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Article

Spatial Structure of National and International Scientific Collaboration in the Brazilian Cerrado Research

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ABSTRACT

The number of authors in papers has increased over the years, indicating collaborative trends in Science and Technology. Besides, scientific collaboration is structured at different spatial scales, for example, within or between institutions in the same country or among countries. Here, we evaluate the scientific collaboration patterns at national and international levels in the Cerrado research. We searched all papers about the Cerrado published between 1945 and 2017 in the Web of Science database. We performed network analyses using pairwise distance matrices to create national and international collaboration networks. We also used spatial correlograms to test the effect of geographic distance on scientific collaboration. The number of papers increased over the years (rs = 0.96), where papers with 3-5 authors had the highest growth rate (rs = 0.96). Moreover, authors from geographically closer institutions tend to collaborate more at the national level, while we found no geographic effect on international collaboration. These results show that Brazilian scientists studying the Cerrado have collaborated more over the years regardless of distance, although locally, scientists are still more likely to work with scientists of close institutions within the biome. This collaboration tendency may be associated with the need in science to deal with more complex and multidisciplinary issues, where collaborative studies promote a greater scientific and social impact.

Keywords: collaboration networks; correlograms; co-authorship; spatial scientometrics.

RESUMO

O número de autores em artigos tem aumentado ao longo dos anos, indicando tendências colaborativas em Ciência e Tecnologia. Além disso, a colaboração científica é estruturada em diferentes escalas espaciais, por exemplo, dentre ou entre instituições no mesmo país ou entre países. Aqui nós avaliamos os padrões da colaboração científica em nível nacional e internacional na pesquisa no Cerrado. Nós buscamos todos os artigos sobre o Cerrado publicados entre 1945 e 2017 no banco de dados *Web of Science*. As análises de rede foram realizadas usando matrizes de distância par-a-par para criar a rede de colaboração nacional e internacional. Correlogramas espaciais também foram utilizados para testar o efeito da distância geográfica sobre as redes de colaboração. O número de artigos aumentou ao longo dos anos (rs = 0.96), onde artigos com 3-5 autores tiveram a maior taxa de crescimento (rs = 0.96). Além disso, autores de instituições geograficamente mais próximas tendem a colaborar mais em nível nacional, enquanto nenhum efeito geográfico sobre a colaboração internacional. Esses resultados mostram que cientistas brasileiros estudando o Cerrado tem colaborado mais ao longo do

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tempo independente da distância, embora localmente, cientistas ainda tendem a trabalhar junto de cientistas de instituições mais próximas dentro do bioma. Essa tendência colaborativa pode estar associada com a necessidade da ciência em lidar com problemas mais complexo e multidisciplinares, ao qual estudos em colaboração promovem um maior impacto cientifico e social.
Palavras-chave: redes de colaboração; correlogramas; coautoria; cienciometria espacial.

1. Introduction

Scientific collaboration can be defined as a joint work of researchers aiming to produce (new) scientific knowledge. It is often measured considering the co-authorship in scientific papers (Liao & Yen 2012), and thus can occur at different levels (e.g., national and international) (Katz & Martin 1997). For example, co-authors can work at the same laboratory or department, at different institutions, or in different countries (Coccia & Wang 2016). Recent studies have shown the increase in international collaborations (Pan et al. 2012; Parreira et al. 2017), evidencing the likelihood of co-authorship, regardless of geographic distance. Furthermore, the increase in the number of papers with international collaboration has followed the scientific development in scientifically emerging countries (Ynalvez & Shrum 2011; Lemarchand 2012; Mêgnigbêto 2013), which benefit from scientific collaboration as an engine of scientific growth (The Royal Society 2011).

Given the importance of scientific collaboration, some studies have focused on co-authorship patterns, such as the spatial structure. Geographically closer researchers tend to show higher collaboration rates than geographically distant researchers (e.g., for international collaboration: Parreira et al. 2017; for national collaboration: Sidone et al. 2017). The scientometric literature has used different statistical methods to evaluate the spatial structure in the scientific collaboration (e.g., Mantel test, regression, spatial autocorrelation, gravity model), paving the way to an important research area, the spatial scientometrics (Ponds et al. 2007). This method is used to evaluate how scientometric indicators (e.g., collaboration) are related to geographic space.

Recent studies have demonstrated that scientific collaboration has increased over the years (Gazni et al. 2012) for many scientific fields, such as Biological Sciences (Nabout et al. 2015), Chemistry (Sangam & Meera 2009), Astrophysics (Jansen et al. 2010), Ecology (Parreira et al. 2017), Genetics (Sangam et al. 2013), and in different themes, such as climate change (Nabout et al. 2012; Haunschild et al. 2016). Since contemporary scientific issues are complex and involve high costs, papers are expected to be increasingly multi-authored. Besides, worldwide scientific collaboration has increased among researchers over the years (Nabout et al. 2015; Huang 2015). Therefore, many authors have studied many global aspects in distinct regions of the world since globalization has facilitated the accomplishment of collaborative studies (Bathelt & Henn 2014).

Socioeconomic aspects encourage scientific collaboration, such as global issues (e.g., climate change, genetic improvement, agriculture technology), that require international participation, modern equipment, financial aid for experiments, exchange programs (Jeong et al. 2014), or even the increase in the number of researchers (Abt 2007). Moreover, the collaboration plays a crucial role in scientific publications, such as increasing the quality of publications (Padial et al. 2010), cost-sharing (Avkiran 1997), scientific marketing (Vermeulen et al. 2013), and decreasing errors and uncertainties (Silberzahn & Uhlmann 2015), among others (Beaver 2001).

In the present study, we used solely co-authorship in scientific papers as the scientific collaboration, and thus, it is important to delimit the papers' research theme. In this sense, we used papers published by researchers studying the Cerrado biome. This biome is a savanna in the central region of Brazil that has been investigated by environmental and agricultural scientists, biologists, among others (Borges et al. 2014). There are public and private institutions focusing their researches in this biome (e.g., Embrapa Cerrado – focusing on sustainable agricultural development) and also research groups and graduate programs focused on studies about this biome (e.g., graduate program in Natural Resources of the Cerrado – focusing on multidisciplinary environmental research in this biome). Furthermore, this biome is one of the biodiversity hotspots for conservation priority (Myers et al. 2000), and thus, raise interest from international researchers collaborating directly with Brazilian researchers (international collaboration), besides being located in Brazil, which, as a consequence, is highly studied by local scientists, allowing the evaluation of national collaboration among Brazilian research institutions. Therefore, the scientific production of this biome is suitable to evaluate the patterns of scientific collaboration at different geographic scales.

