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PALEONTOLOGY

Bibliometric analysis of isotopic studies on Quaternary megafauna available in the Scopus database

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Abstract: The number of isotopic studies on Quaternary megafauna has increased over the last decades, yet, there is no published data addressing the status of scientific production of this research field. The present study shows the results of a bibliometric research carried out in the Scopus database where the publishing trends within this scientific field was analyzed using the open source software tool SciMAT. We retrieved 278 papers published from 1980 to 2019 and observed that a significant increase in publishing has mainly occurred in the last decade analyzed here. We also identified some of the field´s most influential articles and journals; recognized that carbon, oxygen and nitrogen isotopes are the most used markers in these studies; and that the most cited taxa are representatives of Equidae, Bovidae and Proboscidae. Also, Paleoecology is the basic thematic area, whereas Climate and Paleoenvironmental Changes is the one with the greatest development potential. Our results clearly show that the isotopic study on Quaternary megafauna is still under development and that some subjects could be further explored, such as analyzing more ***taxa*** within Carnivora, Pilosa, Notoungulata, Cetartiodactyla and Perissodactyla as well as using other less frequent stable isotope markers, such as strontium, calcium and hydrogen.

Key words: megafauna, Quaternary, isotopes, scientific production, bibliometry.

INTRODUCTION

The continuous expansion of academic knowledge is followed by the exponential increase in scientific publications in the form of articles, reports, and other materials (Linnenluecke et al. 2020). Over the past few decades, a vast number of Quaternary mammal fossils have been recovered and taxonomically identified, demonstrating that a diversified megafauna, i.e., mammals with body masses over 44 kg (Koch & Barnosky 2006), inhabited continents and islands.

Paleoecological researches are important to provide information about the ecological aspects of extinct organisms and allowing to estimate their climatic-environmental setting and causes of extinction. In addition to biomechanics and comparative anatomy, other direct and indirect methods were developed in the last decades: dental microwear, dental calculus, and taphonomic and stable isotope analyses, just to mention some. These tools helped to refine the paleoecological reconstructions of many Quaternary megafauna representatives (e.g. Gröcke 1997, Asevedo et al. 2012, Araújo-Júnior et al. 2017, Domingo et al. 2017, Stacklyn et al. 2017, Uno et al. 2018).

Among the aforementioned methods, stable isotope analysis has being increasingly prominent possibly due to its potential as

a paleoecological tool (Sánchez et al. 2004, 2006, Bravo-Cuevas et al. 2017, Morosi & Ubilla 2019). Despite the huge number of publications addressing this method, there are no published studies aiming to quantify the expansion and analyze the development of this research field on the Quaternary megafauna — an issue that could efficiently be investigated by a bibliometric method.

Bibliometric analysis is a tool widely used to assess quantitative data provided by the scientific literature, allowing to perform an "X-ray" of the scientific production in a particular research field and to measure its productivity, trajectory, gaps in knowledge, and research trends (e.g. Harrison 2006, Nafade et al. 2018, Aparicio et al. 2019, Xie et al. 2020).

There are two main research methods within bibliometrics: performance analyses and scientific mapping. Performance analyses assess the impact of specific groups of agents that compose the scientific activity, i.e., journals, authors, countries or institutions. On the other hand, science mapping allows to identify the cognitive structure of a knowledge area and its development over time through the construction of spatial representations (graphs and networks) containing information about the relationship between scientific agents, documents, disciplines or themes (Cobo et al. 2011, 2012).

Thus, in order to verify the evolution of scientific production on stable isotope analysis of Quaternary megafauna fossils, we performed a bibliometric study of the literature available in the Scopus database to: (i) identify the amount of studies on the subject present in the database and the development of this scientific field over time; (ii) evaluate the main keywords used by authors to identify their research and which journals contain most publications; (iii) analyze the evolution of the most relevant themes and the thematic areas within its conceptual structure.

MATERIALS AND METHODS

Choosing the database

The first step in conducting a bibliometric study is to evaluate the available bibliographic databases, which are important tools that hold information on scientific activity. It is also necessary to evaluate the implications of using each database (Sánchez et al. 2017, Nafade et al. 2018). Today, Web of Science (WoS) and Scopus are the most widely used databases for bibliometric studies of peer-reviewed literature (Singh et al. 2021). Previous comparative analyses between these databases have been performed and showed some differences in their scope, volume of data, and coverage policies (see Gavel & Iselid 2008, Archambault et al. 2009, Boshoff & Akanmu 2017, Singh et al. 2021).

Overall, WoS provides greater time coverage, while Scopus offers a larger number of journals and publication volumes when compared to WoS, but with a slightly more restricted time span (Falagas et al. 2008, Sánchez et al. 2017). However, comparative studies on the overlapping of journal titles between these databases demonstrated that Scopus comprises almost all journals indexed in WoS and indexes about 66% more unique journals as compared to WoS (see Gavel & Iselid 2008, Singh et al. 2021). Additionally, comparative studies on the number of knowledge fields have also demonstrated the advantage of Scopus in respect to WoS, not only within the Natural Sciences field but also in other scientific areas (e.g. Bartol et al. 2014, Boshoff & Akanmu 2017, Singh et al. 2021). Hence, given the previously presented arguments, Scopus was selected as our research database of choice.

Scopus database was accessed through the free online Portal of Periodicals of the

Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), a Brazilian public institution of the Ministry of Education (Brasil 2020). As in other databases, Scopus allows the search of publications based on predetermined keywords present in titles, abstracts or keywords. The user needs to define the search strategy and select the preferred combination of keywords, time period, and publication type(s) that will be mined (Linnenluecke et al. 2020).

To perform our search we combined the following keywords: "isotop* AND (pleistocen* OR quaternary) AND (*mammal* OR megafauna* OR fossil* OR bone* OR t**th)". This choice of wording was based on three sets of terms separated by the connective AND (boolean operator): the first keyword refers to isotopes, the following ones concern the geological epoch or period, and the last terms are related to the animal group or the type material mentioned in the publications. This sequence of terms allow for a first refinement of the search results, showing only publications that strictly contain researches related to the research field of interest.

In order to achieve our objectives we selected in Scopus the complete time period (1960 to 2019) available at the time of our search. We carefully analyzed the title, abstract and main text (whenever necessary) of each article in the results in order to check the presence of the selected keywords and verify if the article addresses the target subject. It was also necessary to refine the search process by selecting researches that performed isotopic analyses directly on a fossil structure (e.g. bones, teeth, horns etc.). By doing so, studies that analyzed inorganic minerals or organic matter from the depositional environment of fossils were rejected.

The list of publications that met the criteria established here was saved within the Scopus platform and then exported in RIS (Research Information Systems) format to be later processed. The Scopus results analyzer was also used to extract some important data for our discussion.

Statistical programs

The RIS file was imported into the SciMAT software version 1.1.04, an open source tool that has advantages over other bibliometric applications because it incorporates methods, algorithms, and measures for all workflow stages necessary to carry out the science mapping, from the data pre-processing to visualization of the results.

In addition, we used RStudio software version 1.2.5033 to build figure 1a. The remaining information related to the performance analysis was obtained from the Scopus database and from SciMAT.

Data pre-processing

The following step was the data pre-processing for each bibliometric entity, such as Author**,** Keyword and Journal. The items that compose each entity must be carefully analyzed for the occurrence of spelling errors or duplicate data. During this phase, it is recommended to standardize keywords that, despite being duplicated or varying in spelling, represent the same concept (Heradio et al. 2016, Linnenluecke et al. 2020).

