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The Use of Spatiotemporal Kriging in Academic Research: A Bibliometric Analysis

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Abstract
Recent advances in capturing spatial data in different periods of time lead to new challenges in predicting missing information from neighboring data, and spatiotemporal kriging is rising as a powerful tool to face this challenge. This research aims to explore the main academic contributions to this statistical technique by performing a bibliometric analysis. From a sample of 953 articles (1990-2022) gathered from the Web of Science database, this study highlights the main contributors on this topic in terms of production and impact (authors, institutions, countries, journals and publishers), and also aims to bring to light the main scientific topics related to spatiotemporal kriging by explore the wording of authors' keywords, titles and abstracts, and the categories in which the papers analyzed are included. These results lead to an integral view of the state of the art on spatiotemporal kriging, to serve as a storefront for researchers who need a comprehensive landscape for this statistical interpolation technique.
Keywords: Spatialtemporal methods. Bibliometrics. Spatial statistics.

O uso do Kriging espaço-temporal na pesquisa acadêmica: uma análise bibliométrica
Resumo
Os recentes avanços na captura de dados espaciais em diferentes períodos geram novos desafios na hora de prever a falta de informações de dados próximos, e o kriging espaço-temporal está se tornando uma ferramenta poderosa para enfrentar esse desafio. Esta pesquisa tem como objetivo explorar as principais contribuições acadêmicas para essa técnica estatística por meio da realização de uma análise bibliométrica. A partir de uma amostra de 953 artigos (1990-2022) coletados do banco de dados Web of Science, este estudo destaca os principais contribuintes para este tema em termos de produção e impacto (autores, instituições, países, revistas e editoras), e pretende trazer à luz os principais temas científicos relacionados com o kriging espaço-temporal, explorando a redação das palavras-chave, títulos e resumos dos autores, e as categorias em que os artigos analisados estão incluídos. Esses resultados conduzem a uma visão abrangente do estado da arte sobre kriging espaço-temporal, com o objetivo de servir como vitrine para pesquisadores que precisam de um panorama completo dessa técnica de interpolação estatística.
Palavras-chave: Métodos espaço-temporais, bibliometria, estatística espacial

El uso del Kriging espaciotemporal en la investigación académica: un análisis bibliométrico
Resumen
Los avances recientes en la captura de datos espaciales en diferentes períodos de tiempo generan nuevos desafíos a la hora de predecir la falta de información de datos próximos, y el kriging espaciotemporal se está convirtiendo en una herramienta poderosa para enfrentar este desafío. Esta investigación tiene como objetivo explorar las principales contribuciones académicas a esta técnica estadística mediante la realización de un análisis bibliométrico. A partir de una muestra de 953 artículos (1990-2022) recopilados de la base de datos Web ofScience, este estudio destaca los principales contribuyentes a este tema en términos de producción e impacto (autores, instituciones, países, revistas y editoriales), y también pretende sacar a la luz los principales temas científicos relacionados con el kriging espaciotemporal explorando la redacción de las palabras clave, títulos y resúmenes de los autores, y las categorías en las que se incluyen los artículos analizados. Estos resultados conducen a una visión integral del estado de la cuestión obre kriging espaciotemporal, con el fin de servir como escaparate para los investigadores que necesitan un panorama completo de esta técnica de interpolación estadística.
Palabras clave: Métodos espacio-temporales. Bibliometría. Estadística espacial.

1. Introduction

One of the main challenges with spatial data is the prediction of unobserved locations, but recently both the availability of large amounts of spatial datasets and advances in geo-statistics and artificial intelligence are allowing researchers to overcome past difficulties in spatial prediction. Particularly, a broad family of techniques, known as “kriging”, is considered as a reference to spatial interpolation (Hengl; Heuvelink; Stein, 2004).

Kriging is a statistical interpolation technique that, starting from spatial observed data, obtains the best linear unbiased prediction for unknown neighboring locations by minimizing mean-squared prediction error (Shtiliyanova *et al*., 2017; Lim; Wu, 2022; Moyeed; Papritz, 2002; Kleijnen, 2009; Hengl; Heuvelink; Rossiter, 2007). Its adaptability has made it suitable for, and used in, different fields of natural sciences (atmospheric, earth, solar, optics...), and even social science, such as finance. Kriging was originally developed in geostatistics by, and named after, the South African mining engineer Daniel G. Krige (1951), and further developed and popularized by Matheron (1963) and Cressie (1993).

Kriging is based on the prior consideration of models that fit the variogram, and researchers have made numerous contributions on the estimation of the variogram. Depending on the assumptions made about the trend function of the underlying process, the main variants for univariate spatial data are simple kriging(Chilès; Delfiner, 2012; Fernández-Casal, 2003; Cressie, 1993), ordinary kriging (Journel; Huijbregts, 1979; Wackernagel, 1998) and universal kriging (Gundogdu; Guney, 2007; Zimmerman; Ruggles; Armstrong, 1999); furthermore it is called cokriging for multivariate spatial data (Lim; Wu, 2022).

However, the consideration of spatial data is insufficient for some phenomena, such as solar radiation, soil permeability, or gas concentration. Here, the time variable is also fundamental, that is, it is necessary to consider the global analysis of what happens in time and space, also assuming that nearby locations will in turn have a similar behavior in time. Spatiotemporal kriging considers the correlation of the observations in different times or space, which reflects the influence caused by the connections between existing points and missing points in time and space (Q. He et al., 2022), allowing to further make predictions.

As Snepvangers *et al.* (2003) rightly point out, the consideration of time is not as simple as adding another variable: while space can present multiple dimensions, and focus is placed on interpolation, time is a one-dimension variable whose main interest is extrapolation. Furthermore, the different origins of dimensions' variations could lead to anisotropic behavior. Despite the difficulties, the development and advances in spatiotemporal kriging have gained great importance in the last ten years (both theoretically and its applications), especially but not exclusively in the field of geostatistics, and endorsed by an increasing availability of massive and detailed datasets (Gervini, 2022). Some results prove that spatiotemporal kriging techniques outperform spatial kriging in terms of accuracy and robustness (Xiao et al., 2020). Again, different types of spatiotemporal kriging emerge, depending on the assumptions about the mean or how to model the trend (ordinary, universal, regression…).