In that regard, this study aimed to evaluate the collaboration patterns of Brazilian scientists at national and international levels, using the Cerrado biome as the research theme. Specifically, we seek to: i) evaluate the temporal tendency of publications and co-authorship in scientific papers; ii) map collaboration networks of collaborative papers at national (among institutions) and international (among countries) levels; iv) assess the effect of geographic distance on co-authorship patterns of collaborative papers at national and international scales.

2. Materials and Methods

2.1 Data collection

We obtained the scientometric data used (number of authors, year of publication, and authors' addresses) of each paper from the Web of Science *Core Collection* database (WoS; www.webofknowledge.com). The *Clarivate Analytics* WoS platform provides information about scientific papers from 1945 to the present. For this study, we used only articles about the Cerrado indexed between 1945 and 2017, whose titles had at least one of these terms: "*Brazilian Savanna**" OR "*Cerrado*". We used this strategy of keywords since they represent the whole aspects of publications about the Cerrado and include all variations in the Cerrado name (e.g., Cerrado biome, Brazilian Cerrado, Brazilian Savannah). However, although the search by titles ensures more specificity (i.e., more assertive search), some papers that do not cite the biome in their titles but may have developed researches in the region were not selected. Besides, in the Web of Science database, the title, abstract, and keywords of the papers are available only from 1991 onwards, whereas, before that year, only the title is available. Therefore, to promote similar sampling efforts of papers throughout the entire time series of the database, the terms mentioned above were searched only in the title of scientific papers.

At least two papers attributes are necessary to evaluate the collaboration at different spatial scales: i) the number of authors and ii) the address of each author, containing the author's institution and country. However, we noticed that most papers available in the WoS database for our search did not have the address of all authors. Therefore, to avoid deleting these papers or using a more restricted time series with complete information (1997-2017), we externally searched for all the papers with addresses omitted in the WoS database. The searches were performed individually using the internet (e.g., Journal's website, institutional repositories).

2.2 Data analysis

We used a Spearman rank correlation (rs) to verify the temporal tendency of publications about the Cerrado, categorizing the papers into single-authored and multi-authored (national and international collaboration) papers. Moreover, we classified all scientific papers into collaboration classes (1 author, 2 authors, 3-5 authors, 6-10 authors, and 10+ authors) and performed Spearman correlations to verify the temporal tendency of publications per year in the different classes of collaboration. The papers published about the Cerrado were later categorized into the authors' nationality (international co-authorship) and research institutions (national co-authorship).

For national collaboration, we created a collaboration network among research institutions. The institution, in this context, is defined as the researcher's workplace (as found in the paper's address), such as universities, research centers, either public or private. To create the inter-institutional collaboration network, we selected the top 30 institutions with more collaborative papers. We used a binary matrix (papers x institutions) to organize the collaboration data, where 1 was given to the institution present in the paper's address field. After that, we built an adjacency matrix (30 x 30) of institutions, where the collaborations between institutions were counted. We then created the collaboration network connections, where each pairwise relationship among institutions is considered a collaboration event. To perform this analysis, we used the *graph.adjacency* function from the *igraph* package (Csardi & Nepusz 2006) in the R software version 3.5.1 (R Core Team 2019). This network informs the relative collaboration of each institution (vertex size from the degree of centrality [DC]: number of links [edges] of each institution) and the intensity of collaboration (direction and thickness of connections). The degree of centrality of each institution *i* (DC*i*) was divided by the number of institutions (30) minus one to calculate the relative degree of centrality (RDC*i*) that indicates the importance of each institution in the collaboration network (Koschützki et al. 2005). Finally, those data were later used to map the national collaboration network within the Brazilian map using each institution's geographic location (headquarters) in the QGIS software version 3.2 (QGIS Development Team 2018).

For the international collaboration, we created a collaboration map using the dissimilarity indexes generated by the Jaccard distance analysis using the function *vegdist* from package *vegan* (Oksanen et al. 2017) in the R software version 3.5.1 (R Core Team 2019). For this, we used a binary matrix (0 or 1) with all countries in columns and all papers in rows, where 1 was given to the country present in the paper's address field. After that, we used the values of similarity (1-dissimilarity) of all countries collaborating with Brazil as multiple-sized network lines to create the collaboration world map. Besides, we plotted in the same map the absolute number of internationally collaborative papers in black gradient colors for each country. This map was built using the QGIS software version 3.2 (QGIS Development Team 2018). Thus, similarity values indicate the proportion of papers of Brazilian scientists in collaboration with non-Brazilian authors. For example, when closer to 1, it indicates a greater collaboration rate with Brazilian authors.

To evaluate the spatial effect of geographic distance on scientific collaboration in the papers, we used the Jaccard distance (binary) to calculate the collaboration distances at national and international levels. For the geographic distance, we used Euclidean distance (continuous) created from the coordinates of institutions' headquarters (national) and the coordinates of countries' centroids (international). Therefore, for national collaboration, we ended up with a Jaccard matrix and a Euclidean matrix, both representing the distances (collaboration and geographic, respectively) among all institutions. For international evaluation, we only calculated the distances (collaboration and geographic) between Brazil and the other countries, using the Jaccard distance values for the collaboration distance and Euclidean distance values for the geographic distance. The data regarding collaboration and geographic distances were used to spatially evaluate the collaboration using spatial correlograms. We generated a Mantel correlogram using the function *correlog.mantel* from package *vegan* for national and international collaboration, a Moran's I correlogram using the function *correlog* of package *pgirmess* (Giraudoux 2018), both packages in the R software version 3.5.1 (R Core Team 2019). Five distance classes were retained for the Mantel correlogram and 12 for Moran's I correlogram. The number of classes was determined by the Sturges equation (Legendre & Legendre 2012).

