measured by several research studies, revealing a greater number of journals indexed by Scopus when compared to Web of Science (Mongeon and Paul-Hus, 2016). With respect to the overlap, 84% of Web of Science titles are also indexed in Scopus, while only 54% of Scopus titles are indexed in Web of Science (Gavel and Iselid, 2008).

2. Material and Methods

Because of its wider coverage (Gavel and Iselid, 2008; Mongeon and Paul-Hus, 2016), the Scopus database was selected in the present work. A complete search of Scopus was performed using the key to search the subfields of: Title, abstract and keywords, to identify publications that address the issue of nitrate leaching. The search was made to the whole data series available, that is, in the last 44 years, from 1960 to 2017. For a complete search of nitrate leaching terms, the exact query was: TITLE-ABS-KEY (nitrat* AND leach*).

Once the manuscripts related to the nitrate leaching had been obtained, the study of research trends was carried out through the analysis of scientific production per year, type of document, distribution in subject categories and source, publication distribution by countries and institutions, and an analysis of index keywords. The analysis of the keywords showed the most studied topics on nitrate leaching. To compare the relative importance among them, these results were represented by a word cloud, given that the size of font in the word cloud indicates frequency in literature. The next step was a specific search for the top countries that have published the most on this topic. For example, the specific query for USA was: TITLE-ABS-KEY (nitrat* AND leach*) AND (LIMIT-TO (AFFILCOUNTRY, "USA")). The same strategy was followed to obtain the main keywords and the most productive institutions within each of the top most productive countries.

The set of articles obtained in the main search were represented by a network with nodes and links between them. Nodes are their keywords and their importance are represented by the size of the node and its centrality in the network. The size of the connection between two nodes represents the number of relationships between the two keywords, so the bigger the connection, the larger the relationship between those two keywords. To find out which parts of the network are more interconnected with each other, a community detection algorithm was employed (Montoya et al., 2018).

3. Results and Discussion

3.1. Temporal evolution of scientific output

A total of 8798 documents with “nitrate leaching” term in the title, abstract or keywords were found in the Scopus database in the 1960-2017 period. The number of documents on this topic has grown since 1960 until nowadays, following a quadratic function in the form $y = 0.172x^2 - 1.676x + 3.075$ (R^2=0.98; Figure 2). In the first ten years of the period, 1960-1969, an average of four documents on nitrate leaching were published per year, but the number of documents published per year nearly doubled in each successive decade. While 23 documents were published per year in the 1970-1979 period, 52 documents were published per year in the 1980-1989 period, 170 documents were published per year in the 1990-1999 decade, 300 documents were published per year in 2000-2009 period, and finally 410 documents were published per year in the 2010-2017 period (note that this period consists of eight years). The maximum number of documents on nitrate leaching was published in the last year of the period, in 2017, with a total of 458.

Overall, the temporal trend in publication on nitrate leaching shows a steady growth in the number documents published per year, at an average rate of 56% increase per decade (Figure 2). This trend evidences a growing awareness in the scientific community on the nitrate leaching issue. Given this tendency, it is envisaged that the number of documents published on nitrate leaching will continue increasing in the coming years.

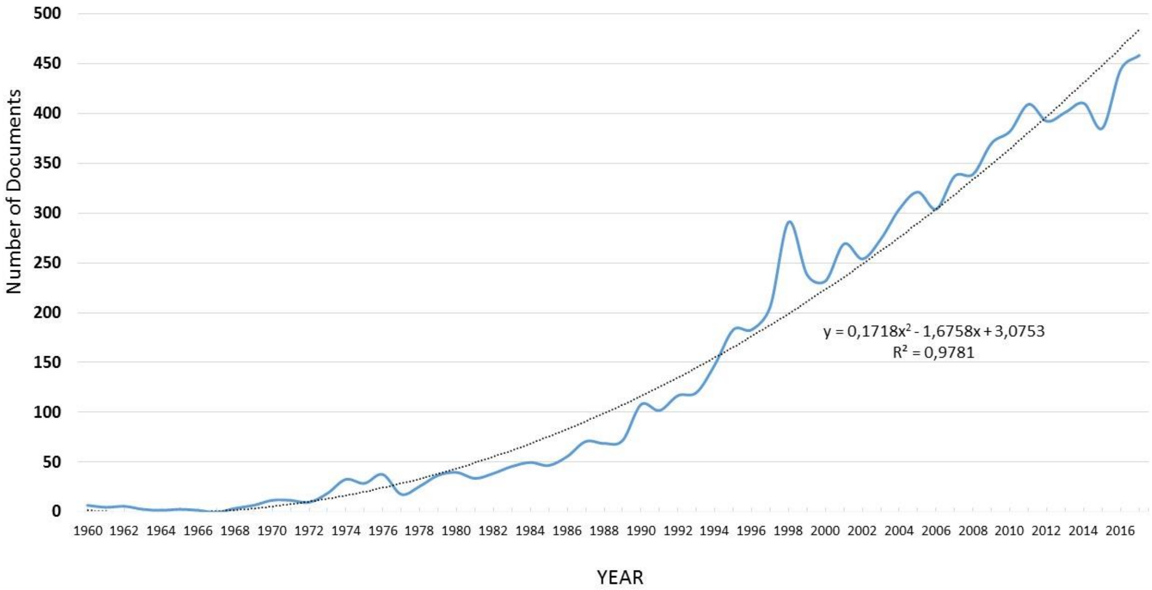

Figure 2. Trends in number of publications on nitrate leaching from 1960-2017.

3.2. Type of documents

The documents recovered from the Scopus database on nitrate leaching were classified into six types (Table 1). The majority of documents were in the form of articles (87.3 %), which totaled 7670 documents. In second place, contributions to conferences accounted for 9.3 % of the total (814 documents). Review articles accounted for 2.5% of the total (218 documents) and book and book chapters accounted for 0.8 % of the total (75 documents). These figures show that knowledge on nitrate leaching is mostly disseminated through scientific papers, both as articles and reviews. This is indicative of nitrate leaching being a consolidated research field, where progress is made mainly by scientific publications. Newer and developing research fields are often characterized by abundant contributions to conferences and less to articles and reviews.