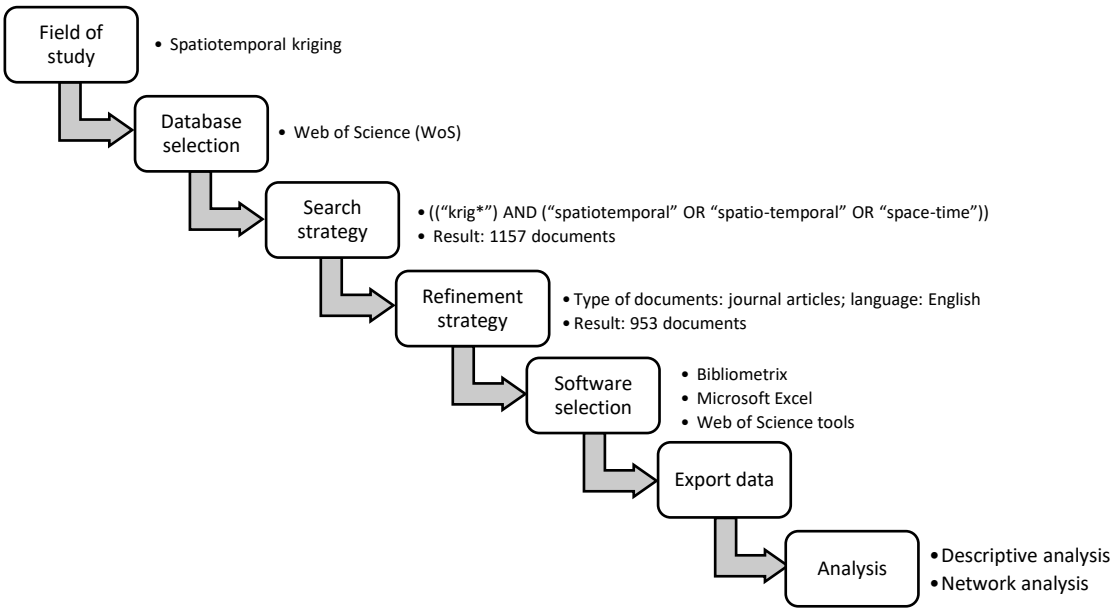
Given the relevant emergence of the topic, the main aim of this manuscript is to examine the main publications, authors, and topics regarding spatiotemporal kriging, that is, to perform a bibliometric analysis. Bibliometrics is the quantitative analysis of scientific research activity (Waltman; Noyons 2018). Researchers use bibliometrics to obtain an overview of their field of research and the scientific articles with the greatest impact in relation to the most referenced. Through a series of statistical techniques like analysis cluster (Fortunato, 2010; Waltman; van Eck; Noyons, 2010), it is possible to evaluate the areas of research in development and those areas that are no longer of interest to the scientific community. In other words, it is very useful for the identification of future lines of research.

Bibliometrics provides multiple information to researchers, since it allows analyzing the currently existing literature on a given area, as well as carrying out a thematic, chronological and geographical analysis (Jiang *et al*., 2021). On the other hand, the analysis of the citation network allows us to know the connections or correlations between articles (co-citation analysis), authors, keywords, areas of interest or cooperation among authors from different countries. To the best of our knowledge, few studies have taken this approach (Abu Bakar; Mahmood; Yoneda, 2026), but it is worth mentioning some recent works: a bibliometric analysis on geographical information systems (Liu et al. 2016), the extensive compendium of kriging variants in Chilès and Desassi (2018), the bibliometric review of the main modelling methods of soil mapping models by Agyeman *et al.* (2021), and the compilation of datasets and methods to study atmospheric CO2 by C. He, Grieneisen and Zhan(2022).

2. Methodology

A research protocol was designed to perform bibliometric analysis according to the various available sources as Web of Science, Scopus, etc. (Costa et al., 2017; Donthu *et al.,* 2021), and whose starting point was selecting the object of analysis, followed by database selection (Figure 1).

Figure 1. Research protocol



Source: own elaboration.

The *Web of Science* (WoS) electronic database is one of the largest interdisciplinary bibliographic databases and is commonly used by authors in their first stages of research. We limit our search to WoS since it is the most used database to perform bibliometric analyses (Singh et al., 2021; Aghaei Chadegani *et al.,* 2013). Given that the most important analyses and authors have their publications in WoS, we have chosen to restrict our analysis to this database.

Next stage was the search strategy and keywords selection, including "krig*" AND "spatiotemporal" OR "spatio-temporal" OR "space-time", in the title, abstract, and authors' keywords fields. The database was queried on January 3, 2023. Prior to 1990, scientific production on the subject was practically nonexistent (Figure 4), so the study period considered was 1990-2022, resulting in a total of 1157 records.

A filter was then applied to drop those documents that do not meet the criteria for "journal article" (170 documents) and written in "English language" (34). The final sample included 953 documents.

For the creation of some figures, the Citation Topics developed by the Centre for Science and Technology Studies (CWTS) have been used, which group documents by their citation networks at different levels (Macro, Meso, Micro).

The Bibliometrix R package (Aria and Cuccurullo 2017) was used to carry out most of the bibliometric analysis. This software allows researchers to perform descriptive analysis (essential bibliometric information) as well as network analysis. It also allows to previously apply statistical dimension reduction techniques such as Multidimensional Scaling (MDS), Principal Component Analysis (PCA) or clustering. Microsoft Excel and Web of Science internal analysis tools were also used to complete the analysis.

3. Results and findings

3.1 Descriptive analysis

3.1.1. Summary of data set

At first glance, the 953 documents of the selected sample were published in 415 different journals (Table1). A total of 3,348 researchers have tackled the topic (42 of which are single authors of 48 single-authored documents) and averaging 0.285 documents per author and 4.35 co-authors per document. Therefore, there exists a high degree of collaboration (3.51 authors and 4.35 co-authors per document). Spatiotemporal kriging is a quite recent topic in

the literature, exhibiting only 7.61 years on average since publication and 22.76 citations per document.