Spatial analyses use different metrics to measure how a given continuous variable is distributed in the geographic space, and among those, we can cite correlograms and gravitational models. Scientometric studies have used some of those to investigate the spatial structure of scientometric indicators (e.g., collaboration) (Frenken & Hoekman 2014). We used correlograms (Mantel and Moran's I) to evaluate how collaboration is related to the geographic distance (among institutions and between Brazil and other countries). In the correlogram, the response variable is collaboration, which in this case is an institution similarity matrix for Mantel, and a vector with the similarity values of each country with Brazil for Moran's I. We generated a similarity index (r for Mantel and I for Moran), varying from -1 to +1. This index is distributed into different distance classes (from lowest to highest). Therefore, positive values in geographically close distance classes indicate a greater collaboration in geographically closer unities (e.g., countries, institutions). The significance of each distance class was tested using randomization (999 permutations), and the classes were considered significant after Bonferroni correction (significance value divided by the number of classes) (Oden 1984).

3. Results

We found a total of 2262 papers (2134 multi-authored and 128 single-authored) published in the WoS platform about the Cerrado between 1945 and 2017. Among the collaborative papers, 1708 were in national collaboration and 426 in international collaboration. The first indexed paper was published only in 1960 with only one author. The temporal analysis of publications about the Cerrado shows an increasing trend in the number of papers over the years ($rs = 0.96$; $p < 0.01$), where the papers with national collaboration had a higher increase ($rs = 0.96$; $p < 0.01$) than the papers with international collaboration ($rs = 0.89$; $p < 0.01$) (Figure 1).

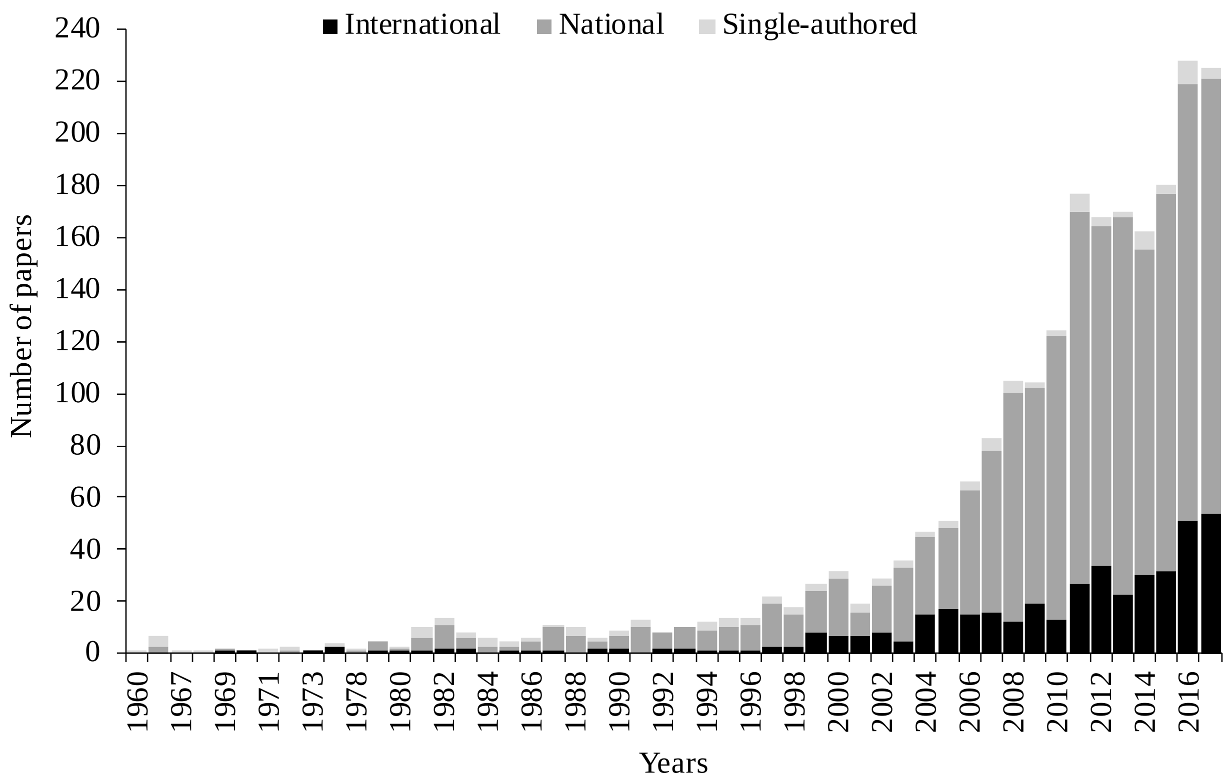

Figure 1. Temporal tendency of papers published about the Cerrado between 1945 and 2017, categorized into international, national, and single-authored papers.

Most papers fall within the co-authorship class of 3-5 authors (52.39%), followed by papers with 6-10 authors (23.34%), papers with 2 authors (17.11%), single-authored papers (5.66%), and papers with more than 10 authors (1.50%). However, until the 1980s, the single-authored papers represented 35.37% of all published papers, being the class with the most papers. All classes of co-authorship showed growth trends over time: single author ($rs = 0.70$; $p < 0.001$); two authors ($r = 0.92$; $p < 0.001$), 3 – 5 authors ($rs = 0.96$; $p < 0.001$), 6 – 10 authors ($rs = 0.87$; $p < 0.001$); and more than ten authors ($rs = 0.64$; $p < 0.001$). However, proportionally to the total number of papers in each year (cumulative percentage), only papers with more than three authors have increased over the years (Figure 2).