SciMAT is an open source software tool which allows the user to group two or more items into just one unit of analysis (Cobo et al. 2012). Thus, we pre-processed the entities cited in the previous paragraph by using this software.

Parameter settings in SciMAT

Science mapping analyses in SciMAT provide results in a longitudinal structure, allowing to assess the development of a knowledge area

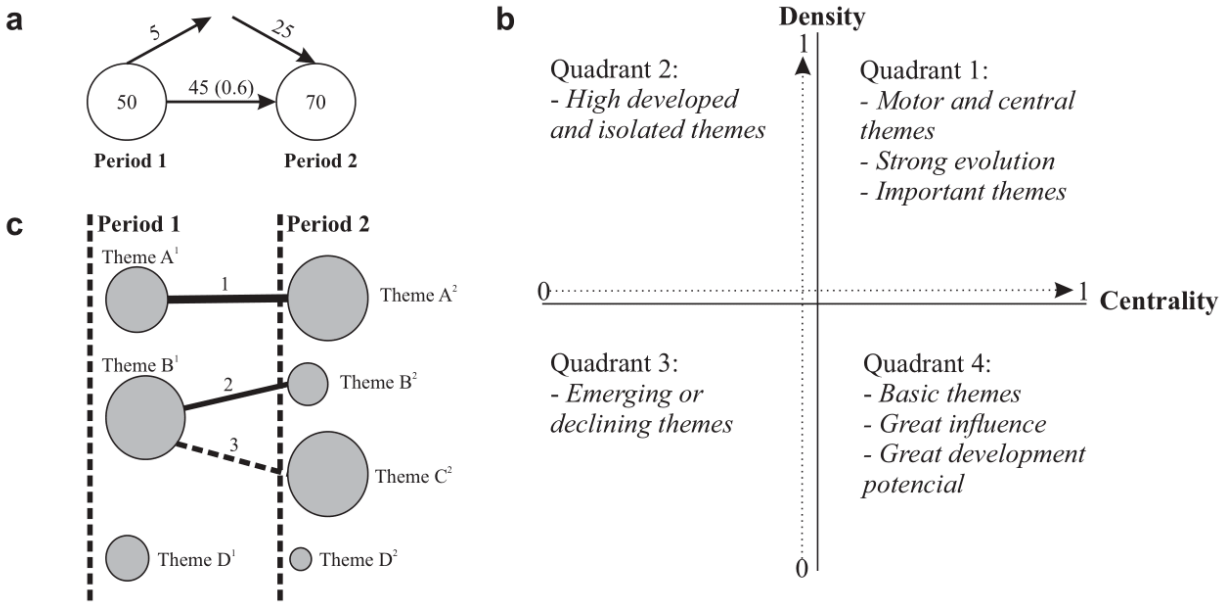

Figure 1. Schemes of the three science mapping tools generated by the SciMAT software. (a) The overlapping map, (b) The strategic diagram, (c) Thematic evolution.

over successive periods. Among the most popular techniques used in scientific mapping, we chose the co-word analysis as it evaluates the conceptual structure and the evolution of research themes (thematic areas), allowing for different forms of visualization (*see* Cobo et al. 2011, 2012).

Here, we performed the analyses in SciMAT using the configurations described in the following. Keyword was the only selected unit of analysis and includes not only the keywords chosen by the authors but also those provided by the Scopus database. At first, all documents found in Scopus and published from 1980 to 2019 were grouped by decades (1980-1989, 1990-1999, 2000-2009, 2010-2019). However, given the low number of papers published in the first decade, we chose to group these documents with those from the second decade (1980-1999) so that the number of articles (43) in the first time period could be representative enough for the analysis.

For each established time period, the co-word analysis detected clusters of keywords (themes) based on the keywords present in the RIS file. The themes were established considering the grouping of keywords using the simple centers algorithm (Cobo et al. 2011, 2012). Each cluster is then labeled by the software based on the most significant keyword within the internal structure of its thematic network (Aparicio et al. 2019). To build the internal structure of the thematic network for each cluster, we used the co-occurrence matrix, in which the frequency of co-occurrences between two keywords is extracted from the number of documents in which both keywords appear together (Cobo et al. 2012). The similarity index used for network normalization was the inclusion index, which was also chosen to analyze the evolution of the selected themes as it can detect conceptual nexuses between themes throughout decades and also identify thematic areas within the selected research field (Cobo et al. 2012, 2015).

Science mapping tools in SciMAT

SciMAT provides three different maps: overlapping map, strategic diagram, and evolution map. Here, the overlapping map

reflects the number of emerging and declining keywords throughout the analyzed periods (Figure 1a). From left to right, each circle depicts a specific time period and, within it, we find the total keyword count of all articles per period. The horizontal lines represent the continuity of keywords along the studied periods and the number outside the brackets indicates the amount of keywords shared between periods, while the number inside the brackets expresses the similarity index. The arrows coming out of the top of the circles (decades) indicate the number of keywords present only in that specific period, while the arrows entering the circles show the number of new keywords in that period (Cobo et al. 2011).

A strategic diagram (Figure 1b) was also created in SciMAT, which allowed examining the evolution of the research themes along the selected periods (Cobo et al. 2015, Xie et al. 2020). Each circle of this map represents one cluster theme and their sizes are proportional to the number of published articles associated with them. Themes were also plotted in a two dimensional space according to their centrality and density values (Callon et al. 1991, Cobo et al. 2011, 2012).

The centrality (0 to 1 values in the horizontal axis) measures the strength of external links with other themes, reflecting the importance of a theme to the development of the research field. When centrality increases, the connection with other themes are strengthened, the theme becomes more important inside the structure of the research field, which improves its chances of development. Density (0 to 1 values in the vertical axis) measures the strength of the internal links between the keywords that compose the research theme (cluster), that is, it measures the degree of association between the keywords within the theme and, therefore, the development of the theme. When density increases, the connections inside the structure of the theme become closer and the theme becomes more developed (Cobo et al. 2011, 2015).

To classify the centrality or density of themes as high, intermediate or low, we used the following values: low (below 0.5), intermediate (between 0.5 and 0.75), and high (above 0.75). From these two measures, the themes were positioned within the quadrants formed by the two-dimensional strategic diagram, and the placement in each quadrant results in different interpretations (see Cobo et al. 2011, 2015, Xie et al. 2020) depicted in figure 1b.

The third mapping tool is the evolution map, which presents the results of the thematic evolution over the analyzed periods. On this map is possible to identify themes by period and the continuity or discontinuity of the research through the connections between themes (Figure 1c). The size of a theme is proportional to its number of occurrences. Solid lines (lines 1 and 2) indicate a stronger connection in which both themes share important analysis units, such as themes A^1 to A^2 and themes B^1 to B^2. Darker and thicker lines represent stronger connections. Dotted lines (line 3) show weaker connections, where themes do not share the main analysis unit, as seen by themes B^1 to C^2. Theme D^1 was interrupted and the cluster D^2 shows that a new theme was created (Cobo et al. 2015, Aparicio et al. 2019, Xie et al. 2020).

For the construction of a clearer evolution map, we reduced the amount of data by using a tool available in SciMAT. For the first period (1980-1999 and 2000-2009), a minimum frequency of keywords was used in approximately 10% of the total articles published in these decades. In the last decade (2010-2019), it was established a minimum occurrence of 10 publications, which is equivalent to twice the number of articles of the previous period.