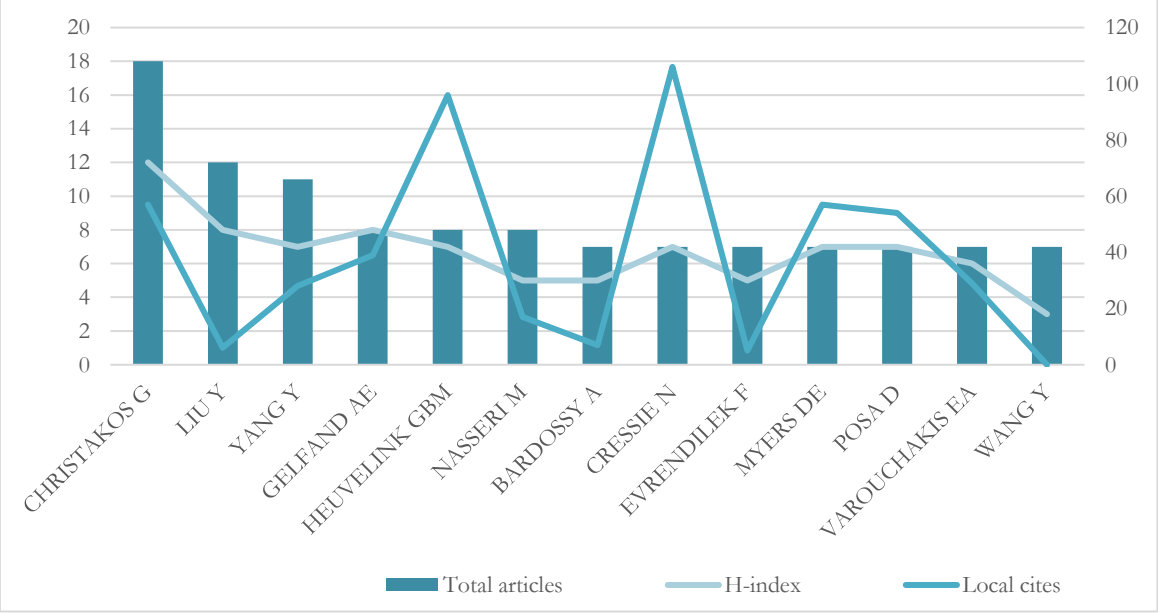
Table 1. Main statistics on documents published in journals

N	Time Span	Average years from publication	Average docs. per year	Sources	Authors	Docs. per author	Co-authors per doc.	Citations per doc.	Average citations per year per doc.
953	1990-2022	7.61	29.781	415	3,348	0.285	4.35	22.76	2.447

3.1.1.1. Authors

The list of authors with higher scientific production(Figure 2) is headed by George Christakos (San Diego State University) with 18 articles, Yajun Liu and Yong Yang (Huazhong Agricultural University of Wuhan) with 12 and 11 articles respectively, and Alan E. Gelfand (Duke University), Gerhard B.M. Heuvelink (Wageningen University) and Mohsen Nasseri (University of Tehran), with 8 articles each. Seven researchers have published seven articles, standing out Noel Cressie, who is considered one of the pioneers of spatial statistics and who has several must-read books, being the most cited author within the sample.

Figure 2. Most relevant authors per number of documents (left axis), H-index (left axis) and local cites (right axis)

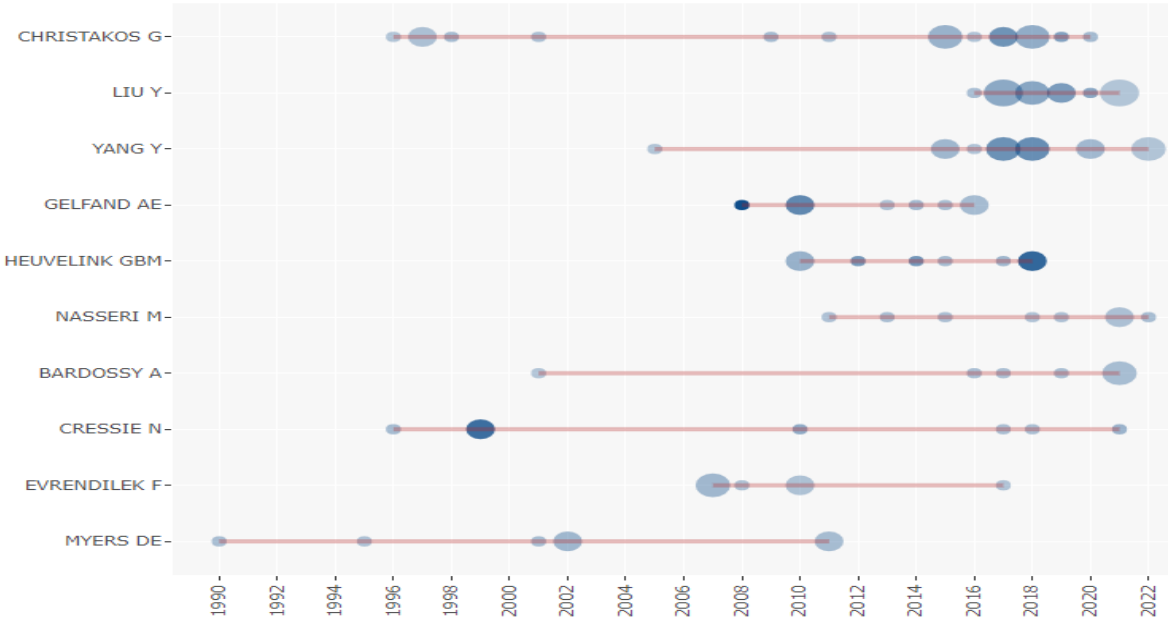


Source: own elaboration.

Considering the three most prolific authors, George Christakos stands out as a pioneering researcher in the development of spacetime kriging, integrating modern geostatistical approaches with Bayesian maximum entropy methods. His scientific output focuses on providing a solid theoretical framework and practical applications for modeling natural phenomena in space and time. Yajun Liu's scientific output on space-time kriging focuses on practical applications of data imputation and prediction with an emphasis on improving accuracy through integration with machine learning techniques and neural networks. Finally, Yong Yang's scientific output on spatiotemporal kriging focuses on the modeling and prediction of contaminants and soil properties, applying spatiotemporal interpolation approaches to improve the accuracy of environmental monitoring. His most notable contribution is a model that combines kriging with depth functions to interpolate contaminants in 3D, extending the spatiotemporal approach to volumetric applications.

Cressie, Christakos, and Gelfand have continued their scientific production for many years (Figure3), and both have devoted their research to innovation within spatial statistics from a theoretical point of view; in the case of Heuvelink, his research has been focused on soil science. Then it is not surprising that Christakos is, to date, the author with the higher impact according to the Hirsch (H) index, which it is defined as the number of papers with citation number greater than “h”, that is, researchers are assigned an index “h” if “h” of their papers has at least “h” citations each(Hirsch 2005; Hirsch and Buela-Casal 2014).