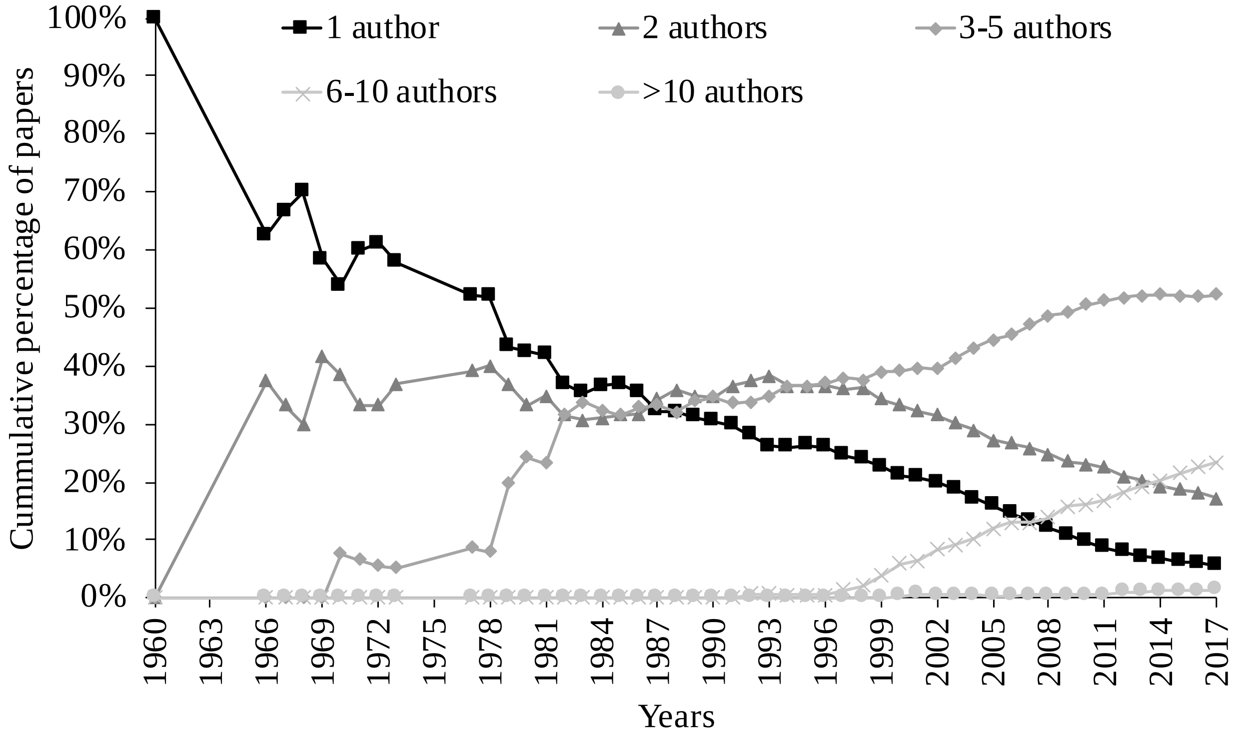

Figure 2. Temporal tendency of papers divided into classes of number of authors (1, 2, 3-5, 6-10, and >10 authors), published about the Cerrado between 1945 and 2017.

Brazil is the country with the most publications about the Cerrado, with 2171 papers (415 international, 1659 national, and 97 single-authored papers), followed by the United States with 209 papers (166 international [160 with Brazil], 25 national, and 18 single-authored papers) and France with 55 papers (All international collaboration with Brazil). The international collaboration map between Brazil and other countries shows a broad international collaboration network, regardless of proximity to the Cerrado. Moreover, we found a great collaboration between Brazilian authors with authors from the U.S. (Jaccard Index [JI = 0.38]), Canada (JI = 0.05), and Europe (e.g., France [JI = 0.13], United Kingdom [JI = 0.12], Germany = [JI = 0.09]). Among those, Brazil collaborates with the U.S. in 40.6% of the collaborative papers analyzed. However, although less expressive, we noticed collaborations with developing countries worldwide, such as India, Indonesia, and Kenya (Figure 3).

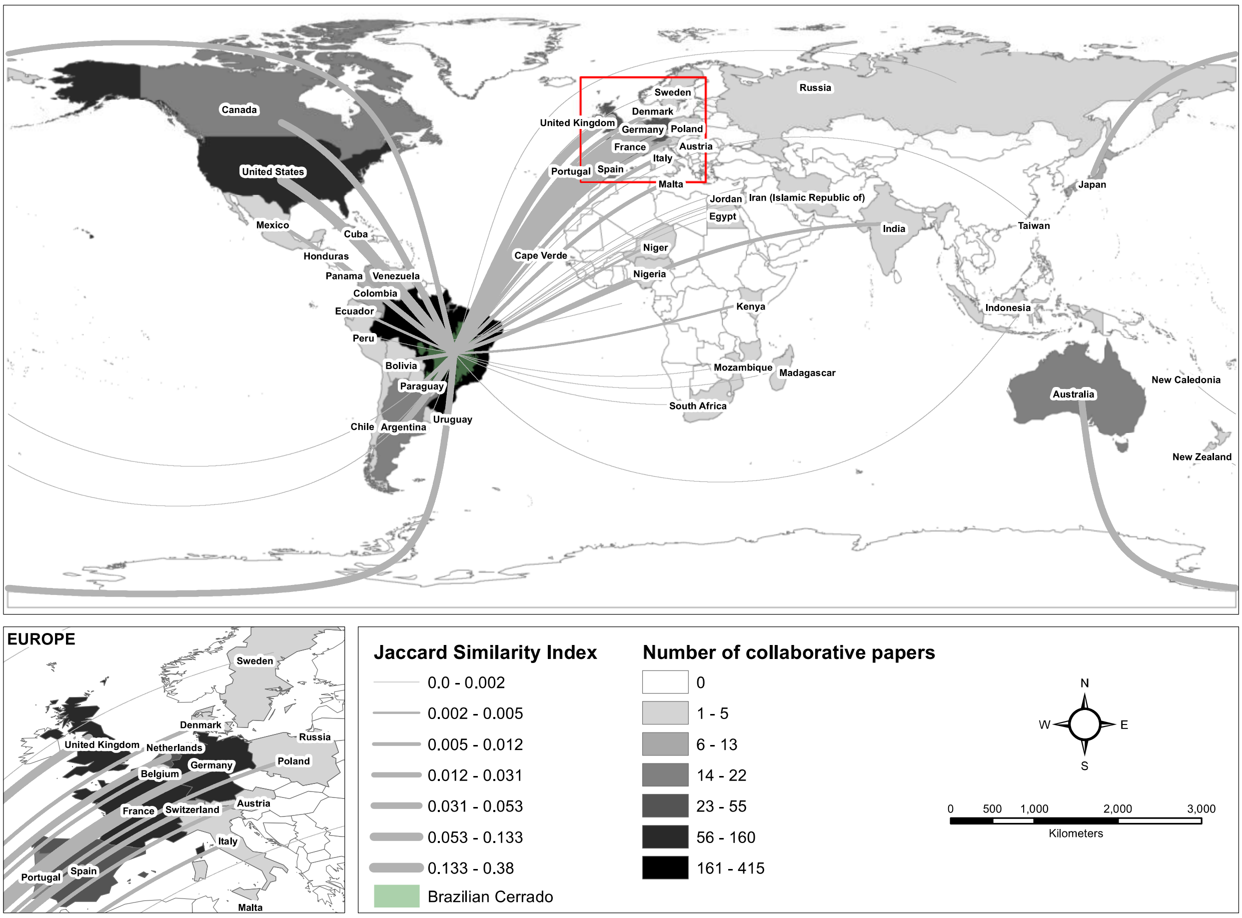

Figure 3. Gradient map with collaboration lines representing the international collaboration network. Black gradients represent the number of internationally collaborative papers of countries. Network lines (i.e., Jaccard Index values) represent the collaboration between Brazil and other countries in papers about the Cerrado between 1945 and 2017. Geographic and collaboration data are available in Table S1.