RESULTS AND DISCUSSION

Number of papers published in the selected area of study over the years

Our search retrieved 2038 publications available in Scopus. After filtering these records, only 278 articles published between 1980 and 2019 address stable isotopes in Quaternary megafauna fossils. The choice of keywords lead to another filtering, resulting in 1760 publications of studies on other organisms, geological periods or stable isotope analyzes on other materials that were in association with fossil specimens. Among the 278 results that were in accordance with our established criteria, most were articles published in scientific journals (267) and only a few were review articles (7) or studies published in conference proceedings (4).

The oldest publication retrieved from Scopus is entitled "Isotopic ecology of deer bones" (Land et al. 1980), which compared the isotopic data obtained from bones of living and fossil mammals and made reservations about the use of stable isotope analysis in fossilized organisms. It is worth mentioning that at the time when this article was published, stable isotope analyses were already widely applied in studies on invertebrates, botanical groups and archeological materials (see van der Merwe 1982), much differently from what was seen in studies on the Quaternary megafauna.

From 1980 to 1993, a very low research activity (Figure 2a) is seen in Scopus as only five articles are available on the subject. This period can be classified as the initial stage of this research field. Some other possible explanations may be the lack of access to the technique, high analytical costs or even the lack of knowledge about the potentiality of stable isotope analysis.

From the mid-1990s onwards there was a substantial increase in production, possibly due to the improvement in the use of the technique, providing more reliability than in earlier researches. This is clearly observed in the 2000s, when at least 10 articles were published on the subject. Hence, we can consider that a development stage spanned until 2009. After 2010, some years have achieved the mark of 20 publications, and this period can be classified as the expansion stage of this research field.

The graph depicting the evolution in publications through decades gives a better understanding on this trend (Figure 2b). The second decade (1990-1999) had almost 10 times the number of papers from the first decade (1980-1989). During the 2000-2009 period, the

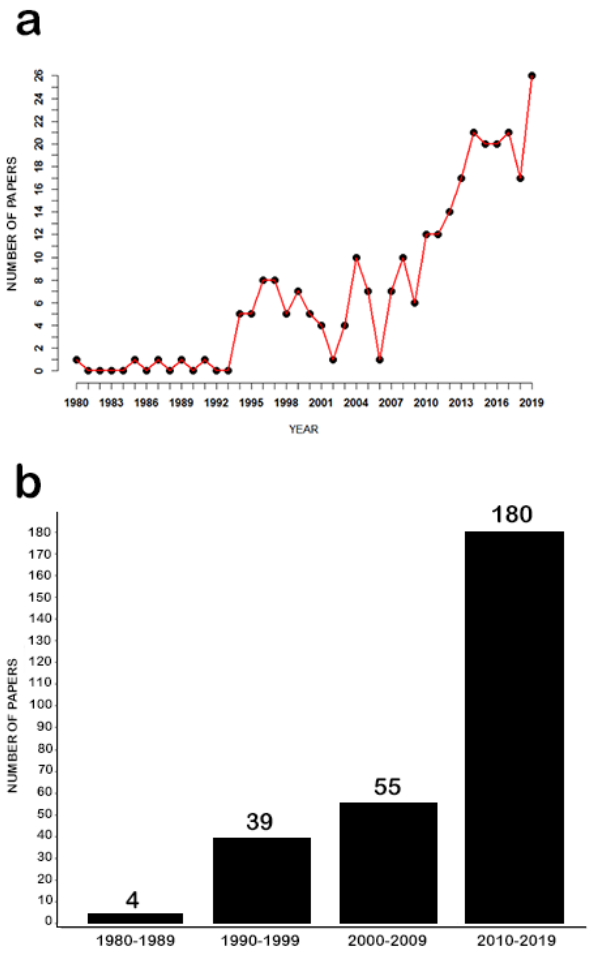

Figure 2. Growth of number of articles published about isotopic studies of Quaternary megafauna fossils. (a) Evolution of quantity of publications per year since 1980, (b) Number of published articles by decade.

number of publications increased about 40% compared to the previous decade, yielding 55 publications. The most significant growth occurred from 2010-2019, when the number of studies increased by 227% compared to the previous decade, and resulted in 180 new published articles. The scientific production in this last decade represents approximately 64.7% of the total articles available in Scopus.

The graphs in figure 2 allow to recognize the increasing of scientific activity in this research field over time, especially in the last decade. There is also a tendency even for a greater increase in the number of publications because, at present, the amount of Quaternary megafauna fossils available is plentiful in all continents where they have existed. Other contributing factors are the popularization of the stable isotopes technique, its potential to retrieve a set of paleoecological information and the excellent results obtained so far. Furthermore, together with other direct and indirect measures, this abundant data production markedly improved the interpretations that were only based on comparative anatomy and biomechanical analyses (França et al. 2015).

The leading journals

Identifying the main journals of a scientific field is important as a guide — especially for new researchers —, to choose the journal that best suits the scope of their study and the intended visibility of their publications. In the scientific field aimed here, the 278 papers retrieved from Scopus were published in 77 journals. Table I presents the list of the top five journals, which together have published 137 of these articles, representing almost half of the total number of studies from our results (49.2%).

The data presented in table I show that Palaeogeography, Palaeoclimatology, Palaeoecology (Palaeo3) has the largest number of publications (55 articles, almost 20% of the total), including the oldest publication available in Scopus. By observing the number of publications per decade, it is noticeable the advantage of Palaeo3 over other journals from the second decade onwards, when the number of articles in this area becomes more significant. As this journal aims to publish multidisciplinary research involving paleoenvironmental and paleoclimatological investigations, and this scope is related to the information retrieved from the isotopic analysis, this could be one the

Table I. Top five journals with the largest number of publications in isotopic studies on Quaternary megafauna fossils, their respective number of articles published by decade, the totals for each journal and current five year impact factors (IF).

Journal	1980-1989	1990-1999	2000-2009	2010-2019	Total number of articles	5 year IF (2020)
Palaeo3	1	7	13	34	55	3.469
Quaternary International	0	1	3	25	29	2.480
Quaternary Science Reviews	0	0	2	21	23	5.07
Quaternary Research	1	4	7	6	18	2.720
Journal of Human Evolution	0	0	1	11	12	3.753

main reasons for the large number of articles published by this journal.

The following three journals on the list are Quaternary International**,** Quaternary Science Reviews and Quaternary Research. When considering the aim on studies of the Quaternary period, these are the most popular journals among authors. We found 70 articles published in these journals, representing about 25% from the total. The possible reason for their presence in the top five list is that, overall, these journals cover several research areas that resolve issues related to the Quaternary period, such as paleontology and its subdivisions (paleoecology, paleobotany, paleogeography, paleoclimatology, among others). Thus, their scopes are similar to Palaeo3, yet, it remain specific to the Quaternary period.

The last of the top five journals is the Journal of Human Evolution, which addresses aspects of human evolution such as paleoanthropological, phylogenetic, and paleobiological aspects of human and primate fossils. The presence of this journal at this ranking is explained by the fact that fossils of giant primates and other megafaunal species are often found associated with human fossils (e.g. Garret et al. 2015, Uno et al. 2018).