As for the evolution of type of documents, scientific papers, both as articles and reviews, have been the most abundant contribution to the field of nitrate leaching since the beginning of the study period (Table 1). Conference papers appeared in the 1980-1989 period with an approximate contribution of 8%, which was roughly maintained with ups (12%) and downs (7%) in the following decades (Table 1).

Table 1. Evolution of percentage of type of documents of worldwide research on nitrate leaching, as classified by Scopus, in the 1960-2017 period.

Type of document	% of documents						
	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010-2017	Total
Article	100.0	99.3	90.7	88.6	83.7	88.3	87.3
Review	-	-	0.8	1.1	3.3	2.9	2.5
Conference paper	-	-	7.8	10.2	12.2	7.3	9.3
Book chapter	-	-	-	-	0.8	1.5	0.8
Book	-	-	-	0.1	-	0.0	0.0
Others	-	0.7	0.8	-	-	-	0.1

3.3. Distribution of output in subject categories

Both the Agricultural and Biological Sciences area and the Environmental Science area were the subject areas with more number of documents dealing with nitrate leaching, each accounting for 33% of the total documents in the whole study period. The following subject areas were the Earth and Planetary Sciences area and the Engineering area, accounting for approximately 10% and 5% of the total, respectively. Other subject areas accounted for less than 4% of the total documents each, such as Chemistry, Biochemistry, Genetic and Molecular Biology, Chemical Engineering, Materials Science, Medicine and Immunology and Microbiology. It should be noted that an article may be allocated in two or more areas at the same time.

Regarding the evolution of distribution of scientific output in subject areas (Figure 3), the most notable tendency was the reduction in contribution to the Agricultural and Biological Sciences area from the 1960-1969 decade (43%) to the 1970-1979 decade (32%) and following decades. This was a consequence of the increase in contributions on nitrate leaching to the Environmental Science area from the 1960-1969 decade (9%) to the 1970-1979 decade (28%). It is very likely that this change was due to increasing awareness of environmental issues in scientific journals.

Overall, the dominance of Agricultural, Biological and Environmental Sciences areas in nitrate leaching research, clearly indicated that the majority of documents dealt with nitrogen losses from agroecosystems and farmlands and the associated impact on the environment. Documents focusing on the relationships between nitrate leaching and human health were a minority given the low number of documents classified in the Medicine, Immunology and Microbiology, and Nursing areas (Figure 3).

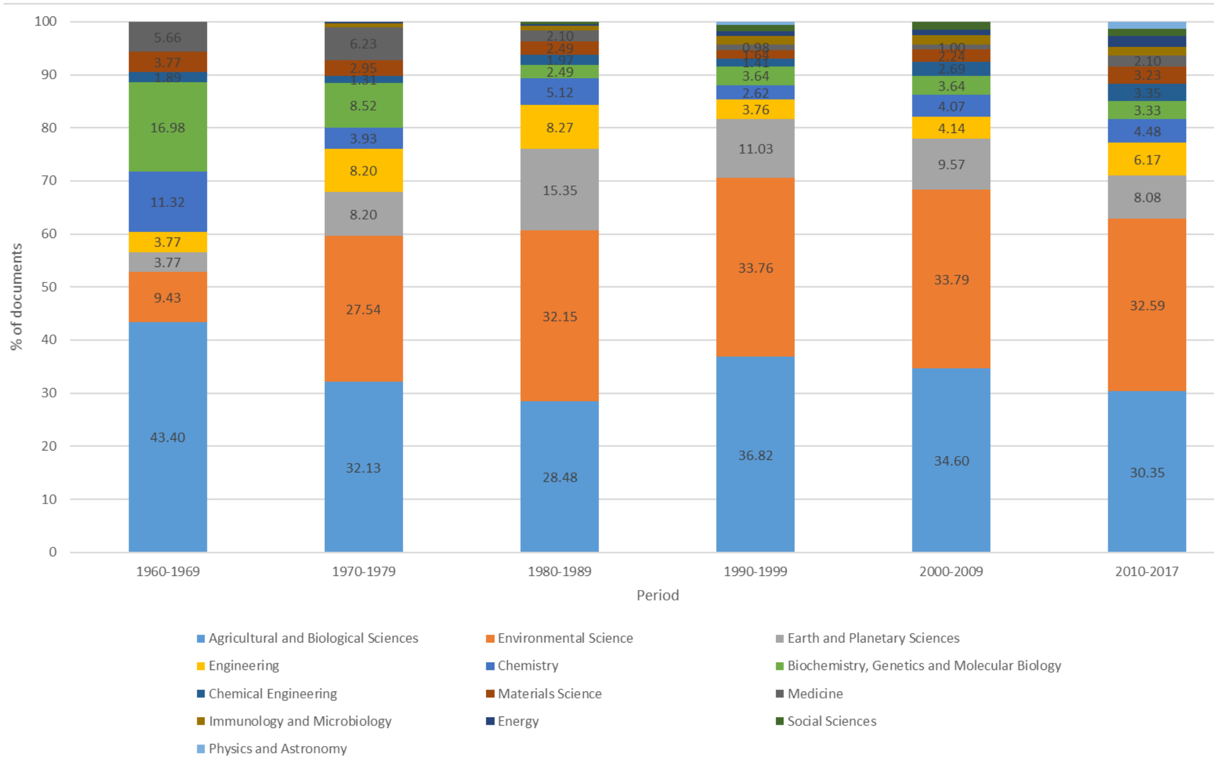

Figure 3. Evolution of subject category **d**istribution (%) of worldwide research on nitrate leaching as classified by Scopus.

3.4. Distribution of output by source

Regarding the main sources that publish nitrate leaching research, results showed that the *Journal of Environmental Quality* was indisputably the journal that published the most scientific documents on the topic with highest h-index and total citations (Table 2). Indeed, the number of documents published in this journal nearly doubled those published in the second and third-ranked journals, *Agriculture, Ecosystems and Environment* and *Plant and Soil*, respectively, both of which with a very similar number of documents published and h-index (Table 2). The fourth and fifth journals in terms of number of documents published on nitrate leaching were *Water, Air and Soil Pollution* and *Soil Use and Management*.