We found 297 Brazilian institutions and 387 institutions from 44 countries in the collaborative papers about the Cerrado between 1945 and 2017. Of the institutions analyzed, the first 30 most collaborative institutions are all from Brazil and represent 66.8% of all collaborative papers from Brazilian institutions and 59.8% of all institutions (national and international). Once we verified the collaboration network among the 30 most collaborative institutions, we identified strong collaborations among them (at least 5 institutions in collaboration) and that UnB, UFG, and USP showed the highest degree of centrality. Furthermore, it is possible to notice that most institutions are within or near the Cerrado area, except for some southeastern institutions; however, institutions such as UNESP have campuses within the Cerrado area (Figure 4).

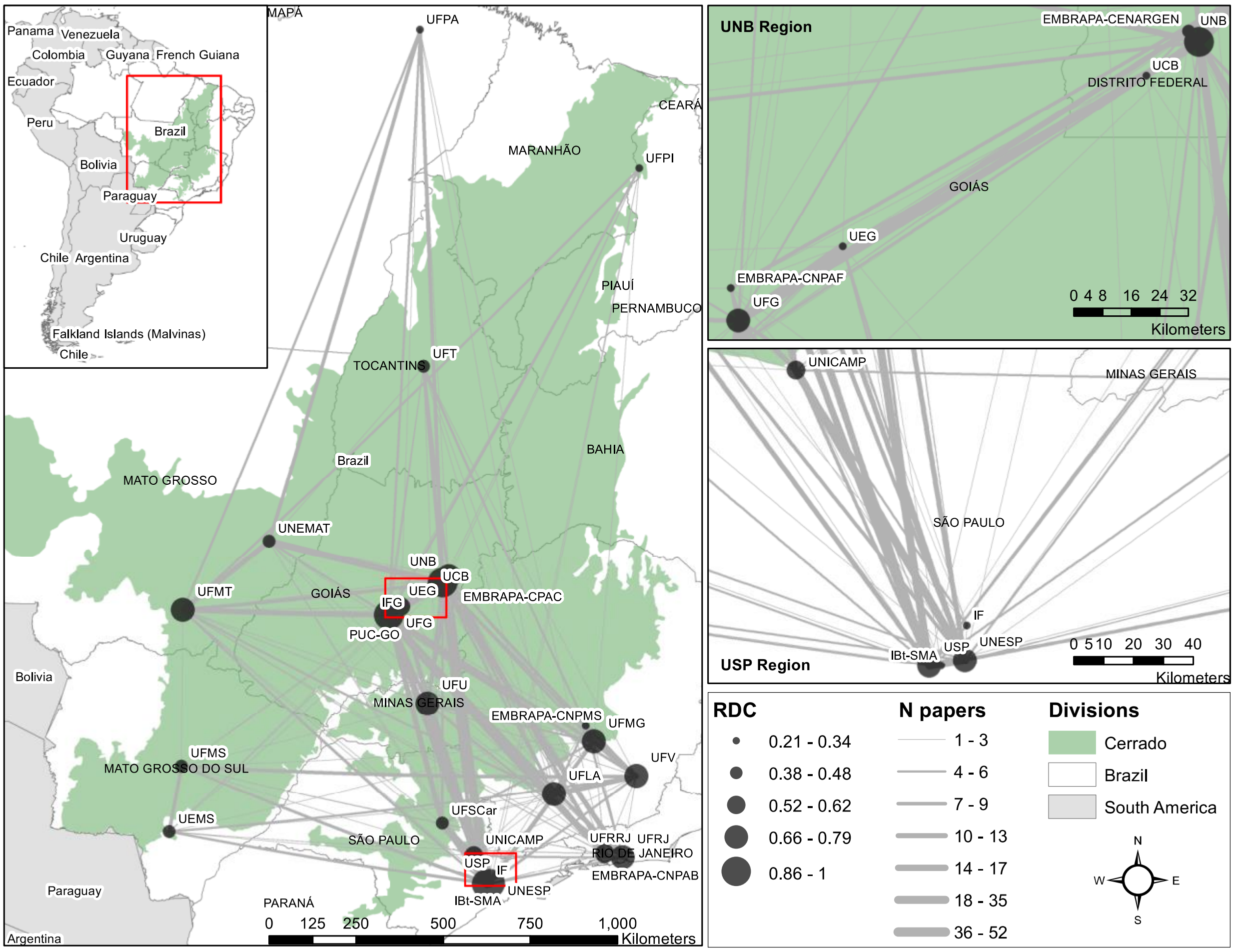

Figure 4. Collaboration network map of the 30 institutions with more papers about the Cerrado between 1945 and 2017. Circle sizes (RDCi) indicate the relative contribution of institutions (i) in the collaboration network. The relationship between institutions (lines) indicates the number of papers in collaboration between two institutions (thickness of lines). Complete names of institutions and geographic data are available in Table S2.

The effect of geographic distance on national and international collaboration was tested in papers with the term Cerrado in the title. In the international collaboration, according to Moran's I correlogram, no distance class was significant since all p-values of classes were higher than the p-value generated by the Bonferroni correction ($p = 0.004$). That is, we found no effect of geographic distance on scientific collaboration at the international level (Figure 5a). In the national collaboration, the Mantel correlogram showed that only the first class (123.62 km; $p = 0.001$) was significant, lower than Bonferroni p-value ($p = 0.01$). This result indicates that national collaboration is higher in close distances (lower than 123 km) and that this collaboration decreases as the geographic distance between institutions increases (Figure 5b).