It is evident that none of the top five journals is specialized in isotopes or geochemistry. Journals aimed at this scope and with good impact factors (IF) appear far below in the ranking of publications when we observe the complete list of journals available in Scopus or SciMAT, as is the case of Geochimica et Cosmochimica Acta (3 publications, 5 year IF 2020 = 5.01), Chemical Geology (1 publication, 5 year IF 2020 = 4.015) and Isotopes in Environmental and Health Studies (1 publication, 5 year IF 2020 = 1,721). These performances can possibly be explained by the fact that, despite the intimate relationship of isotopic research with the geochemistry field, this technique also retrieves paleoecological and paleoenvironmental information, which would justify the choice of journals that meet these requirements.

Palaeontology (5 year IF 2020 = 4.073; 2 articles published), Paleobiology (5 year IF 2020 = 2.892; 7 papers published) and Journal of Vertebrate Paleontology (5 year IF 2020 = 2.380; 1 paper published) are another three journals that appear in the full list for addressing paleontological issues and show impact factors similar to the top five journals. If we consider both the scope and impact factor of these journals, they could be taken more into consideration by researchers for future publications, and the same would apply to the previously mentioned journals specialized in geochemistry.

In respect to the review articles, there are only two specialized journals: Quaternary Science Reviews and Earth-Science Reviews. Despite the higher number of published articles in Quaternary Science Reviews, possibly because it also accepts new data (especially if the study also performs a review), Earth-Science Reviews has a much higher impact factor (5 year IF 2020 = 13.307). This journal also has a broader scope on Earth Sciences than Quaternary Science Reviews, therefore, it is an excellent option for publication of scientific reviews and should be better considered by researchers.

Most cited articles

Table II presents the top ten most cited articles among the 278 found in the Scopus database, in addition to their respective authors, year of publication, and journal name. The articles were ranked according to the number of received citations since their publication date, as citations are an important indicator of the research relevance in the scientific community. All articles in table II were published before the 2000s, not only indicating a longer time for being

Table II. Top ten most cited articles within the Scopus platform. Legend: TC (Total Citation in Scopus).

Authors	Title	Journal	Year	TC
Koch et al.	The effects of sample treatment and diagenesis on the isotopic integrity of carbonate in biogenic hydroxylapatite	Journal of Archaeological Science	1997	567
Lee-Thorp & van der Merwe	Carbon isotope analysis of fossil bone apatite.	South African Journal of Science	1987	303
Bocherens et al.	Diet, physiology and ecology of fossil mammals as inferred from stable carbon and nitrogen isotope biogeochemistry: implications for Pleistocene bears	Palaeogeography, Palaeoclimatology and Palaeoecology	1994	238
Bocherens et al.	Isotopic biogeochemistry (^{13}C, ^{18}O) of mammalian enamel from african pleistocene hominid sites	Palaios	1996	229
Bocherens et al.	Paleobiological Implications of the Isotopic Signatures (^{13}C, ^{15}N) of Fossil Mammal Collagen in Scladina Cave (Sclayn, Belgium)	Quaternary Research	1997	208
Koch et al.	Oxygen isotope variation in the tusks of extinct proboscideans: a measure of season of death and seasonality	Geology	1989	185
Koch et al.	The isotopic ecology of late Pleistocene mammals in North America Part 1. Florida	Chemical Geology	1998	167
Hoppe et al.	Tracking mammoths and mastodons: Reconstruction of migratory behavior using strontium isotope ratios	Geology	1999	165
Bocherens et al.	Palaeoenvironmental and palaeodietary implications of isotopic biogeochemistry of last interglacial neanderthal and mammal bones in Scladina Cave (Belgium)	Journal of Archaeological Science	1999	164
MacFadden & Cerling	Mammalian herbivore communities, ancient feeding ecology, and carbon isotopes: A 10 million-year sequence from the neogene of Florida	Journal of Vertebrate Paleontology	1996	164

cited but obviously evidencing their quality and impact on other researches. Many articles receive citations during a popularity time span, but this trend is soon interrupted (Hirsch 2005). Our results indicate that these articles were cited until 2019 or 2020, which reveals that their methodologies and interpretations still form the basis for several modern works.

Considering the topics covered by these articles, three of them address isotopic analyses specifically on proboscidean mammals, such as mastodons and mammoths (Koch et al. 1989, 1997, Hoppe et al. 1999) and one on bear fossils (Bocherens et al. 1994). The other six examine more than one taxon, such as cetartiodactils, perissodactils, proboscideans and carnivorans (see Lee-Thorp & van der Merwe 1987, Bocherens et al. 1996, 1997, 1999, MacFadden & Cerling 1996, Koch et al. 1998).

In six of these articles, the analyses were performed only on bone or teeth hydroxyapatite (Lee-Thorp & van der Merwe 1987, Koch et al. 1989, 1998, Bocherens et al. 1996, MacFadden & Cerling 1996, Hoppe et al. 1999), two on collagen and hydroxyapatite (Bocherens et al. 1994, Koch et al. 1997), and two exclusively on

collagen (Bocherens et al. 1997, 1999). Regarding the isotopic analyses, among the ten most cited articles eight of them analyzed stable carbon isotopes, four studies investigated stable oxygen isotopes (three of them in association with carbon), only one evaluated stable strontium, and three assessed stable nitrogen in association with carbon isotopes.

Of the ten most cited articles, two papers describe methodological issues related to isotopic analyses in hydroxyapatite. An example is how the chemical treatment during fossil preparation and fossil diagenesis could affect the isotopic composition of the enamel, dentin and bone hydroxyapatite, and the feasibility of using these materials in isotopic analyses (Lee-Thorp & van der Merwe 1987, Koch et al. 1997). The other eight articles focused on paleoecological interpretations based on isotopic values recovered from the analysis of mammal bones or teeth, more specifically, diet reconstructions, phytophysiognomy, climatic variations, and migration patterns.

We observed that the ten most cited articles in our results cover various aspects of isotopic studies on the Quaternary megafauna. First, these articles investigate different groups of mammals with distinct feeding habits, such as herbivores, omnivores and carnivores. They also analyzed different types of isotopes in many animal tissues, having different goals other than paleoecological and paleoenvironmental reconstructions, such as discussions on methodological issues. The wide variety of topics covered by these articles may explain the large number of citations received by them and, therefore, they could be considered an excellent bibliography to compose the theoretical framework of future studies in this research field.

Main keyword groups used in the studies

A total of 1697 keywords represent the 278 articles found in our search in Scopus. As previously mentioned, the pre-processing of keywords was carried out in order to group synonyms and eliminate possible typos. The total was then converted into 1344 keyword groups and used later to create maps in SciMAT. Table III presents the thirty most used keywords so far based on the results from Scopus.

The most cited keyword is Pleistocene (160 documents), referring to the longest epoch of the Quaternary, followed by the animal group of interest (Mammal, 149 documents), and the chosen analytical method (Stable Isotopes, 148 documents). The keyword Holocene, another epoch of the Quaternary period, appears far behind in only 15 documents. This is probably related to the higher time period and megafauna species richness in the Pleistocene, providing more samples for isotopic analyses and, thus, more studies about this geological epoch.

Among stable isotopes, carbon is the most analyzed marker (alone or in association with other isotopes), followed by oxygen and nitrogen. When observing the complete list, there are mentions of other isotopes such as strontium, calcium, and hydrogen, but in much fewer studies (i.e. Hoppe et al. 1999, Barbieri et al. 2008, Martin et al. 2018).

Table III also presents other interesting results on the fossil structures that hold the isotopic information. Dental enamel is the most cited structure when compared to bone collagen and, because of this, mentions on teeth is greater than on bones. The higher number of citations on tooth enamel possibly indicates greater preference of researchers to this type of material, mainly because collagen is not always available in fossils. This may be related to the greater resistance of enamel hydroxyapatite to

Table III. Top thirty most used keywords in isotopic studies on Quaternary megafauna fossils.