The scope of the journals that comprised the top five ranking was on the anthropogenic impact on the environment (*Journal of Environmental Quality*, *Water, Air, & Soil Pollution*), on the influence of soil-crop-animal systems in the environment and how such changes in the environment impact agroecosystems (*Agriculture, Ecosystems & Environment*), and on fundamental and applied aspects of plant-soil interactions (*Plant and Soil*). All journals' scope that comprised the top 30 most productive sources in nitrate leaching research were specific for environmental issues, agriculture and agronomy, plants and animals, soil and water resources, and on the interaction between any of these features (Table 2). There was a clear underrepresentation of multidisciplinary journals, such as *Plos One*, which was ranked in 65th position. This finding was expected given the relatively novelty of the *Plos One* journal (launched in 2006).

A notable case in the present study was with the journals *Communications in Soil Science and Plant Analysis* and *Acta Horticulturae*, ranked in the seventh and ninth position, respectively (Table 2). The journal *Communications in Soil Science and Plant Analysis* had a low IF (classified as a Q3 journal), and the journal *Acta Horticulturae* had no IF because it is not indexed in JCR. However, they published a great deal of documents on nitrate leaching. The explanation for so many contributions in lower-tiered journals may be in the limited findings of research submitted to these journals. For instance, *Acta Horticulturae* commonly publishes symposium's oral and poster presentations, with a restrictive limit of eight printed pages including figures and tables. Because of its policy and short format, it is very likely that most contributions are still preliminary and based on on-going research.

As for the Impact Factor (IF) (Journal Citation Report), the journal that led the ranking in terms of number of publications, h-index and total citations on nitrate leaching, *Journal of Environmental Quality*, was classified in the second quartile (Q2) of JCR (Table 2). These results indicated that the number of documents published on nitrate leaching in a given journal are not directly related to its impact factor. This was expected since journals' focus is on a wide range of topics.

Table 2. Bibliometric data of the top sources dealing with nitrate leaching research from 1960-2017, using the Scopus database.

Rank	Source	Number of documents (N)	IF‡	Quartile‡	Category‡	h-index	Total citations (TC)	TC/N	CiteScore	SNIP
1	*Journal of Environmental Quality*	377	2.344	Q2	Environmental Sciences	62	10167	27.0	2.54	1.066
2	*Agriculture, Ecosystems & Environment*	208	4.099	Q1	Agriculture, Multidisciplinary	48	6643	31.9	4.32	1.636
3	*Plant and Soil*	199	3.052	Q1	Agronomy	46	5631	28.3	3.7	1.435
4	*Water, Air, & Soil Pollution*	150	1.702	Q2	Water Resources	29	2807	18.7	1.9	0.728
5	*Soil Use and Management*	148	2.117	Q2	Soil Science	40	3171	21.4	1.69	0.749
6	*Science of the Total Environment*	142	4.900	Q1	Environmental Sciences	30	3672	25.9	4.98	1.65
7	*Communications in Soil Science and Plant Analysis*	134	0.589	Q3	Agronomy	19	1530	11.4	0.74	0.559
8	*Agricultural Water Management*	131	2.848	Q1	Agronomy	36	2589	19.8	3.49	1.814
9	*Acta Horticulturae*	123	-	-	-	11	468	3.8	0.23	0.276
10	*Nutrient Cycling in Agroecosystems*	115	1.843	Q3	Soil Science	30	3876	33.7	2.19	0.954
11	*Water Science and Technology*	104	1.197	Q3	Environmental Sciences	23	1670	16.1	1.34	0.574
12	*Forest Ecology and Management*	102	3.064	Q1	Foresty	38	3076	30.2	3.5	1.501
13	*Environmental Pollution*	96	5.099	Q1	Environmental Sciences	33	3742	39.0	5	1.46
14	*Soil Science Society of America Journal*	94	1.844	Q3	Soil Science	34	3037	32.3	2.21	1.056
15	*Soil Biology and Biochemistry*	84	4.857	Q1	Soil Science	37	3896	46.4	5.63	1.856
16	*Environmental Science and Technology*	80	6.198	Q1	Environmental Sciences	36	3463	43.3	6.58	1.941
17	*Australian Journal of Soil Research*	79	3.443	Q1	Soil Science	24	1460	18.5	-	-
18	*Journal of Hydrology*	78	3.483	Q1	Water Resources	32	2478	31.8	4.06	1.71
19	*Biogeochemistry*	73	3.428	Q1	Environmental Sciences	32	2919	40.0	3.79	1.253
20	*Journal of Agricultural Science*	72	1.291	Q1	Agriculture, Multidisciplinary	26	1371	19.0	1.43	0.749
21	*European Journal of Agronomy*	69	3.757	Q1	Agronomy	28	1840	26.7	3.94	1.828
22	*Agronomy Journal*	66	1.518	Q2	Agronomy	26	1949	29.5	2.08	1.265
23	*Journal of Environmental Management*	64	4.010	Q1	Environmental Sciences	21	1811	28.3	4.54	1.705
24	*New Zealand Journal of Agricultural Research*	60	1.265	Q2	Agriculture, Multidisciplinary	19	796	13.3	1.2	0.869
25	*Environmental Monitoring and Assessment*	56	1.687	Q3	Environmental Sciences	17	982	17.5	1.86	0.848
26	*Soil and Tillage Research*	56	3.401	Q1	Soil Science	23	1768	31.6	4.31	1.946
27	*Waste Management*	54	4.030	Q1	Environmental Sciences	21	1169	21.6	4.94	2.059
28	*Transactions American Society of Agricultural Engineers*	53	-	-	-	20	1103	20.8	-	-
29	*Canadian Journal of Soil Science*	52	1.590	Q3	Soil Science	18	656	12.6	1.19	0.619
30	*Journal of Hazardous Materials*	52	6.065	Q1	Environmental Sciences	26	2076	39.9	6.75	1.96
31	*Fertilizer Research*	50	-	-	-	19	1172	23.4	-	-
32	*Water Research*	50	6.942	Q1	Environmental Sciences	27	3144	62.9	7.55	2.358