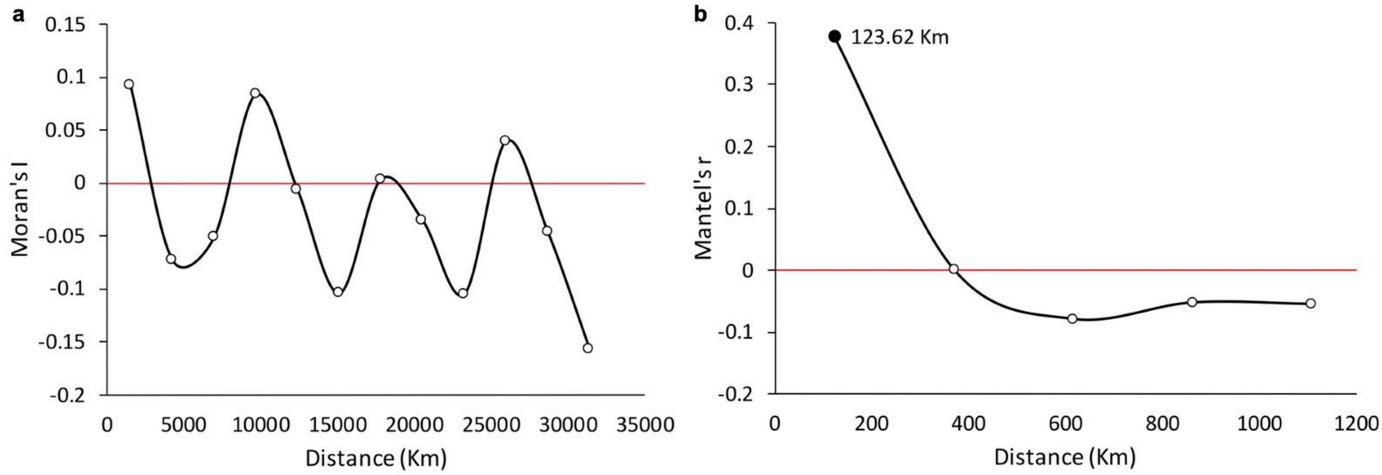

Figure 5. Spatial correlogram with geographic distance classes in kilometers. a) Moran's I correlogram representing the spatial effect on international collaboration. b) Mantel correlogram representing the spatial effect on national collaboration. The filled circle represents the distance class with a significant p-value. Horizontal lines in the y-axis represent the null hypothesis (i.e., absence of spatial autocorrelation).

4. Discussion

Our results show a strong increase in scientific collaboration at different spatial scales about the Brazilian Cerrado. Besides, even for a regional scale (biome), the international collaborations (among authors from different countries) showed an increasing tendency, following the pattern found in studies with broad research areas or larger spatial scales (Nabout et al. 2015; Sidone et al. 2017; Parreira et al. 2017). The spatial effect of geographic distance divided into two scales (national and international) shows the effect of geographic distance (predictor) on scientific collaboration (response). Among institutions (national), we found that collaboration is greater between closer institutions up to a distance of 123 km (first distance class – Mantel correlogram), decreasing as the geographic distance increases. However, this same effect was not found among countries (international), where the collaboration is not dependent on geographic distance since no distance class of the Moran's I correlogram was significant.

The number of papers about the Cerrado has increased over the years nationally and internationally, addressing several themes, mainly related to the biome biodiversity (Borges et al. 2014). This increasing tendency of the number of papers is similar for many areas (de Souza & Ferreira 2013; Sangam et al. 2013; Nabout et al. 2015; Parreira et al. 2017). This phenomenon can be explained by the need of solving problems of the last decades (e.g., scarcity of natural resources, global warming, public health) and the increasing volume of scientific studies (Ivancheva 2013). Moreover, high productivity can assure more funding and fortification of research groups (de Meis et al. 2003). In Brazil, this increase has occurred from the 1980s onwards, of which after 20 years, the production has reached almost six times more published papers (Mugnaini et al. 2004). Due to the creation of the federal funding agencies, Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and the Conselho Nacional de Desenvolvimento Científico e Desenvolvimento Tecnológico (CNPq), the last 50 years were marked by great progress in the Brazilian scientific production, becoming a reference in research and postgraduate programs in Latin America (Andrade & Galembeck 2009).

The great majority of papers published about the Brazilian Cerrado were multi-authored papers at the national level, especially papers with 3-5 and 6-10 authors. Besides, the growth trend in the number of papers from the 1980s onwards follows the change from single-authored to multi-authored papers in the same period. Other studies with other subject areas have also found this trend in changes from single- to multi-authored over the years (Nabout et al. 2015; Huang 2015). Increasingly, science is becoming collaborative in Brazil, also aiming at international collaboration (Leta & Chaimovich 2002; Santin et al. 2016). The country has greatly collaborated with other countries such as the United States, Germany, Canada, the United Kingdom, among others (Gazni et al. 2012; Santin et al. 2016). This collaboration allows the investigation of complex multidisciplinary problems, which requires a team of researchers from different areas of knowledge (Jeong et al. 2014). Another factor that must be taken into consideration is financial resources, where involving more authors may save costs of study development (Vermeulen et al. 2013).

The institutions with the most publications were also the most collaborative. UnB, USP, UFG, EMBRAPA-CPAC, and UNESP together represented more than half of all published papers and a third of all collaborative papers about the Cerrado. A comparative study found that USP, UNESP, and UnB were among the ten most productive universities between 1991 and 2010, both in Scopus and WoS platforms (Leta 2012). Many institutions in the papers analyzed are located within the Cerrado biome, which indicates an interest of local researchers in studying their local region. Additionally, some of these most collaborative institutions are geographically closer (e.g., USP and UNESP; UFG and UnB), demonstrating a spatial structure in the collaboration between Brazilian scientists about the Cerrado.

The geographic distance might be a limiting factor of collaboration, despite globalization (Larivière et al. 2006; Ponds et al. 2007; Parreira et al. 2017). In this sense, collaboration tends to be greater among authors located in geographically closer institutions (national) or countries (international) (Larivière et al. 2006; Parreira et al. 2017), especially on regional scales. In our study, we found a relationship between geographic distance and research collaboration at the national level. In this case, authors from geographically close institutions tend to collaborate more, with collaboration decreasing as the distance increases. This result might be related to the fact that most institutions with authors publishing about the Cerrado are located within this biome (e.g., UnB, UFG, and UFMT) or have campuses situated in the Cerrado (e.g., UNESP, UFMG). At the international level, we did not find any relationship between geographic distance and research collaboration, different from other studies that show more collaboration among authors from geographically close countries (Larivière et al. 2006; Parreira et al. 2017). Because it is a biome located in a large-scale country, it is expected an intra-national variation, different, for example, from European biomes, where the variation is more noticed on an international scale (e.g., biomes of temperate forests; Woodward et al. 2004), given the small size of those countries in comparison to Brazil. Therefore, these results indicate a change in the spatial pattern of collaborations depending on the geographic scale used.