Figure 3. Top authors’ production over the time. The size of the circle indicates a higher volume of publications in that year.



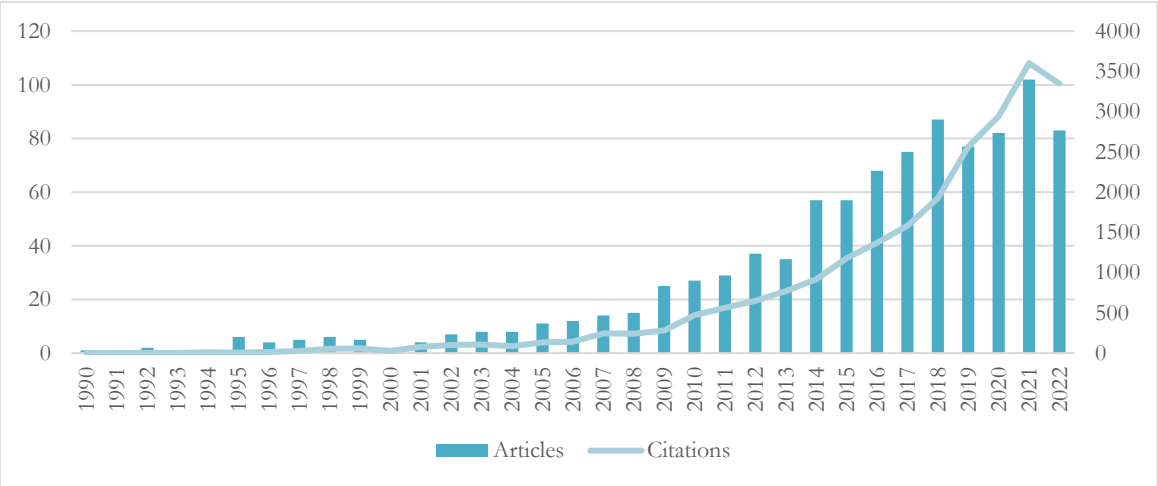
Source: own elaboration.

Three universities of the United States are among the five main institutions in terms of scientific production, closely followed by their Chinese colleagues. The hegemony of USA and China is also confirmed focusing on country-wise production and total citations. However, USA exhibit a higher rank in terms of average article citations per document (38.6 vs. 13.85), meaning that authors from the Asian country produce many documents, but they do not impact proportionally other studies. Spain is a quite similar case: it is the eighth country in production but presents a low citation rate (12.65). On the opposite side, Netherlands, France, and Switzerland flag a smaller number of documents, but the highest citation rates (48.74, 31.39 and 36.4 average citation per document respectively). Finally, the most important funding institution is by far the National Natural Science Foundation of China (154 articles funded).

3.1.1.2. Documents

The exponential growth of scientific production in recent years is noteworthy (Figure4), with an annual growth rate of 15.32% and reaching a maximum in 2021, in which 102 documents were published (83 articles have been published in 2022 up to the date of this research). This result alone indicates that spatiotemporal kriging is a methodology arising interest among researchers. Citations have also been rising at a similar pace, reaching a total of 3,603 in 2021 and 3,348 in 2022. The analyzed time span totalizes 953 documents, 23,616 times cited (21,953 without self-citations), and 18,748 articles cited, and an impact factor (H-index) of 73.

Figure 4. Annual scientific production(bar) and citation volume (line)



Source: own elaboration.

3.1.2. Keywords

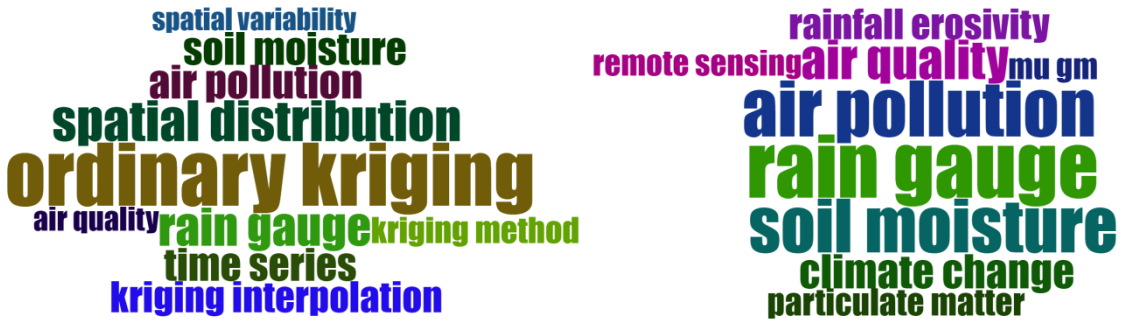
Keywords point out which are the main topics for researchers about their work. In this dataset (2,762 keywords), the most frequent words used by authors in the keyword section (Figure5) are kriging (195 mentions), geostatistics (91) and air pollution (45). Removing those words related to the method itself, it can be found the main features for which spatiotemporal kriging has been used to date: studies about air pollution (45), precipitation (26) or geographic information systems (GIS).Taking the above into account, it is significant that the kriging methodology has been put into practice mainly in climate and soil studies. In fact, the most prolific authors have stood out for their studies on air pollution, water, and soil quality, as well as various atmospheric phenomena. This consideration may explain the type of journals where these works are published, which we will analyze below.

Figure 5. Authors' keywords cloud (left) and filtered authors' keywords cloud (right)

Source: own elaboration.

Attending to the most repeated words in the abstracts (choosing bigrams instead of single words), similar results can be found terms related to the method itself, such as ordinary kriging (223 mentions), spatial distribution (145) and rain gauge (135), are the most frequent (Figure6). When removing method-related concepts, similar terms as in Figure 10 arise: rain gauge is still the most mentioned concept (135), followed by air pollution (119) and soil moisture (115). One can deduce then the main applications (to date) of spatiotemporal kriging: air quality and rain-derived effects on the soil.