IF, Impact Factor; ‡JCR year 2016; SNIP, Source Normalized Impact per Paper

3.4.1. Distribution by country of scientific output published in journals

Figure 4 showed that most of the articles published on nitrate leaching in the *Journal of Environmental Quality* was from the United States (67%), followed by far by Canada (7%) and New Zealand (4%). The dominance of North American research on nitrate leaching in this journal is thus unquestionable. Figure 4 also showed that articles on nitrate leaching from the United States were dominant in journals such as *Communications in Soil Science and Plant Analysis* (46%), *Agricultural Water Management* (28%), *Water Air and Soil Pollution* and *Forest Ecology and Management* (both with 27%), *Agriculture, Ecosystems and Environment* (24%) and *Water Science and Technology* (19%). However, the degree of dominance of articles from the United States in these journals was lower than in *Journal of Environmental Quality*. It was notable that more than fifty percent of the articles on nitrate leaching published in *Soil Use and Management* were from the United Kingdom (55%), which contrasted with the lower contribution of the second-ranked (Denmark) and third-ranked (New Zealand) country, which accounted for 14 and 11%, respectively, of the total articles on nitrate leaching published by this journal (Figure 4). This suggests a clear preference of reseachers from this country for publication in this journal. Both the United Kingdom and the United States were the countries that have published more articles on nitrate leaching in *Science of the Total Environment* (Figure 4), acounting for 23 and 18%, respectively, of the articles published on this topic in this journal. The largest contributors to *Plant and Soil* were the United States, Germany and the United Kingdom, with 19, 15 and 15%, respectively, of the total articles on nitrate leaching published in this journal (Figure 4). Finally, 20% of the articles on nitrate leaching research published in *Acta Horticulturae* were from Spain; Germany and the United States accounted each for 14% of the articles published on this topic in this journal (Figure 4).

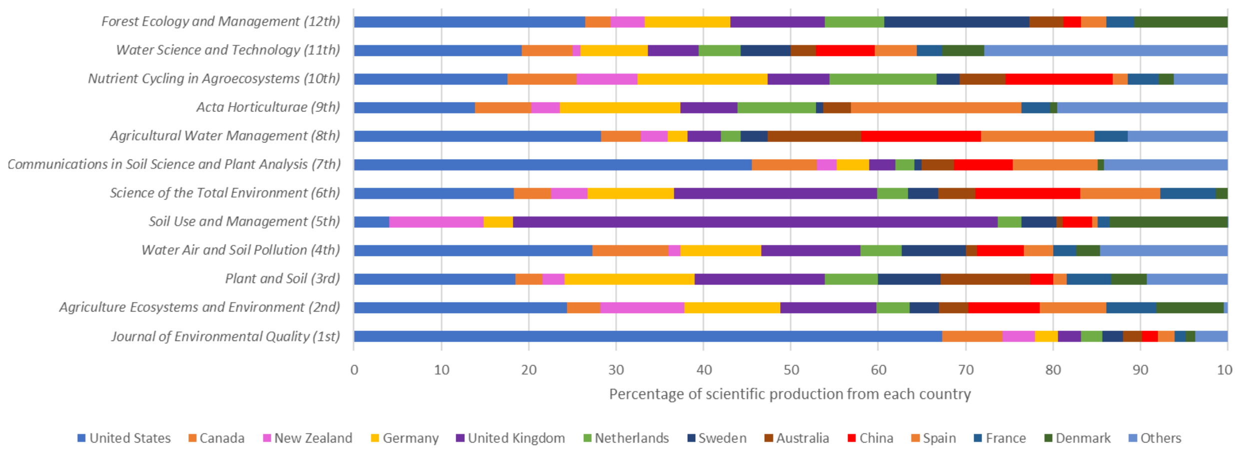

Figure 4. Percentage of scientific production from each country published in the top 12 sources, from 1960-2017.

3.5. Analysis of keywords

The analysis of keywords in scientific contributions are of interest for identifying tendencies in a particular field (Choi et al., 2011). Keywords of a contribution are used to identify the focus of the research. Authors tend to list a number of keywords that facilitate framing the scientific contribution in the field or subject matter most closely related to the topic addressed in their study. It is also common for reviewers and especially editors to expand such information with additional keywords obtained from databases based on the subject text in the publication.

The study of the evolution of main keywords in the study period (Table 3), showed that In the 1960s, specific analytical chemistry techniques were developed for the study of soil, especially those related to radioactivity (Levine and Lamanna, 1965). In the following decade, studies of the accumulation of certain fertilizers in the soil and its subsequent content in the plant began to be important (Williams and David, 1976). In the decade of the 80s, the largest number of studies focused on water quality, highlighting the terms "Water Quality" and "Groundwater" (Table 3), for example in studying nitrate-nitrogen in tile drainage as affected by fertilization (Baker and Johnson, 1981). In the nineties, soil studies returned mainly to research related to nitrate leaching and soil pollution, along with water quality, and agriculture was already in prominent positions

(Table 3), for example, with nitrogen balances (David et al., 1997). In the following decade, already in the 21st century, the tendency of main keywords continued with the previous themes, but it drawed attention to the emergence of Eurasia as an outstanding keyword (Table 3), because there were specific studies conducted in the area, such as intensive cropping systems on the North China Plain (Ju et al., 2007, 2006), in France (Beaudoin et al., 2005), and in Spain (Chapagain and Orr, 2009; Gallardo et al., 2009; Thompson et al., 2007a, 2007b, 2004). Already in the last period, from 2010 to 2017, the works related to "Groundwater" and "Water Quality" on a large scale were dominant (Table 3), playing a very relevant role the hydrology (Abbaspour et al., 2015) and agricultural issues (Soane et al., 2012).

Table 3. Evolution of main keywords on nitrate leaching research from 1960-2017, using the Scopus database. Numbers in brackets show the number of documents.