In addition to geographic distance, the collaboration pattern may be due to other factors, such as the number of researchers (Abt 2007) or even research financial aid (Jeong et al. 2014). We must also emphasize that the collaboration has increased over the last years given the collaboration networks due to factors such as (i) internet, which has facilitated interactions and contact among researchers; (ii) scientific events such as conferences, symposiums, and congresses, for information exchange and discussions; and (iii) exchange students (both at national and international levels) that, by collaborating to other researchers, increase the collaboration networks among researchers (Köseoglu et al. 2018). Besides, other factors such as common language between countries, historical relationships, economic and innovative capacity, and administrative barriers can be relevant factors that influence the collaborative network (Orazbayev 2017; Parreira et al. 2017; Gui et al. 2019). Another significant factor is that larger research groups tend to publish more studies (Youngblood and Lahti 2018) with higher impact (Larivière et al. 2015), reinforcing the idea of collaborative science. Finally, it is important to consider that our analysis did not investigate the temporal variation of the collaboration network (Fonseca et al. 2017). Yet, the spatial structure presented here is a snapshot of the collaboration network among institutions and countries. The current spatial structure is a result of the temporal change in collaborations, however, occurring on intra- and international scales.

The United States is the country that collaborates the most with Brazil in papers about the Cerrado. This result was expected since the US is the second country with more publications about the Cerrado. Moreover, the US collaborates in many areas with Brazil, such as agriculture (Chinchilla-Rodríguez et al. 2010), Evolutionary Biology (Santin et al. 2016), Geosciences, Biomedicine, Chemistry, Medicine, Neuroscience, Engineering, Biology, and Math (Vanz & Stumpf 2012). We also found a high collaboration between Brazilian and European institutions. Besides the interest of European and American scientists in developing studies in the Cerrado, this collaboration may be due to the need of developing countries for specialized scientific facilities and financial resources from developed countries (Frenken 2002). These collaborative studies between international institutions tend to generate high-quality papers because they have increasingly complex problematizations (Leta & Chaimovich 2002) and also high impact in the scientific community, as well as socioeconomic resources that help in developing globally relevant researches.

In conclusion, there is a general trend towards multi-author studies that seek to answer fundamental scientific questions since discussions nowadays can be developed on a global scale. These trends in collaboration patterns are associated with the need for science to deal with complex and multidisciplinary issues, which requires research groups to collaborate to promote high-impact studies. For the Cerrado, particularly, environmental (e.g., anthropic impacts), social (e.g., scientific education), and agricultural (e.g., food security) issues are required to be discussed by research groups from different scientific areas both at national or international levels. Collaborative studies have promoted significant changes in the development of science. Thus, it is an expected trend in future studies, mainly because collaboration allows the production of an increasing number of high-impact researches.

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References

Abt HA 2007. The publication rate of scientific papers depends only on the number of scientists. *Scientometrics* 73(3):281–288.

Andrade JB de, Galembeck F 2009. QUALIS: Quo Vadis? *Quim Nova* 32(1):5–5.

Avkiran NK 1997. Scientific collaboration in finance does not lead to better quality research. *Scientometrics* 39(2):173–184.

Bathelt H, Henn S 2014. The Geographies of Knowledge Transfers over Distance: Toward a Typology. *Environ Plan A Econ Sp* 46(6):1403–1424.

Beaver DD 2001. Reflections on Scientific Collaboration (and its study): Past, Present, and Future. *Scientometrics* 52(3):365–377.

Borges PP, Oliveira KAF de A, Machado KB, Vaz ÚL, Cunha HF da, Nabout JC 2014. Trends and gaps of the scientific literature on the Cerrado biome: A scientometric analysis. *Neotrop Biol Conserv* 10(1):2–8.

Chinchilla-Rodríguez Z, Vargas-Quesada B, Hassan-Montero Y, González-Molina A, Moya-Anegóna F 2010. New Approach to the Visualization of International Scientific Collaboration. *Inf Vis* 9(4):277–287.

Coccia M, Wang L 2016. Evolution and convergence of the patterns of international scientific collaboration. *Proc Natl Acad Sci* 113(8):2057–2061.

Csardi G, Nepusz T 2006. The igraph software package for complex network research. *InterJournal, Complex Syst* 1695(5):1–9.

Fonseca B de PF e, Silva MVP da, Araújo KM de, Sampaio RB, Moraes MO 2017. Network analysis for science and technology management: Evidence from tuberculosis research in Fiocruz, Brazil. *PLoS One* 12(8):e0181870.

Frenken K 2002. A New Indicator of European Integration and an Application to Collaboration in Scientific Research. *Econ Syst Res* 14(4):345–361.

Frenken K, Hoekman J 2014. Spatial Scientometrics and Scholarly Impact: A Review of Recent Studies, Tools, and Methods. In *Measuring Scholarly Impact*. Springer International Publishing, Cham, p. 127–146.

Gazni A, Sugimoto CR, Didegah F 2012. Mapping world scientific collaboration: Authors, institutions, and countries. *J Am Soc Inf Sci Technol* 63(2):323–335.

Giraudoux P 2018. pgirmess: Spatial Analysis and Data Mining for Field Ecologists. R package version 1.6.9.

Gui Q, Liu C, Du D 2019. Globalization of science and international scientific collaboration: A network perspective. *Geoforum* 105:1–12.

Haunschild R, Bornmann L, Marx W 2016. Climate Change Research in View of Bibliometrics. *PLoS One* 11(7):e0160393.

Huang D 2015. Temporal evolution of multi-author papers in basic sciences from 1960 to 2010. *Scientometrics* 105(3):2137–2147.

Ivancheva L 2013. Science - Society Relations Enhancement: Policy Implications and Some Scientometric Evidences. *Bulg J Sci Educ Policy* 7(2):49–66.

Jansen D, von Görtz R, Heidler R 2010. Knowledge production and the structure of collaboration networks in two scientific fields. *Scientometrics* 83(1):219–241.