Rank	Groups of words	Number of documents	Rank	Groups of words	Number of documents
1	Pleistocene	160	16	Equidae	50
2	Mammal	149	17	Climatic change	45
3	Stable isotopes	148	18	Nitrogen isotopes	45
4	Carbon isotope	127	19	Herbivores	44
5	Paleoecology	93	20	Fossil record	42
6	Diet	84	21	Collagen	40
7	Paleoenvironment	81	22	Bone	39
8	Oxygen isotope	77	23	Extinction	38
9	Enamel	71	24	Paleontology	36
10	Isotopic analysis	69	25	Bovidae	32
11	Paleoclimate	68	26	United States	31
12	Animals	64	27	Poaceae	29
13	Fossil	61	28	Equus	28
14	Tooth	55	29	Bison	25
15	Isotopic composition	53	30	Ungulates	25

diagenetic alterations when compared to bones, which better preserves isotopic information.

It is also worth noting that representatives of the Equidae and Bovidae families are the most cited in these studies. When analyzing the mammalian taxa that appear in the full list, we observed that members of Perissodactyla, Cetartiodactyla and Proboscidea are preferred for these analyses. In addition to the need for improving ecological interpretations on these taxa, our study indicates the existence of good research opportunities on mammals of less studied orders, such as Pilosa, Cingulata, Notoungulata, some groups within Carnivora or even within the three most mentioned groups.

The mentions on feeding habits show that studies on herbivores are more frequent when compared to others. This may be related to the fact that ^{12}C and ^{13}C are the main isotope species analyzed in Quaternary megafauna remains, as the ratio between both reflect the photosynthetic pathways prevalent in the organism's diet and, consequently, in its habitat (MacFadden et al. 1999, Sánchez et al. 2004, Suraprasit et al. 2018). This is evidenced not only because the term "herbivores" is one of the most cited in the articles, but also because terms related to herbivore taxa also appear in table III.

Regarding the primary information obtained from the isotopic values of Quaternary megafauna, the main keywords in our results were, in decreasing order, Paleoecology, Diet, Paleoenvironment, Paleoclimate, and Climatic Change. Paleoecology can be considered a more generic term that includes much information from the ecological niche of a species, such as

diet, trophic position, and abiotic conditions of the ecosystem. This information is fundamental to elucidate the climatic and environmental aspects of the habitats where the megafauna lived (e.g. MacFadden 2000, Szabó et al. 2017, Stacklyn et al. 2017), which would explain why these were the most cited keywords among the accessed articles.

Figure 3 presents the overlapping map of the three analyzed periods. The map shows the existence of 207 keywords from 1980 to 1999, 426 keywords between 2000 and 2009 and 1097 keywords between 2010 and 2019. This result clearly shows a substantial increase of keywords over the decades, and the last analyzed decade has more than five times the number of keywords than the first decade. In addition, both the number of shared keywords and the similarity index between periods increased through time, indicating that the terminology used in this scientific field is consolidating.

The growing number of keywords is directly proportional to the number of published articles. This reflects the expansion of the method over time due to its potential use in mammalian fossils, which led to the increase of isotopic analyses in paleoecological studies. The most used keywords along decades allow us to conclude that they encompass all aspects of this research field, as the studied group, the technique, the geological period or epoch, and the interpretations from the isotopic signatures. Choosing keywords that best represent the study

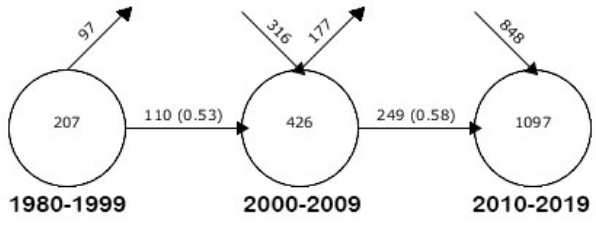

Figure 3. Overlapping map for the three analyzed periods (1980-1999, 2000-2009, 2010-2019). Source: SciMAT.

is important to make it more easily accessible in the scientific databases. It also contributes for other studies, like the present one, allowing for a better understanding of the structure and evolution of a scientific field (Chen & Xiao 2016).

Analysis of the main research themes

We used the strategic diagrams created in SciMAT to visualize the evolution of the themes from 1980 to 2019, to analyze the hot spots and predict future trends (Figure 4). Table IV shows the number of documents and citations from our results, and the centrality and density values for each theme present in the strategic diagrams. The maps for each period are discussed henceforth.

The 1980-1999 period

The strategic diagram of this period shows four important themes related to the isotopic studies of Quaternary megafauna fossils: Pleistocene, Carbon Isotope, Oxygen Isotope, and Paleoclimate (Figure 4a). The theme Pleistocene is completely within quadrant 1 because of its high density and centrality values, indicating that it is a well-developed theme with a strong connection to other themes (Table IV). For this reason, Pleistocene is the only driving theme in this period for having the greatest evolution and expansion, becoming highly relevant to the research field structure during this initial phase. Pleistocene is also a driving theme in subsequent decades (figure 4b-c), and this is possibly explained by the large number of citations of the keyword Pleistocene, which may also indicates that most Quaternary fossils analyzed in stable isotope studies are assigned to this geological epoch. The intermediate density and high centrality values (Table IV) demonstrate that the theme Oxygen Isotope was still developing, despite having a good connection strength with other themes in the

area and indicating that it was on its way to becoming a central theme.

The theme Carbon Isotope has high density and intermediate centrality, demonstrating that it was well developed and highly employed during this period. However, as this theme was not strongly connected to others, it cannot yet be considered a central theme here. Lastly, Paleoclimate, the only theme located in quadrant 3 with low density and centrality values, can be considered as emergent as it is still weakly developed here. Furthermore, the number of citations for Paleoclimate is much lower when compared to the other three themes during this same period.

In addition to the first three themes previously discussed, it is interesting to note the emergence of the Paleoclimate theme in this period. We can infer that, at the time, isotopic studies focused mainly on reconstructing the animals' diet, but discussions about the microclimate of their habitats were already a growing topic.

The 2000-2009 period

This decade presents a rise in the number of themes, which was expected considering the continuous increasing in the number of published articles (Figure 4b). Pleistocene and Carbon Isotopes were the only themes from the previous period that remained relevant, while there is an emergence of themes related not only to isotopic study (Stable Isotopes and Isotopic Analysis) but also to the study location (Eurasia and United States), to paleoecological aspects (Diet) and to the geological period of interest (Quaternary).

From the nine main themes of this period, Pleistocene, Mammal and United States are the driving ones showing higher centrality values, in addition to density values equivalent to well-developed and central themes (Table III). The Mammal theme rises up in part from the Pleistocene theme and in part from the Oxygen Isotope theme present since the previous period, as its main keyword became more relevant and started a larger cluster that includes the keyword Oxygen Isotope. This was expected since this scientific field is focused on this animal group and there were an increase in the number of published articles.

The main keyword that labeled the theme United States can be considered relevant only as a reference to the leading country in this research field, because it is not an important topic in the cognitive structure of the scientific field aimed here. However, this theme is related to discussions about paleoecology and extinction during glacial periods, and the growth of articles that discussed these issues may explain the relevance of this cluster in this decade.