Period	Total documents	Main Keywords				
		1st	2nd	3rd	4th	5th
2010-2017	3288	Groundwater (480)	Soil (438)	Fertilizer Application (413)	Water Quality (403)	Agriculture (358)
2000-2009	2997	Soil (801)	Eurasia (377)	Groundwater (350)	Water Quality (339)	Fertilizer Application (309)
1990-1999	1697	Soil (170)	Water Quality (156)	Soil Pollution (152)	Denitrification (148)	Agriculture (147)
1980-1989	524	Nonhuman (59)	Water Quality (49)	Theoretical Study (48)	Groundwater (46)	Soil (44)
1970--1979	229	Soil (28)	Environmental Health (22)	Theoretical Study (21)	Groundwater (19)	Fertilizers (18)
1960-1969	39	Chemistry, analytical (4)	Cesium (2)	Cesium radioisotopes (2)	Plutonium (2)	Radiation protection (2)

The creation of a word cloud with the most abundant keywords is of a great value to easily identify the main topics on which contributions are dealing with in the nitrate leaching research. Figure 5 shows the word cloud based on the main keywords related to nitrate leaching worldwide research for the whole study period, 1960-2017. This figure shows that *soil* and *fertilizer* were the two most abundant keywords, with 1920 and 1900 documents, respectively; these keywords were followed by *groundwater* (1537 documents), *leachate* (1002 docments) and *water quality* (950 documents). The next five keywords that comprised the top ten were *agriculture*, *denitrification*, *ammonia*, *nitrification* and *Zea mays*, with 819, 768, 766, 680 and 620 documents, respectively. This analysis of keywords showed the dominance of environmental and agricultural issues in nitrate leaching research, with great relevance of the soil nitrogen cycle, fertilizer use in agriculture and water quality issues.

Figure 5. Word cloud based on the main keywords related to nitrate leaching worldwide research for the 1960-2017 period.

As for crop species, it is very notable that *Zea mays* (latin name for maize) was listed in the tenth position of most abundant keywords in nitrate leaching research. The position in the ranking would have increased to fith position should we had summed up the documents that used as keyword the common name, i.e., *maize* (359 documents). The second most abundant crop in nitrate leaching research worldwide, based on abundance of keywords, was wheat, which was included in a total of 598 documents, either as the latin name *Triticum aestivum* (353 documents) or as the common name *wheat* (245 documents). The third most abundant crop was grass (331 total documents), either as the common name *grass* (180 documents) or the latin name of the taxonomical family *Poaecea* (151 documents).

The evolution of main crop species involved in nitrate leaching research in the study period (Figure 6), showed a rising relevance of research conducted on maize, wheat and grass from 1990 onwards; before 1960, there was little research conducted on specific crops. However, from 1990 onwards, the tendency was of an increase in number of documents on these crops, with a tendency to plateau off from in 2010.

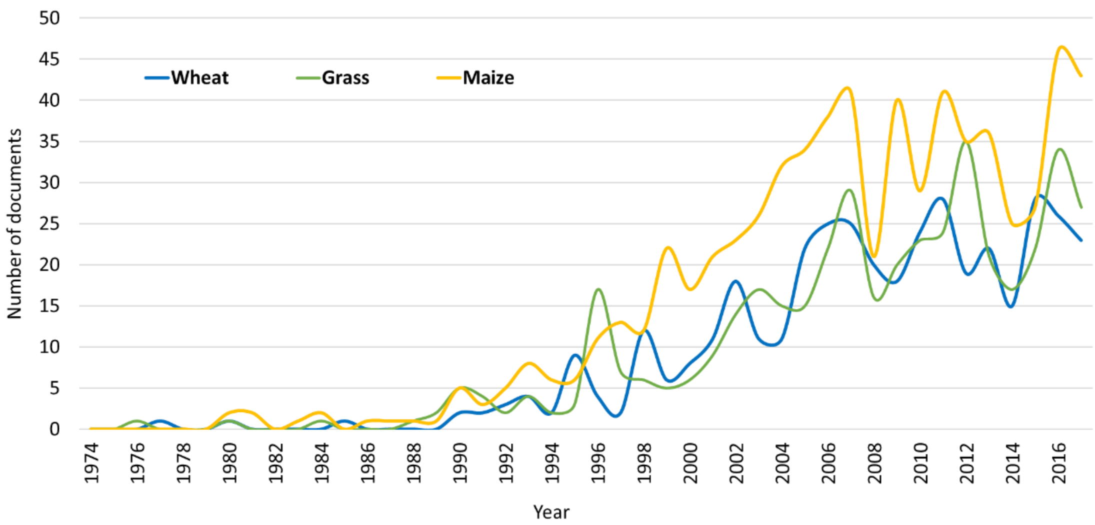

Figure 6. Evolution of main crop species on nitrate leaching research from 1960-2017.

3.6. Publication distribution by country

A total of 133 countries have published documents dealing with nitrate leaching in the period analyzed. Most documents published were indisputably from the United States, with 2182 documents that accounts for 21% of the total, followed by China, the United Kingdom and Germany, which accounts for 9%, 8% and 6% of the total with 877, 806 and 605 documents, respectively (Figure 7). Countries such as Canada, Australia, New Zealand, France, Spain, The Netherlands and Sweden have published between 251 and 500 documents; they belong (in the indicated order) to the top eleven countries according to the number of publications (Figure 7). Altogether, these eleven countries have published 68% of the total number of documents dealing with nitrate leaching. It is notable the low contribution of African, South American and Asian countries to the field of nitrate leaching, with the exception of China (mentioned before) and India, Japan and Brazil, which published 248, 229 and 175 documents, respectively (Figure 7).

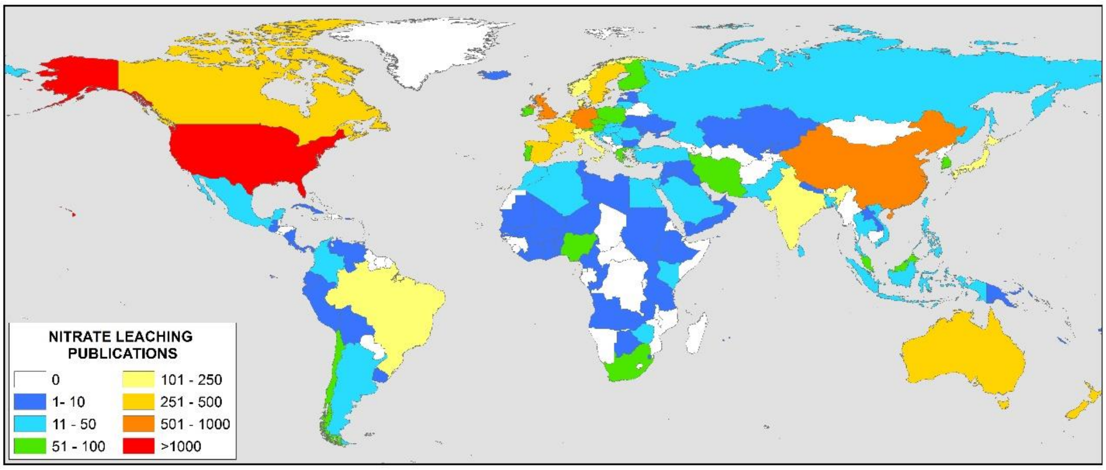

Figure 7. Distribution map of worldwide research on nitrate leaching from 1960-2017 based on number of publications.