Figure 6. Abstracts' keywords cloud (left) and filtered abstracts' keywords cloud (right)

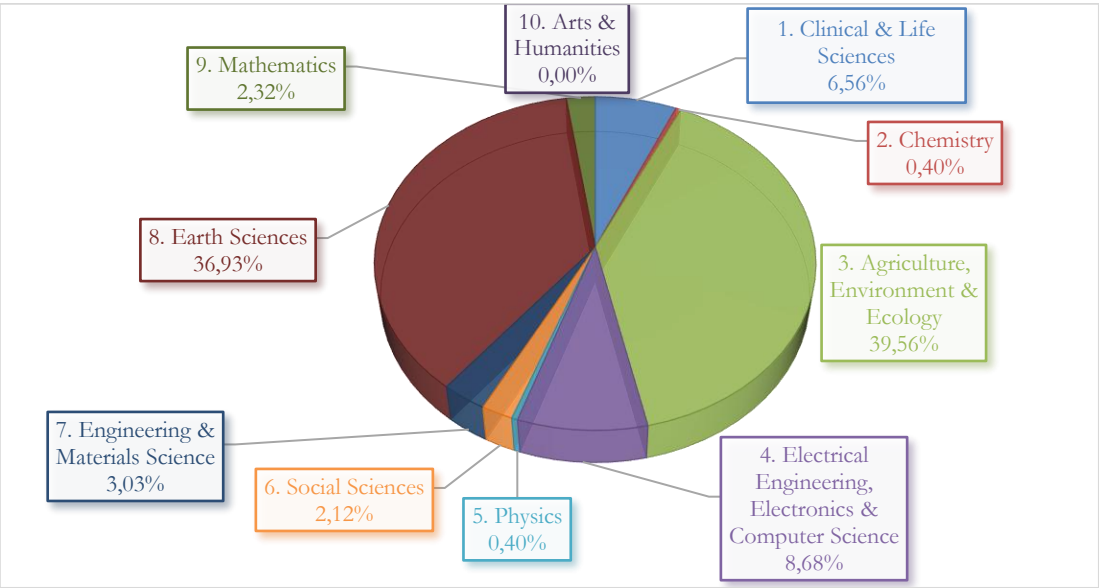


Source: own elaboration.

3.1.3. Categories

Web of Science provides information regarding the categories in that each article can be classified, and a subclassification called "CWTS Citation Topics." The main WoS classification shows that 16.02% of the articles are considered into the Environmental Sciences label, followed by Water Resources (7.86%), Statistics Probability (7.67%), Geosciences Multidisciplinary (7.42%), Meteorology Atmospheric Sciences (6.14%) and Engineering Civil (3.98%). These categories include roughly 50% of the papers. More interestingly, the "Citation Topics" is a citation-based classification algorithm that groups papers via citation. It is a hierarchical document-level classification system with three levels: 10 macro-topics, 326 meso-topics and 2,457 micro-topics. The *Web of Science* allows easy access to the macro and meso-topics classification. In the first case (Figure7), 39% and 38% of articles are labelled into the topics "Agriculture, Environment and Ecology" and "Earth Sciences" respectively, being the most important macro-categories.

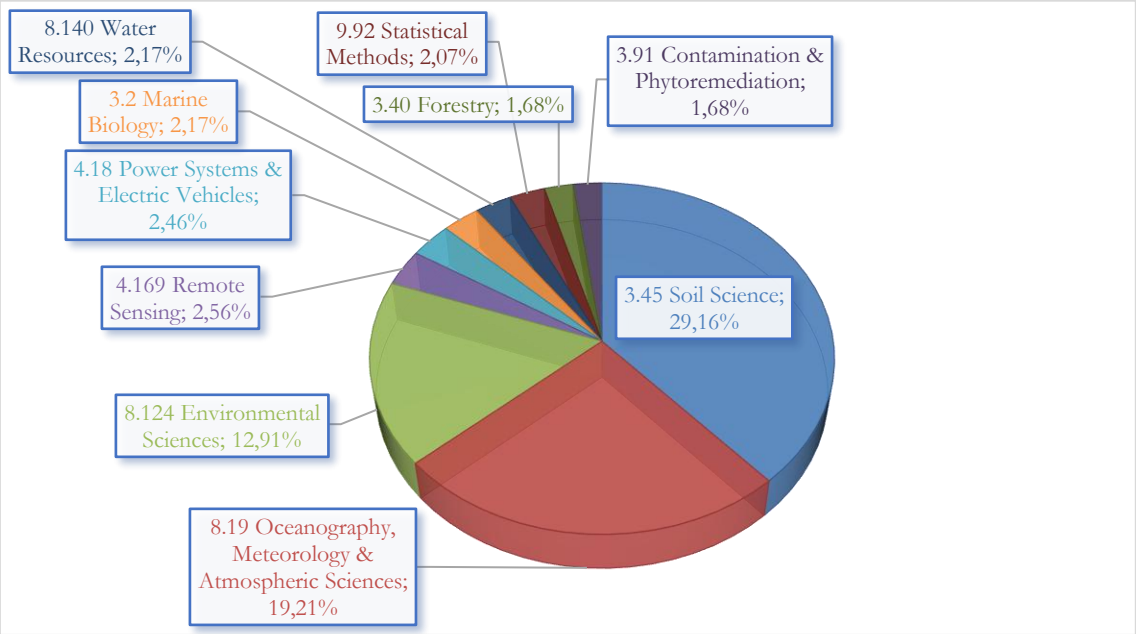
Figure 7. CWTS Citation Macro-Topics: ten very broad scientific fields.



Source: own elaboration.

The analysis of the meso-topics (Figure8), along with the keywords, allow us to identify the main branches of knowledge in which spatiotemporal kriging has been applied. Soil science is the most important meso-topic (29.16% of the articles can be classified into this category), followed by Oceanographic, Meteorology and Atmospheric Sciences (19.21%) and the generic Environmental Sciences (12.91%). It is worth noting that roughly 2.32% of the papers are classified in “Mathematics”, meaning that very few papers have made a huge impact in the remaining 97.68% of papers, mainly from the natural sciences.]