Two themes with high density and low centrality are located in quadrant 2: Eurasia and Stable Isotopes. Despite being considered developed clusters, during this decade they showed little connection with other themes in the studied research field. The theme Stable Isotopes occupies a more peripheral position in the diagram despite being a term directly related to the subject analyzed here. However, when we look at the strategic diagram of the subsequent decade (Figure 4c), its evolution towards the central theme is evident, as would be expected in this case. This can be explained by the relationship of this theme with issues such as climate reconstruction in addition to topics related to isotopic analysis.

Eurasia also appears in this decade only as a peripheral theme. Despite being an important location for these studies, the keyword Eurasia is not fundamental to the cognitive structure of this scientific field. This theme is also related with paleoclimate reconstruction based on the

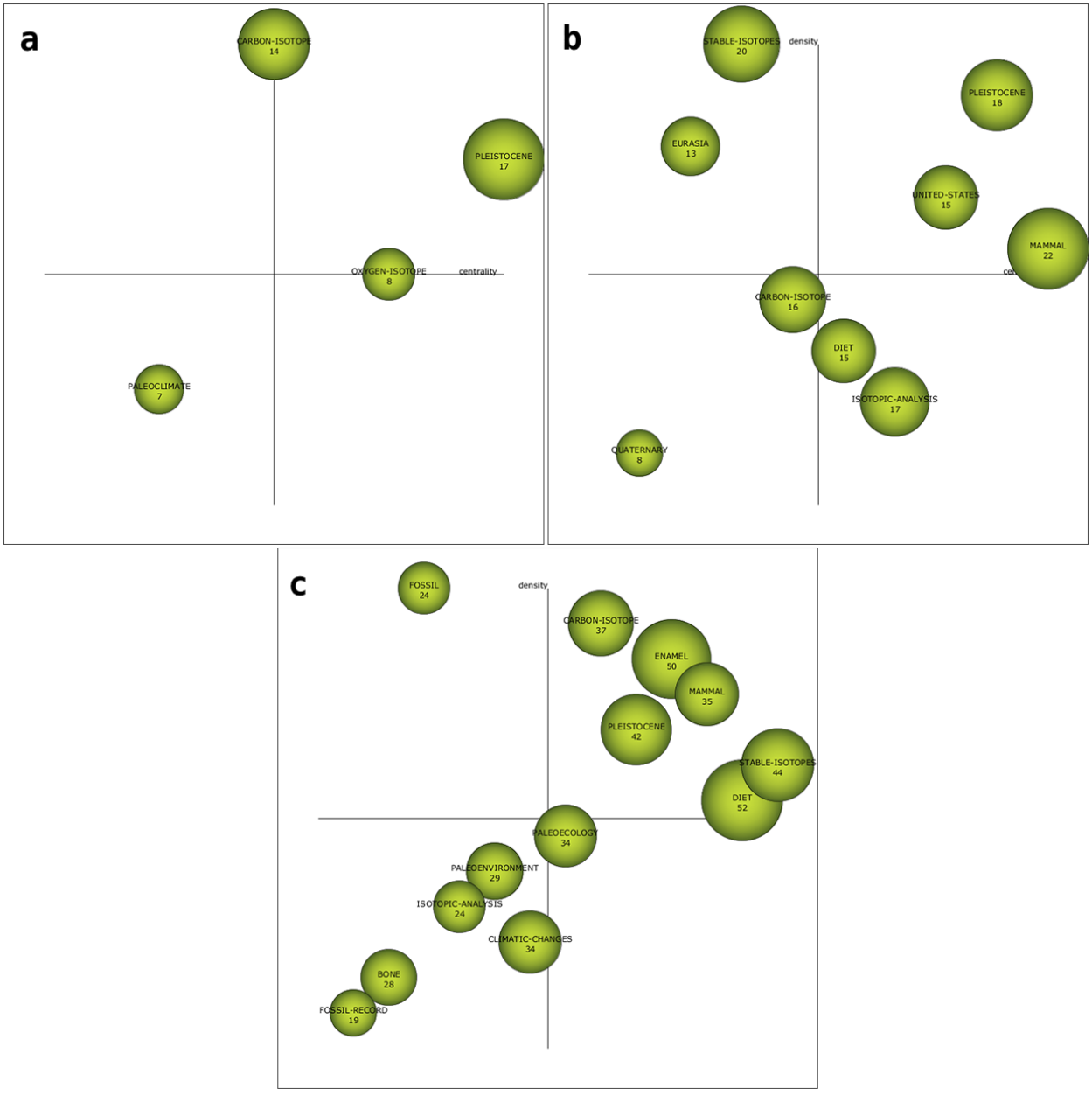

Figure 4. Strategic diagrams for each of the analyzed periods. (a) Strategic diagram for the 1980-1999 period, (b) Strategic diagram for the 2000-2009 decade, (c) Strategic diagram for the 2010-2019 decade. Source: SciMAT.

isotopic composition of fossils, indicating that environmental and climate reconstructions are important topics of some themes from this decade.

In quadrant 3, the themes Carbon Isotope and Quaternary appear as emerging ones (Figure 4b). The first theme was well developed and had little connection with other topics in the area until 1999, but its centrality and density decreased in this second period. Yet, we cannot consider it a declining topic, because carbon is the most used element in isotopic studies of Quaternary megafauna (Table II). Nevertheless, when observing the subsequent period, the theme was still under development until 2009, becoming a central theme only in the last

Table IV. Most ranked themes per period and respective number of documents in which they are mentioned, number of citations received, and centrality and density values.

Period	Cluster	Number of documents	Number of citations	Centrality range	Density range
1980-1999	Pleistocene	17	1809	1	0.75
	Oxygen-isotope	8	1326	0.75	0.5
	Paleoclimate	7	446	0.25	0.25
	Carbon-isotope	14	1694	0.5	1
2000-2009	Mammal	22	1268	1	0.56
	Pleistocene	18	1046	0.89	0.89
	United States	15	956	0.78	0.67
	Stable isotope	20	1245	0.33	1
	Eurasia	13	728	0.22	0.78
	Carbon isotope	16	932	0.44	0.44
	Quaternary	8	569	0.11	0.11
	Isotopic analysis	17	858	0.67	0.22
	Diet	15	1009	0.56	0.33
2010-2019	Stable isotopes	44	586	1	0.62
	Diet	52	1042	0.92	0.54
	Mammal	35	613	0.85	0.77
	Enamel	50	674	0.77	0.85
	Pleistocene	42	721	0.69	0.69
	Carbon isotope	37	783	0.62	0.92
	Fossil	24	228	0.23	1
	Climatic change	34	595	0.46	0.23
	Paleoenvironment	29	450	0.38	0.38
	Isotopic analysis	24	392	0.31	0.31
	Bone	28	484	0.15	0.15
	Fossil record	19	228	0.08	0.08
	Paleoecology	34	578	0.54	0.46

decade. While in the previous period the theme Carbon Isotope was related to topics such as diet and environment, in this decade it broadens the focus to discussions on eating behaviors and environmental changes. The Quaternary cluster also appears in this period as an emerging theme, although it did not remain relevant in the following decade.