3.6.1. Main keywords by country

An analysis of the most abundant keywords showed that research topics of the top-ten most productive countries on nitrate leaching were soil and groundwater (Table 4). This was expected as nitrate leaching is a process that occurs in the soil, and that may have important environmental issues in the groundwater whenever the leachate infiltrates deeply and arrives the aquifers (Gianquinto et al., 2013; Hester et al., 1996). These findings also confirm that the awareness of nitrate leaching effects on groundwater is a global phenomenon that expand to all continents (Ju et al., 2006; Prakasa Rao and Puttanna, 2006; Pulido-Bosch et al., 2000). The geographical context was of great relevance for research that deals with nitrate leaching, and the country where the research was conducted was included as one of the main keywords in most countries' scientific production on nitrate leaching (Table 4). In many instances, the country where the research was carried out is the main keyword of a country's production on nitrate leaching (Table 4). In China, the fact that both the Latin name and the common name for wheat was ranked in the third position of most abundant keywords in documents published by this country (Table 4), indicated that this crop was very relevant for Chinese research focused on nitrate leaching.

Table 4. Main keywords used in the most productive countries in nitrate leaching research worldwide. Number of documents of each keyword are shown in brackets.

Country	Main Keywords		
	1st	2nd	3rd
USA	Soil (609)	Groundwater (509)	United States (486)
China	China (259)	Soil (242)	*Triticum aestivum* + wheat (193)
UK	United Kingdom (198)	Soil (195)	Fertilizer (88)
Germany	Germany (115)	Soil (103)	Groundwater (79)
Canada	Canada (125)	Soil (114)	Groundwater (92)
Australia	Australia (92)	Soils (57)	Denitrification (49)
New Zealand	New Zealand (133)	Pasture (86)	Nitrification (56)
France	Soil (83)	France (70)	Agriculture (36)
Spain	Spain (61)	Irrigation (48)	Fertilizer Application (43)
Netherlands	Netherlands (77)	Groundwater (54)	Ammonia (45)
Sweden	Sweden (81)	Soil (73)	Forestry (37)
India	Groundwater (78)	India (65)	Water Quality (38)
Denmark	Denmark (77)	Europe (32)	Agriculture (26)
Japan	Japan (43)	Groundwater (33)	Denitrification (30)
Italy	Italy (46)	Fertilizer Application (28)	Groundwater (21)
Brazil	Brazil (30)	*Zea mays* (25)	Groundwater (15)
Belgium	Belgium (39)	Agriculture (22)	Soil (21)
Switzerland	Switzerland (17)	Europe (15)	Agriculture (14)
Norway	Norway (27)	Europe (24)	Catchment (21)
Austria	Austria (20)	Ammonia (12)	Controlled Study (10)
Finland	Finland (29)	Europe (15)	Phosphorus (12)
South Korea	Denitrification (12)	Korea (12)	Nonhuman (12)
Iran	Groundwater (20)	Iran (17)	Water Quality (12)
Poland	Ammonia (22)	Poland (21)	Denitrification (18)
Ireland	Ireland (16)	Agriculture (13)	Groundwater (12)
Portugal	Portugal (14)	Europe (9)	Ammonia (8)
Czech Republic	Acidification (19)	Czech Republic (17)	Forestry (14)
South Africa	South Africa (18)	Africa (8)	Fertilizer Application (8)
Chile	Caliche (7)	Chile (7)	Groundwater (7)
Greece	Greece (19)	Groundwater (15)	Ammonia (11)

3.7. Publication distribution by institution

The most productive institutions in terms of number of documents dealing with nitrate leaching research, h-index and total citations, were located in the United States, China and the Netherlands (Table 5). The United States Department of Agriculture stood out, followed by the Chinese Academy of Sciences (CAS). Other North American institutions that ranked in the top ten institutions on nitrate leaching were University of Florida and Iowa State University. China Agricultural University was the ninth institution, and the second institution in China after CAS. The third institution with more documents on nitrate leaching was Wageningen University and Research, located in the Netherlands. Most research conducted on nitrate leaching in the Netherlands is accomplished in that institution (Table 5). Agriculture et Agroalimentaire Canada is by far the most productive institution from Canada. In the United Kingdom, nitrate leaching research was evenly distributed among Centre for Ecology & Hydrology, Agricultural Development and Advisory Service and Rothamsted Research.

Table 5. Ranking of the most productive institutions in nitrate leaching research worldwide and bibliometrics of institutions.

Rank	Institution	Country	Number of documents	h-index	Total citations	Average citations per document
1	United States Department of Agriculture	USA	347	55	10159	29.28
2	Chinese Academy of Sciences	China	244	37	4347	17.82
3	Wageningen University and Research	Netherlands	173	40	5146	29.75
4	University of Florida	USA	167	32	2775	16.62
5	Agriculture et Agroalimentaire Canada	Canada	146	30	2155	14.76
6	Sveriges lantbruksuniversitet	Sweden	140	37	4351	31.08
7	Centre for Ecology & Hydrology	UK	118	40	3417	28.96
8	Lincoln University	New Zealand	106	33	2532	23.89
9	Iowa State University	USA	103	28	1772	17.20
10	China Agricultural University	China	103	25	2314	22.47
11	Agricultural Development and Advisory Service	UK	88	30	2079	23.63
12	Rothamsted Research	UK	97	30	2636	27.18
13	United States Geological Survey	USA	81	35	3549	43.81
14	UC Davis	USA	79	29	2582	32.68
15	Cornell University	USA	76	32	2865	37.70

3.7.1. Use of keywords by institution

An analysis of the most abundant keywords used by the top-five most productive institutions revealed that research focused most on soil aspect of nitrate leaching (Table 6). Similarly, the inclusion of the country where the research was conducted was among the most abundant keywords in these top five institutions, revealing again that framing the geographical context of the research was of importance in nitrate leaching research. There was a dominance of research with wheat in the Chinese Academy of Sciences and in Agriculture et Agroalimentaire Canada, and a dominance of maize in the United States Department of Agriculture (Table 6).