Jeong S, Choi JY, Kim J-Y 2014. On the drivers of international collaboration: The impact of informal communication, motivation, and research resources. *Sci Public Policy* 41(4):520–531.

Katz JS, Martin BR 1997. What is research collaboration? *Res Policy* 26(1):1–18.

Koschützki D, Lehmann KA, Peeters L, Richter S, Tenfelde-Podehl D, Zlotowski O 2005. Centrality Indices. In Brandes U, Erlebach T eds. *Network Analysis*. Springer, Berlin, Heidelberg, p. 16–61.

Köseoglu MA, Okumus F, Putra ED, Yildiz M, Dogan IC 2018. Authorship Trends, Collaboration Patterns, and Co-Authorship Networks in Lodging Studies (1990–2016). *J Hosp Mark Manag* 27(5):561–582.

Larivière V, Gingras Y, Archambault É 2006. Canadian collaboration networks: A comparative analysis of the natural sciences, social sciences and the humanities. *Scientometrics* 68(3):519–533.

Larivière V, Gingras Y, Sugimoto CR, Tsou A 2015. Team size matters: Collaboration and scientific impact since 1900. *J Assoc Inf Sci Technol* 66(7):1323–1332.

Legendre P, Legendre L 2012. *Numerical Ecology*. Elsevier, Amsterdam, 853 pp.

Lemarchand GA 2012. The long-term dynamics of co-authorship scientific networks: Iberoamerican countries (1973–2010). *Res Policy* 41(2):291–305.

Leta J 2012. Brazilian growth in the mainstream science: The role of human resources and national journals. *J Scientometr Res* 1(1):44–52.

Leta J, Chaimovich H 2002. Recognition and international collaboration: the Brazilian case. *Scientometrics* 53(3):325–335.

Liao CH, Yen HR 2012. Quantifying the degree of research collaboration: A comparative study of collaborative measures. *J Informetr* 6(1):27–33.

Mêgnigbêto E 2013. International collaboration in scientific publishing: the case of West Africa (2001–2010). *Scientometrics* 96(3):761–783.

de Meis L, Velloso A, Lannes D, Carmo MS, de Meis C 2003. The growing competition in Brazilian science: rites of passage, stress and burnout. *Brazilian J Med Biol Res* 36(9):1135–1141.

Mugnaini R, Jannuzzi PDM, Quoniam L 2004. Indicadores bibliométricos da produção científica brasileira: uma análise a partir da base Pascal. *Ciência da Informação* 33(2):123–131.

Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J 2000. Biodiversity hotspots for conservation priorities. *Nature* 403(6772):853–858.

Nabout JC, Carvalho P, Prado MU, Borges PP, Machado KB, Haddad KB, Michelan TS, Cunha HF, Soares TN 2012. Trends and Biases in Global Climate Change Literature. *Nat Conserv* 10(1):45–51.

Nabout JC, Parreira MR, Teresa FB, Carneiro FM, da Cunha HF, de Souza Ondei L, Caramori SS, Soares TN 2015. Publish (in a group) or perish (alone): the trend from single- to multi-authorship in biological papers. *Scientometrics* 102(1):357–364.

Oden N 1984. *Assessing the significance of a spatial correlogram*. 16, 1–16 pp.

Oksanen J, Blanchet F, Friendly M, Kindt R, Legendre P 2017. Vegan: community ecology package. R package version 2.4-3.

Orazbayev S 2017. International knowledge flows and the administrative barriers to mobility. *Res Policy* 46(9):1655–1665.

Padial AA, Nabout JC, Siqueira T, Bini LM, Diniz-Filho JAF 2010. Weak evidence for determinants of citation frequency in ecological articles. *Scientometrics* 85(1):1–12.

Pan RK, Kaski K, Fortunato S 2012. World citation and collaboration networks: uncovering the role of geography in science. *Sci Rep* 2(1):902.

Parreira MR, Machado KB, Logares R, Diniz-Filho JAF, Nabout JC 2017. The roles of geographic distance and socioeconomic factors on international collaboration among ecologists. *Scientometrics* 113(3):1539–1550.

Ponds R, van Oort F, Frenken K 2007. The geographical and institutional proximity of research collaboration. *Pap Reg Sci* 86(3):423–443.

QGIS Development Team 2018. QGIS Geographic Information System. Open Source Geospatial Foundation Project.

R Core Team 2019. A language and environment for statistical computing. R Foundation for Statistical Computing.

Sangam SL, Arali U, Patil CG, Megeri MN 2013. Scientometrics analysis of Genetics Literature. *Collnet J Sci Inf Manag* 7(2):173–190.

Sangam SL, Meera 2009. Research Collaboration Pattern in Indian Contributions to Chemical Sciences. *Collnet J Sci Inf Manag* 3(1):39–45.

Santin DM, Vanz SAS, Stumpf IRC 2016. Collaboration networks in the Brazilian scientific output in evolutionary biology: 2000-2012. *An Acad Bras Cienc* 88(1):165–178.

Sidone OJG, Haddad EA, Mena-Chalco JP 2017. Scholarly publication and collaboration in Brazil: The role of geography. *J Assoc Inf Sci Technol* 68(1):243–258.

Silberzahn R, Uhlmann EL 2015. Crowdsourced research: Many hands make tight work. *Nature* 526(7572):189–191.

de Souza CG, Ferreira MLA 2013. Researchers profile, co-authorship pattern and knowledge organization in information science in Brazil. *Scientometrics* 95(2):673–687.

The Royal Society 2011. *Knowledge, networks and nations: Global scientific collaboration in the 21st century*. Elsevier, London, 113 pp.

Vanz SA de S, Stumpf IRC 2012. Scientific Output Indicators and Scientific Collaboration Network Mapping in Brazil. *Collnet J Sci Inf Manag* 6(2):315–334.

Vermeulen N, Parker JN, Penders B 2013. Understanding life together: A brief history of collaboration in biology. *Endeavour* 37(3):162–171.

Woodward FI, Lomas MR, Kelly CK 2004. Global climate and the distribution of plant biomes. *Philos Trans R Soc London Ser B Biol Sci* 359(1450):1465–1476.

Ynalvez MA, Shrum WM 2011. Professional networks, scientific collaboration, and publication productivity in resource-constrained research institutions in a developing country. *Res Policy* 40(2):204–216.