Quadrant 4 shows two themes considered as elementary in this research field, with intermediate centrality and low density: Isotopic Analysis and Diet. During this period, both themes were already established in the area and showed a good development potential to become central themes. Here, the theme Isotopic Analysis mainly aims at is discussing the paleoenvironment of Quaternary mammals. The Diet theme emerges from the Carbon isotope theme from the previous period, which indicates that discussions on paleodiet reconstruction gained even greater relevance throughout this decade. This theme is strongly linked to herbivorous and climate change topics, demonstrating an interest not only in understanding the paleodiet of the studied taxa, but also how it has been affected by climate change or how changes in diet indicate environmental modification of a given region. Our study indicates that topics related to paleoenvironment reconstructions and climate

changes based on isotopic data started to be more debated during this decade.

The 2010-2019 period

This last analyzed decade shows the persistence of six themes from the previous period (Pleistocene, Mammal, Stable Isotope, Carbon Isotope, Diet, and Isotopic Analysis) and that seven other new themes appeared in the strategic diagram (Figure 4c). Pleistocene and Mammal continued as driving and central themes. Carbon Isotope, Diet, and Stable Isotope, which were previously positioned as basic, peripheral or emerging themes, also appear as central themes of this research field, but together with the new theme Enamel. Table IV shows that among these six driving themes, Carbon Isotope and Enamel are the most developed ones due to their highest densities, while Stable Isotope and Diet have more connections with other themes due to their higher centrality values. Except for Stable Isotopes, the driving themes have the highest number of citations in this period, followed by the emergent cluster Climatic Change.

It is worth to note that Diet remains a separate theme from Carbon Isotope, which demonstrates not only the importance of carbon isotope within the research field, but also that diet reconstruction is a central theme with a marked evolution in these studies. The theme Stable Isotope becomes a central and motor theme in this period, probably due to the great increase in the number of published articles. During this period, this cluster is related with feeding behavior and climate topics, showing that these are the two main information retrieved from isotopic analyses.

The new motor theme, Enamel, emerges from the theme Mammal present in the previous decade, demonstrating the relevance of tooth enamel as source material in isotopic studies of Quaternary megafauna. This cluster is related with Bioapatite, Oxygen Isotope, C4-plants, and Paleoclimate topics, and the number of documents in this cluster suggests that the paleoenvironmental and paleoclimate information seems to be more correlated to studies using tooth enamel in this decade.

The Pleistocene theme is the most cited in the analyzed articles and is strongly linked to topics related to Niche. The usefulness of isotopes in elucidating aspects of the environmental conditions and resources available to the Pleistocene megafauna may explain the association of this geological epoch with the term Niche, so much that some authors consider the isotopic information as part of the species' isotopic niche, an analogy to the traditional definitions of ecological niche (Newsome et al. 2007, 2012).

The theme Fossil is a peripheral and isolated theme, as it is highly developed and has low centrality values (Table IV) in this decade. The peripheral positioning of the theme Fossil may indicate a greater importance given to terms linked to fossil materials (e.g. bone, teeth, tusk) or elements extracted from the specimens (e.g. enamel, dentine, bioapatite, and collagen) for isotopic analysis.

Quadrant 3 presents five themes that may be emerging or in a declining trend (Xie et al. 2020). However, as the use of isotopes in researches with Quaternary mammals is relatively recent compared to other areas, all themes can be considered in ongoing development, especially Climatic Change, Paleoenvironment and Isotopic Analysis. Even Bone and Fossil Record, which have the lowest centrality and density values, do not show a declining trend due to the presence of basic and important terms within their structures, and because they are essential themes to the cognitive structure of this research field.

In this decade, the research conducted in the theme Climatic Changes was mainly related to the Extinction topic. The theme Paleoenvironment is the most developed among all themes in quadrant 3 and is mainly focused on Glacial Period and Reconstruction topics, while studies conducted in the theme Isotopic Analysis covers aspects linked to Radiocarbon and Environmental Changes. The keywords Paleoenvironment and Climatic Change were members of other clusters in the previous three periods and have emerged in the last decade as independent themes, showing their increased relevance in discussions on these isotopic researches.

It is evident here that a substantial increase occurred in discussions about environmental and climatic changes throughout the Quaternary and how these changes could have affected the megafauna extinction (e.g. Fabre et al. 2011, Raghavan et al. 2014, DeSantis et al. 2017, Ecker et al. 2018).

The theme Isotopic Analysis has persisted in this last period but with a different emphasis, which may explain its shift from a basic to an emergent theme. The most interesting result in the research conducted in this theme is the topic Radiocarbon. França et al. (2014) stated that most isotopic data were dissociated from chronological information, which is an obstacle for more accurate paleoenvironmental reconstructions and better understanding of the extinction events. Therefore, the presence of the keyword Radiocarbon in the structure of the theme Isotopic Analysis may indicate an increased association between isotopic data and radiocarbon dating in this decade.

The theme Paleoecology evolved from the theme United States in the previous period and has become a basic theme in quadrant 4, with good development and influence in the area of study. This theme is also positioned at the boundary to become a central theme. By tracking information regarding feeding habits, food web, migration, and environmental conditions, stable isotopes allow the reconstruction of animal paleoecology (West et al. 2006, Dantas et al. 2017, Uno et al. 2018, Silva et al. 2019). Hence, it is possible to expect an ever-growing number of studies in this research field that will make Paleoecology a motor and central theme due to its relevance.

Evolution of the conceptual structure of the field

Figure 5 shows the thematic evolution map for the research field analyzed here. Of the four clusters present in the first period, two are maintained in the two subsequent periods (Carbon Isotope and Pleistocene), showing the great importance of these themes in developing this scientific area.

Between 2000 and 2009, seven themes emerge (Stable Isotopes, Isotopic Analysis, Mammal, United States, Eurasia, Diet, and Quaternary), with four persisting in the last decade (Stable Isotopes, Isotopic Analysis, Mammal, and Diet), a period when new themes appeared in our analysis (Fossil, Paleoecology, Enamel, Paleoenvironment, Climatic Changes, Bone, and Fossil Record).

The analysis of this evolution map allows verifying the existence of four main thematic areas:

(1) Paleoecology of Pleistocene mammals. This thematic area was identified in the following sequence (Figure 5): Pleistocene → Pleistocene, United States → Paleoecology. From that, our study confirms that Paleoecology is the main thematic area for isotopic studies of Quaternary megafauna, corroborating the claims of some authors that the use of stable isotopes to study this thematic has grown considerably in recent years (e.g. MacFadden &