Figure 8. CWTS top ten Citation Meso-Topics: more specific thematic areas within a Macro Topic



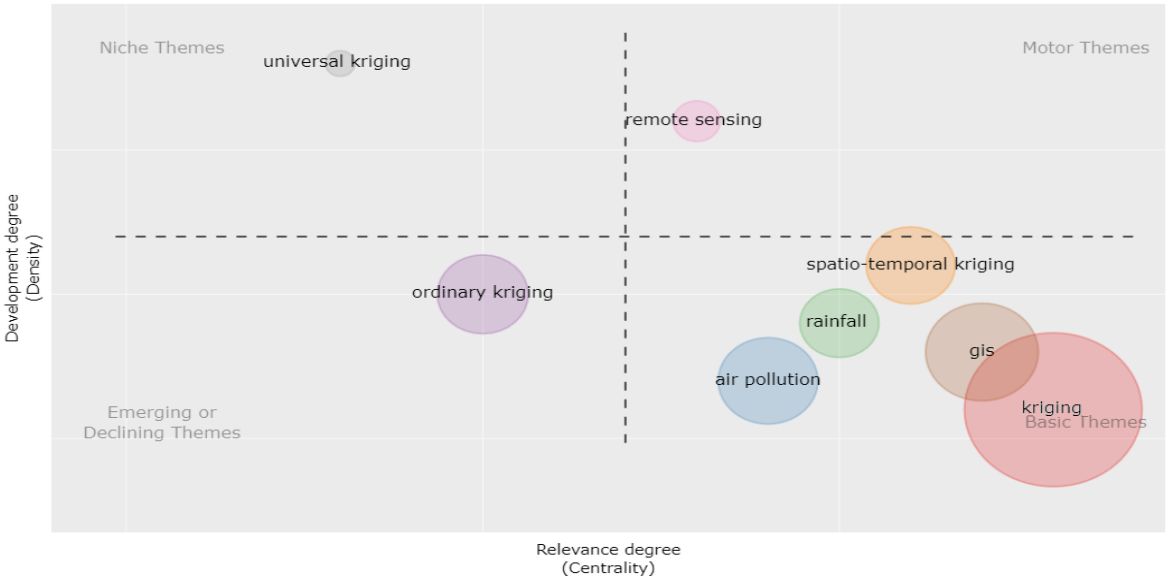
Source: own elaboration.

3.2. Network analysis

3.2.1. Conceptual structure

Network analysis focuses on revealing connections between different data in the sample, and it is organized in conceptual, intellectual, and social structure. The conceptual structure tackles word-related connections in different ways and from different sources (Keywords Plus, authors' keywords, words in the title or words in the abstract). In this research, authors' keywords are the unit of analysis. We first try to identify clusters (represented by circles) to help finding themes in spatiotemporal kriging, to further classify them into four quadrants based on density and centrality. Eight clusters can be identified (15 minimum cluster frequency per thousand docs, 500 words) (Figure9), highlighting well established topics related to methodology (kriging and spatiotemporal kriging) and applications (air pollution, rainfall, GLS), and a niche topic related to remote sensing as a recent motor topic.

Figure 9. Thematic map with clusters based on authors' keywords and quadrants based on density and centrality

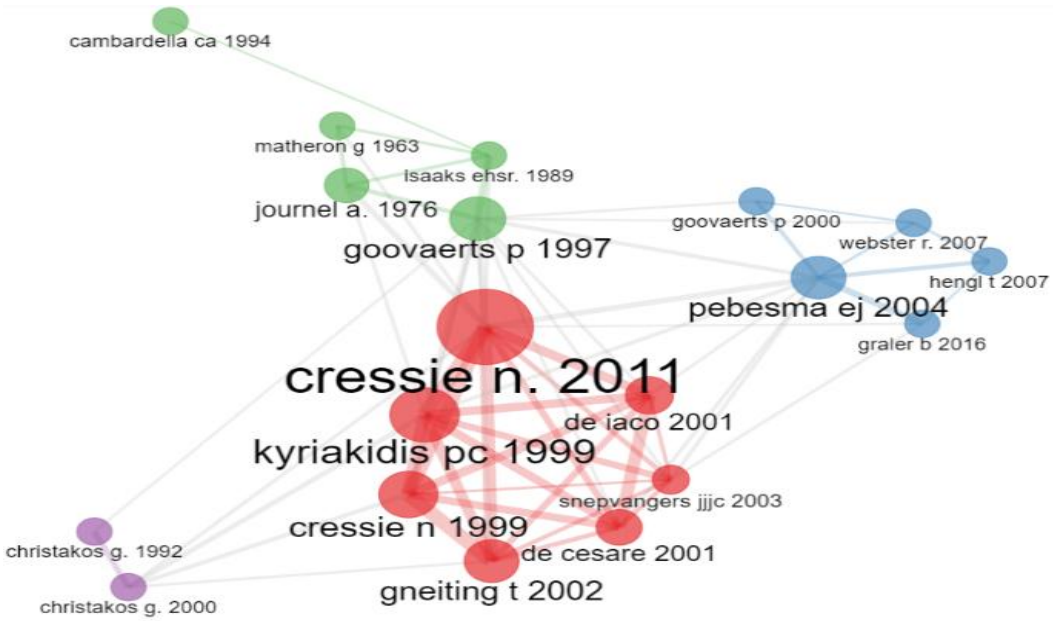


Source: own elaboration.

3.2.2. Intellectual structure

The intellectual structure analyzes citation relationships and is based on co-citation analysis, which involves identifying works that are cited together in the selected papers (co-citation analysis differs from bibliographic coupling in that the latter arises when two papers cite a same third article). As can be observed in Figure10, “Statistics for Spatio-Temporal Data” (Cressie; Wikle, 2011) is the most cited source within the sample, and it is commonly cited along with Ressie and Huang (1999), Gneiting (2002) and Kyriakidis and Journel (1999). This (red) cluster includes the main papers in spatio-temporal data, similarly to the green cluster headed by the book of Goovaerts (1997).

Figure 10. Co-citation network which shows the intellectual structure based on the analysis of co-citation



Source: own elaboration.