Table 6. Main keywords used in the ranking of the five most productive institutions in nitrate leaching research worldwide. Number of documents of each keyword are shown in brackets.

Institution	Main Keywords		
	1st	2nd	3rd
United States Department of Agriculture	Soil (129)	United States (129)	*Zea mays* + maize (126)
Chinese Academy of Sciences	China (104)	Soil (83)	*Triticum aestivum* + wheat (70)
Wageningen University and Research	Groundwater (60)	The Netherlands (60)	Soil (37)
University of Florida	Soil (43)	Fertilizer (40)	Groundwater (38)
Agriculture et Agroalimentaire Canada	Canada (58)	*Triticum aestivum* + wheat (37)	Fertilizer application (34)

3.8. Analysis of the interconnection between keywords: community detection

Communities or clusters are often the ones that are more likely to interact with each other than with members of other clusters (de la Cruz-Lovera et al., 2017). Identifying communities is an attractive problem in our case since it will show us around which main themes the publications are grouped. For this specific search, what was done was a specific download of the keywords of each publication separately, generating a file line with up to 6 keywords used in each publication, this file was imported into a software network analysis, which detected the main communities. Clusters with different colors have been represented in the form of a neural network, with each node being a keyword and the thickness of the link between nodes representing the frequency of that relationship (Figure 8). Four communities have been detected using a community detection algorithm; to identify each cluster, a proposed name is offered in the last column of Table 7. By order of importance, clusters deal with agriculture/agronomy, soil processes, groundwater pollution and environment and ecosystem.

Table 7. Main keywords used by the communities detected in the topic nitrate leaching.

Cluster	Color	Main keywords	Topic
1st	Green	Fertilizer application, *Zea mays*, cover crop, grass, pasture, wheat, glycine max	Agriculture/Agronomy
2nd	Red	Denitrification, ammonia, leachate treatment, heavy metals, copper, alkalinity, pH, nitrification, landfill, waste disposal	Soil processes
3rd	Blue	Ground water, ground pollution, aquifer, contamination, soil pollution, river water	Ground water pollution
4th	Yellow	Atmospheric deposition, forest, acid rain, acidification, ecosystem	Environment and ecosystem

As a part of community detection analysis, a temporal analysis was also done to identify which groups of keywords were used most often over a period of time. From all the historical series analyzed, the period of greatest change was from 2004 to 2010 (Figure 9). It was observed that at the beginning of period, in 2004, research was more focused on topics such as groundwater pollution, soil processes or fertilizer. Later on, from 2006 to 2008, research focused more on topics related to denitrification, ammonia, landfill, or specific crops, such as *Lolium* spp., *Trifolium* spp., legume species, wheat, potato *(Solanum tuberosum*), *Glycine max*. Already in the last period, 2008 to 2010, research focused on subjects related to leachate treatement, nitrogen removal, oxidation-reduction, fertilizer application, metabolism.

3.9. Analysis of the interconnection between institutions: community detection

There was a first, large community cluster that consisted of intercontinental interaction between institutions from Europe, Asia and South and North America (Table 8). Some of the institutions belonging to this cluster were Wageningen University and

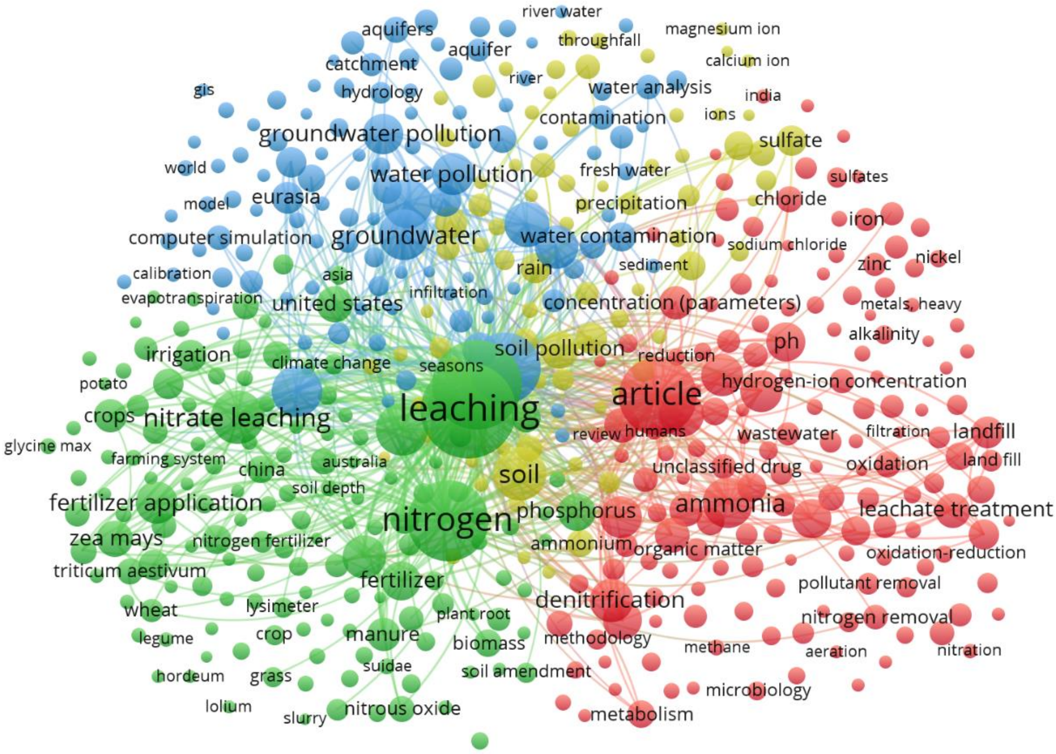

Figure 8. Keywords network and their community detection related to nitrate leaching worldwide research.