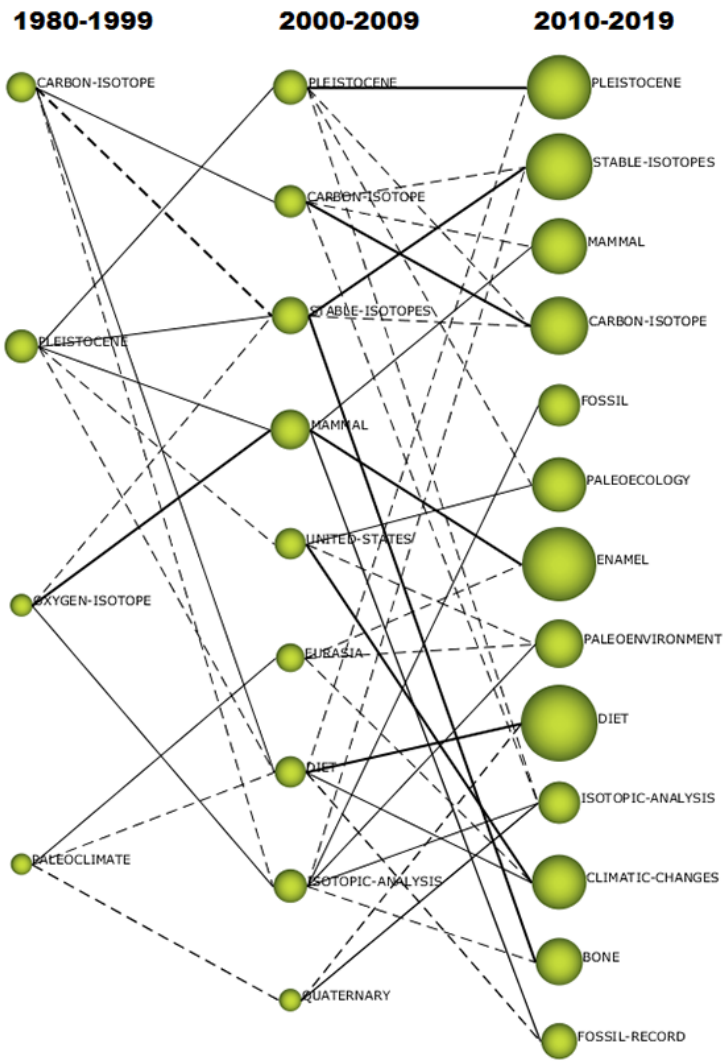

Figure 5. Thematic evolution of the isotopic study in Quaternary megafauna fossils between 1980 and 2019. Source: SciMAT.

Shockey 1997, Sánchez et al. 2006, Silva et al. 2019). Stable isotope analyses have become one of the most important tools to obtain additional information on various paleoecological aspects of megafauna species, in addition to allowing testing hypotheses based on morphological and biomechanical data (França et al. 2014, Dantas et al. 2017, Pérez-Crespo et al. 2018). This thematic area could be considered the most general one of the thematic map, as it also covers other specific areas that will be discussed hereafter.

(2) Isotopic analysis in bones and teeth of Pleistocene mammals. This area is mainly composed by the connection between the themes Pleistocene, Mammals, Stable Isotopes, Isotopic Analysis, Enamel, and Bone. Over the three periods, the themes appeared in the following sequence: Pleistocene → Pleistocene → Pleistocene, Isotopic Analysis; Pleistocene → Stable Isotopes → Stable Isotopes, Bone; Oxygen Isotopes → Isotopic Analysis, Mammal → Isotopic Analysis, Enamel; Pleistocene → Mammal → Mammal, Fossil Record, Enamel. Bones and teeth were the most analyzed materials. Horns and hair are less frequently analyzed due to its scarcity in the fossil record, either because it requires specific conditions for preservation (hair) or because of the lesser

number of species that have it (horn). Among the main analyzed materials, it appears that terms referring to teeth (Tooth, Teeth and Enamel) are more frequent compared to bone, and in the last examined decade the theme Enamel appears as a central theme. Some authors have long cited an increasing number of isotopic studies using dental enamel as an alternative to bones due to its high mineral concentration (95% hydroxylapatite), making it a denser material more likely to preserve its original mineral composition (Lee-Thorp & van der Merwe 1987, Lee-Thorp et al. 1989, MacFadden & Shockey 1997, MacFadden et al. 1999, Harrison & Katzenberg 2003). Therefore, it is interesting to note that our study shows a growing trend in studies analyzing dental enamel.

(3) Paleodiet from stable carbon isotopes. Among the isotopes mentioned in the analyzed publications, carbon is the element with the highest number of citations in the Scopus database. Its importance in forming a specific thematic area is evident in the evolution map, since the theme Carbon Isotopes is present in all periods investigated here. The flow sequences of this thematic area are: Carbon Isotope → Stable Isotopes → Carbon Isotope; Carbon Isotope → Carbon Isotope → Carbon Isotope, Isotopic Analysis; Carbon Isotope → Diet → Diet. In two of the three analyzed periods, the theme Carbon Isotope is linked to the topics Bone, Collagen, Nitrogen Isotopes, Feeding Behavior and Environmental Changes. The association of carbon and nitrogen isotopic ratios complement the interpretations on feeding behavior, trophic network, and aspects of the habitat vegetation, enabling a more complete paleoecological characterization (Post 2002, Kuitems et al. 2015, Schwartz-Narbonne et al. 2015, Pandolfi et al. 2017) and explaining the existence of a thematic area related to this subject.

(4) Paleoenvironmental and climatic changes. In the evolution map, the four flows grouped within this thematic area are: Oxygen Isotope → Isotopic Analysis → Paleoenvironment; Paleoclimate → Eurasia → Paleoenvironment, Climatic Change; Carbon Isotope, Paleoclimate → Diet → Climatic Change. The topics covered by the themes that compose this thematic area shows that carbon, oxygen, and nitrogen isotopes are important for the discussions about Quaternary environmental changes, because these isotopic ratios allow the reconstruction of aspects related with paleoecology, paleoenvironment and paleoclimate (e.g. Iacumin et al. 1997, Suraprasit et al. 2018, McDonald et al. 2019). One of the main goals of scientists over the past few years has been understanding how climatic variations occurred during the Quaternary and the role of this phenomenon in changing the paleoenvironment and contributing to the extinction of most terrestrial megafauna. Thus, the use of stable isotope analysis has been increasingly frequent for these purposes and this may be the explanation for this thematic area being one of the most promising within this research field, especially considering the position of the themes in the strategic diagram from the last decade.

CONCLUSIONS

This first bibliometric study in the Scopus database to assess isotopic studies on Quaternary megafauna fossils demonstrated how this research area had a quantitative and qualitatively growth over the years, mainly by the significant increase in number of published papers in the last decade. Additionally, by elucidating the main cited keywords, articles and journals for publishing new data in this area, researchers may more properly prepare and organize their future works.

Paleoecology is the basic thematic area of this research field, since this type of analysis retrieves many information related to the ecological aspects of a species. The increasing number of articles published over the past 40 years reinforces the idea that stable isotope analyses have gained importance within the mammalian Paleoecology field. Carbon isotopes are the main analyzed tracers and compose one of the central thematic areas related to paleodiet reconstruction. Oxygen and nitrogen stable isotopes are also frequently used; however, calcium, hydrogen, and strontium isotopes are not common in the studies, which may indicate a field to be further explored.

Another central thematic area is the use of bones and tooth enamel in these analyses, particularly the latter because of its resistance to diagenetic changes. This is possibly the reason for the greater use of tooth enamel in studies from the last decade onwards. However, considering the four thematic areas presented here, our analysis suggests that the one referring to paleoenvironmental and climatic changes is considered to have the greatest potential for development.

Lastly, some limitations of our study need to be pointed out. First, a methodological bias can be identified during the pre-processing phase, when grouping the synonymous keywords and selecting the parameters to generate the maps in SciMAT. However, we consider that the best parameters have been defined to avoid the appearance of bibliometric maps that are too complex to understand. Second, it is possible that some articles were left out of our analysis, as they were not published in journals indexed in the Scopus database. Probably, the inclusion of these articles in the analysis would not change the general interpretations made here, mainly when it comes to the increasing development of the field over the last few years and the main trends in the thematic areas. Even so, in future studies we intend to include other databases in order to obtain an even more complete comprehension of the area.

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Lucas de M. França designed the study, participated in data collection and analysis, worked on data interpretation and wrote the preliminary and final version of the manuscript. Mário André T. Dantas designed the study, worked on data interpretation and collaborated on writing and reviewing the manuscript. Hermínio Ismael de Araújo-Júnior designed the study, worked on data interpretation and collaborated on writing and reviewing the manuscript.