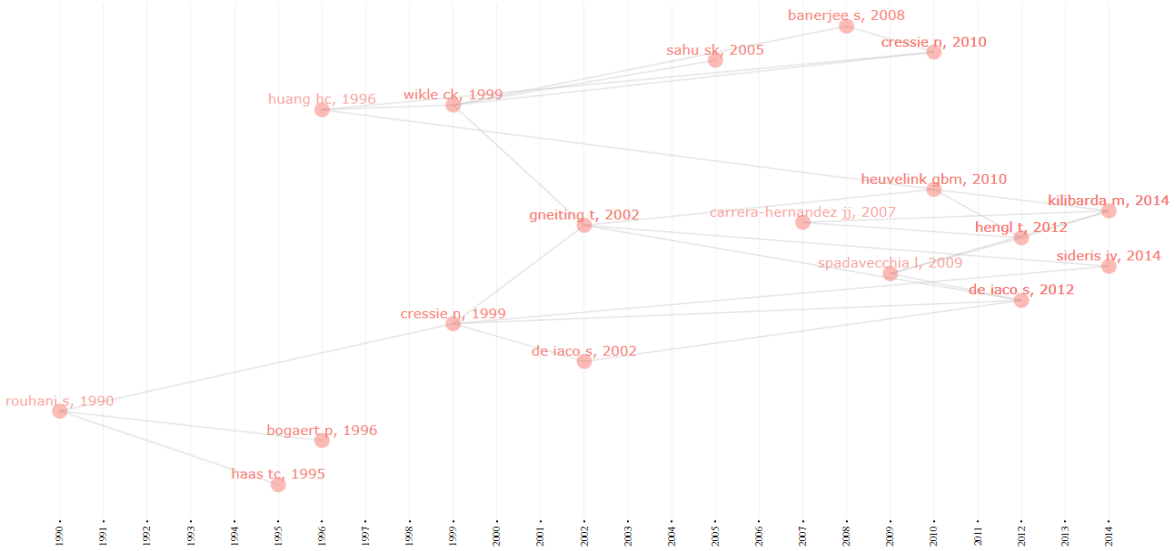
More recent trends in co-citation are represented by the blue cluster, led by the paper of Pebesma (2004) about geostatistical mapping, and Christakos (2012) on modern spatiotemporal statistics. From a different standpoint, it can also be drawn a historical direct citation network from the data frame 1990-2022, a bibliometric tool to trace the historical development of a certain branch of knowledge (Klavans; Boyack, 2017). According to our sample, the works by Rouhani and Myers (1990) and Huang and Cressie (1996) can be considered the origins of spatiotemporal kriging research. Table 2 shows the set of local citations within the database analyzed in this work and the global citations across the entire Wos database for the most relevant articles in the historical network of direct citations. Figure 11 reflects this citation network graphically.

Table 2. The 20 most relevant papers for historical direct citation network

Paper	Year	Local citations	Global citations
Rouhani and Myers (1990)	1990	19	87
Haas (1995)	1995	15	110
Huang and Cressie (1996)	1996	15	92
Bogaert (1996)	1996	12	36
Cressie and Huang (1999)	1999	51	399
Wikle (1999)	1999	23	266
De Iaco *et al.* (2002)	2002	20	43
Gneiting (2002)	2002	53	442
Sahu and Mardia (2005)	2005	13	82
Carrera-Hernández and Gaskin (2007)	2007	11	112
Banerjee *et al.* (2008)	2008	16	584
Spadavecchia and Williams (2009)	2009	13	54
Yu *et al.* (2009)	2009	11	45
Cressie *et al*. (2010)	2010	14	109
Heuvelink and Griffith (2010)	2010	27	61
Sampson *et al.* (2011)	2011	11	85
De Iaco and Posa (2012)	2012	12	25
Hengl *et al.* (2012)	2012	28	155
Sideris *et al.* (2014)	2014	12	105
Kilibarda *et al.* (2014)	2014	26	137

Source: own elaboration.

Figure 11. Historical direct citation network (1990-2022)

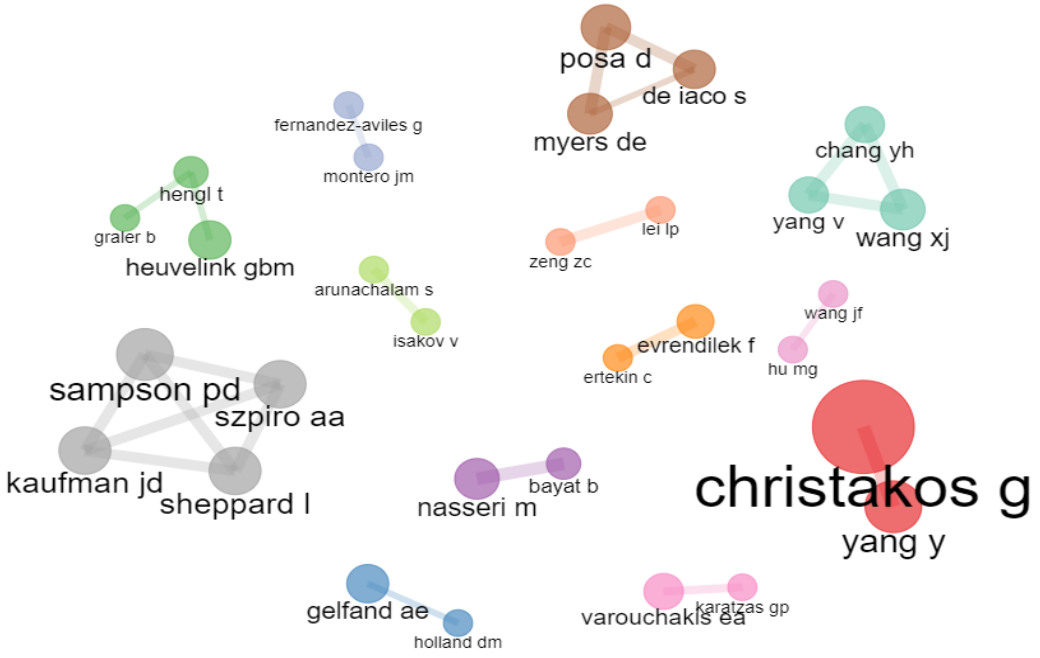


Source: own elaboration.

3.2.3. Social structure

Network analysis ends with the social structure of spatiotemporal kriging research. We first analyze relationships between authors, that is, co-authoring (Figure12). Among the most significant collaborations is that of Christakos and Yang, who have collaborated on studies about pollution in China, probably due to Christakos' affiliation with Zhejiang University for three years and Yong Yang's affiliation with Huazhong Agricultural University. There is also a close institutional relationship between Sandra de Iaco and Domenico Posa, both affiliated with the University of Salento (Italy). Donald E. Myers is linked to the University of Arizona (USA) and, although he has no direct affiliation with de Iaco and Posa, he has influenced their lines of research. Other authors share research projects such as the Multi-Ethnic Study of Atherosclerosis and Air Pollution (MESA Air), of which Sampson, Sheppard, and Szpiro are a part.