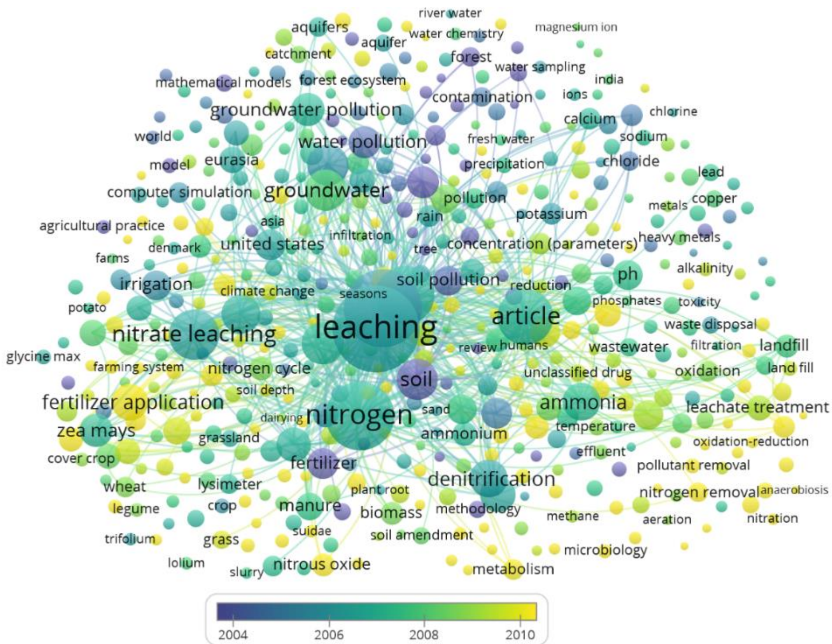

Figure 9. Keywords network and their temporal evolution as community detection related to nitrate leaching worldwide research.

Research (The Netherlands), China Agricultural University, Trent University (Canada) and Universidad Central de Venezuela. A second, large intercontinental cluster was detected with institutions from Europe, South America and Asia; Justus Liebig University (Germany), Universidad Austral de Chile and Jiangsu Center (China) belonged to this second cluster (Table 8). There was a cluster that consisted of five institutions from the same country, New Zealand, and a cluster that consisted of just one institution, such as the United States Geological Survey (Table 8). The cases of New Zealand's cluster and the United States Geological Survey's cluster are examples of lack of international connection with other institutions on nitrate leaching. There were two clusters that involved connection between North American and Chinese institutions, one among University of California, Chinese Academy of Sciences and Chinese Academy of Forestry, an another among Oklahoma State University, Ohio State University and Chinese Academy of Sciences (Table 8). It follows that the Chinese Academy of Sciences is very active in establishing connections with North American institutions on nitrate leaching research, particularly with University of California, Oklahoma State University and Ohio State University.

Table 8. Main institutions that compose each cluster of collaboration detected by community analysis on the topic of nitrate leaching.

Cluster	Institutions
1st	Wageningen University and Research, China Agricultural University, Trent University, Universidad Central de Venezuela, Lancaster University, Manchester University, Unite States Department of Agriculture, Rothamsted Research, Tsinghua University, Nanjing Normal University, The James Hutton Institute
2nd	Justus Liebig University, Universidad Austral de Chile, Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing Normal University, University College Dublin
3rd	AgResearch Ruakura Research Centre, University of Waikato, Massey University, GNS Science, Landcare Research NZ
4th	University of California, Chinese Academy of Sciences, Chinese Academy of Forestry
5th	United States Geological Survey
6th	Oklahoma State University, Ohio State University, Chinese Academy of Sciences

4. Concluding remarks

Nitrate leaching is the process whereby the nitrate anion moves downwards in the soil profile with soil water. It is commonly associated with chemical fertilizers used in agriculture and by emission in localized sources. Nitrate leaching losses from soil into water not only represent a loss of soil fertility but also a threat to the environment and to human health. Nitrate leaching is a global phenomenon that has prompted social and political pressure to reduce nitrate leaching and contamination of water bodies.

The results of this bibliometric study on nitrate leaching research showed a rising interest by the scientific community in the last decades. Given the growth tendency over the study period (1960-2017), it is envisaged that the awareness on nitrate leaching will continue increasing in the coming years. New knowledge on nitrate leaching was mostly disseminated through scientific publications, both as journal articles and reviews, classified in the Scopus database in the Agricultural, Biological and Environmental Sciences areas. The majority of documents dealt with soil nitrogen losses from agroecosystems and farmlands and the associated impact on the environment, and were published in journals with a focus on the influence of anthropogenic and soil-crop-animal systems in the environment and how such changes in the environment impact agroecosystems. Most documents published on nitrate leaching were indisputably from the United States, followed by China, the United Kingdom and Germany.

An analysis of the main keywords showed an overall dominance of the soil nitrogen cycle, fertilizer use in agriculture and water quality aspects. The evolution of main crop species involved in nitrate leaching research in the study period showed a rising relevance of research conducted on maize, wheat and grasses from 1990 onwards.

The most productive institutions in terms of number of documents dealing with nitrate leaching research, h-index and total citations, were located in the United States, China and the Netherlands. The U.S. Department of Agriculture stood out, followed by the Chinese Academy of Sciences and Wageningen University and Research. There were clusters of institutions with intercontinental interaction, on nitrate leaching research, between institutions from Europe, Asia and South and North America. However, there were some clusters of institutions with a lack of international connection with other institutions on nitrate leaching.

Overall, this study has analyzed from a bibliometric perspective the effort made in the last decades by the scientific community to generate new knowledge in the field of nitrate leaching. Progress in this field has been made particularly on the impact of the soil-plant-animal system on the environment and agroecosystems, and on fundamental and applied aspects of plant-soil interactions with an emphasis in agronomic crops.

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