Figure 12. Collaboration network (authors): relationships between authors through co-authorship

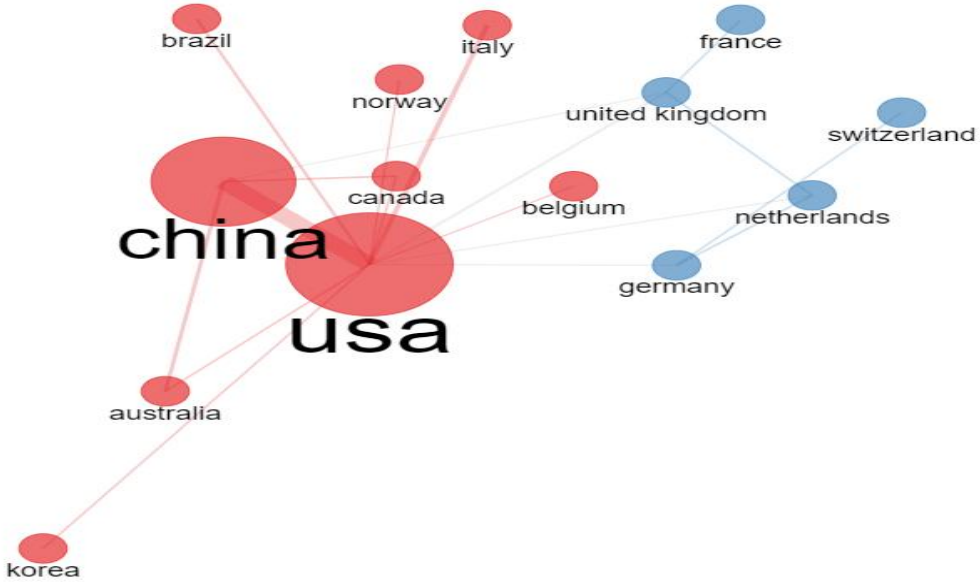


Source: own elaboration.

It can be observed that intra-country collaboration is far more frequent that intercountry collaboration and that the most productive and collaborative countries are China and USA (Figures 13 and 14).

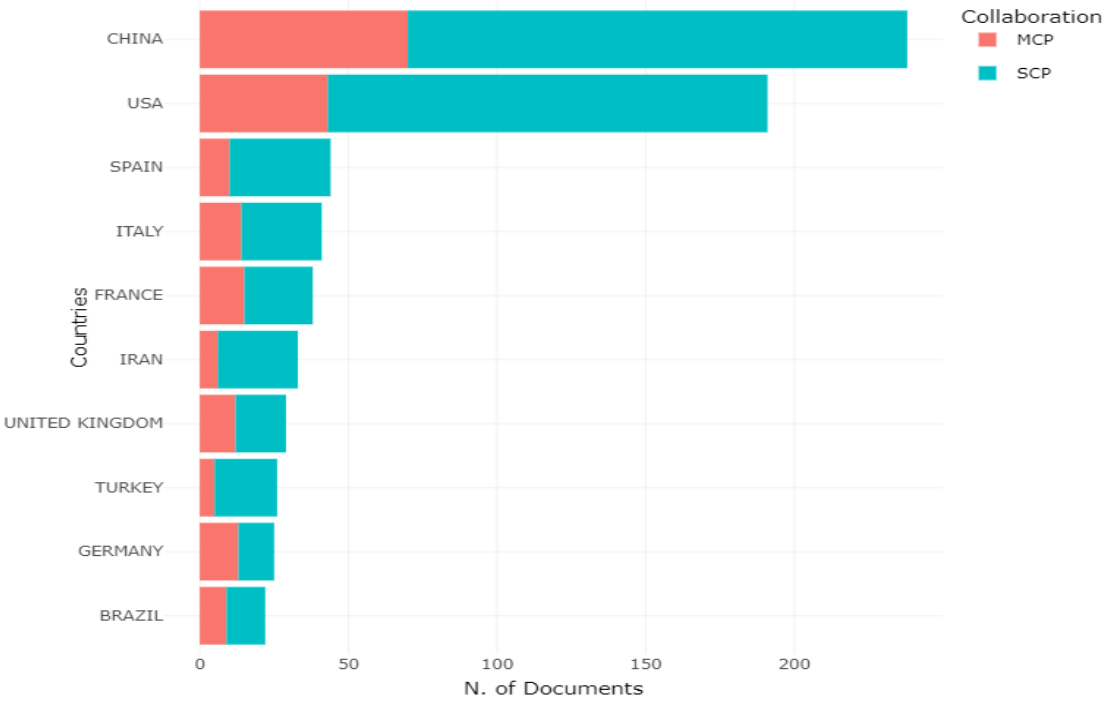
Figure 13. Collaboration network by country:

relationship between the fifteen most important countries



Source: own elaboration.

Figure 14. Corresponding author's country in the ten most productive countries: intra (SCP) vs. inter-country (MCP) collaborations



Source: own elaboration

4. Conclusion

As spatiotemporal analyses are growing in relevance in the scientific arena, spatiotemporal kriging has increasingly been applied to become one of the main methods to extrapolate data to predict missing values. This work contributes to a deeper insight into the state of the art through a bibliometric analysis with two distinct parts: a descriptive analysis and a network analysis.

The descriptive analysis shows that researchers from USA and China (and its institutions) are ahead in terms of scientific production and its impact on the academic community. We also paid attention to the most prolific and relevant publishers and, relatedly, the type of publication with regard to the "fees" (traditional submission vs. open access), highlighting that, although documents published in the traditional subscription system slightly surpass those published in open access, the impact of the open published articles is much lower in terms of total citations, citations per document and H-index. This work also explored the most cited authors' keywords and the categories in which the documents are included, concluding that, leaving aside terms related to the instrument and its methodology, authors' keywords focus mainly on the applications of kriging in different scientific areas: air pollution, particulate matter, rain gauge…. Thus, it is not surprising that the main WoS macro and micro categorizations (topics) are in line with authors' perspective.

The network analysis supports the descriptive in that the word-related connections show that studies about precipitation and pollution usually appeal to this technique to analyze the data. Improvements in remote sensing in the last years allow researchers to face new challenges using spatiotemporal kriging.

Future research could focus on specific scientific areas or subareas to provide a deeper understanding on how spatiotemporal kriging can be used in each specific field (soil sciences, atmospheric sciences…). Researchers from natural sciences will find this kind of research truly enlightening. Another possible line of future research could extend this bibliometric analysis and deepen into the different versions and applications of spatiotemporal kriging, by performing a systematic literature review and/or a content analysis.

Regarding the limitations of this study, the information used was obtained from the Web of Science (WoS), but it would be interesting to use other databases such as Scopus and compare results. Furthermore, the analysis period should be extended, as the last year considered was 2022.

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