

Article

# The Role of Climate in the Collapse of the Maya Civilization: A Bibliometric Analysis of the Scientific Discourse

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**Abstract:** This bibliometric analysis deals with research on the collapse of the Maya civilization—a research topic with a long-lasting history, which has been boosted significantly by recent paleoclimatic research. The study is based on a publication set of 433 papers published between 1923 and 2016. The publications covered by the Web of Science (WoS) show a significant increase since 1990, reaching about 30 papers per year at present. The results show that the current discourse on the collapse of the Maya civilization is focused on the role of climate as a major factor for the demise of this ancient civilization. The bibliometric analyses also reveal that (1) paleoclimatic records become numerous and are increasingly better dated; (2) the explanatory power of the records has been significantly increased by analyzing samples from regions closer to the relevant Maya sites; and (3) interdisciplinary cooperation of the humanities (archeology, anthropology, history) with natural sciences disciplines (geoscience, ecology, paleoclimatology, meteorology) seems to be highly promising. The collapse of the Maya civilization is a good example of how natural sciences entered research in the humanities and social sciences (anthropology, archeology, history) and boosted research (and solutions) around long-discussed, but unsolved questions.

**Keywords:** Maya civilization; climate change; citation analysis; altmetrics; RPYS

## 1. Introduction

At least since the travels of John Lloyd Stephens and Frederick Catherwood around 1840 [1,2], we know that the Maya have established one of the great cultures of the ancient world. The ruins of their monuments, including massive pyramids, temples and other ceremonial buildings within large cities throughout the Yucatan Peninsula, covering Belize, parts of Guatemala, and southern Mexico, have become highly attractive tourist objectives. Although the Maya did not use the wheel for transportation (only for toys) and were without metal tools, they had a sophisticated knowledge of astronomy (a calendar based on the solar year), developed a hieroglyphic script and a counting system with base number 20 (including the concept of zero). The Classic period of the Maya civilization (around AD 250–1000) reached its zenith around AD 750 and disintegrated during the Terminal Classic period (AD 750–1000). “Millions of people disappeared, and until now, there has not been a convincing explanation of what happened” [3]. While the southern Maya civilization (today: Belize, Guatemala) collapsed, the north not only survived but enjoyed relative prosperity with the rise of a number of urban centers (with Chichen Itza as one of the greatest). But according to recent data [4] and contrary to previous belief, also the north had suffered a decline in the 9th century and eventually collapsed in the Postclassic 11th century. Therefore, we speak here of “Maya collapse” instead of

“Classic Maya collapse”. We use the term “collapse” although it is somewhat misleading, because the downfall happened at different Maya sites at different times, and overall during a period of more than two centuries.

The decline of the Maya civilization has been analyzed and discussed since the discovery of their ruins and remained one of the great anthropological mysteries. Over the years, scholars have discussed not less than one hundred different possible causes, ranging from internal warfare, foreign intrusion, environmental degradation, and outbreaks of diseases to climate change [3]. Until recently, mostly internal factors have been proposed as possible explanations for the collapse of the Classic Maya civilization (i.e., the collapse was their own fault). Since 1995, however, paleoclimate records from lake and marine sediments as well as stalagmites have provided unambiguous evidence, that unusual shifts in atmospheric patterns caused a series of devastating drought episodes, which are coincidental with the decline period of the Maya civilization. Climate research has revealed that the annual shift of the intertropical convergence zone (an atmospheric feature resulting in dry winter and wet summer seasons) sometimes extends too far to the south, resulting in insufficient rainfall in summer. Researchers have found a striking correlation between periods of severe drought indicated by paleoclimatic records as proxy data and the fall of the Maya civilization during the 9th–11th century [4–7].

In contrast to the above findings, some earlier scholars [8,9] had discussed a shift from an arid to the current wetter climate with tropical conditions during the summer and choking jungle vegetation, which made agriculture in the Maya Lowlands of Yucatan increasingly difficult. This is quite similar to the global cooling discussion before 1980, which soon shifted to the global warming discussion at present [10]. Before paleoclimatic data entered, there was a long-lasting and often very controversial discussion, in which the various possible causes of the Maya collapse were given different weights. For example, Wilhelmy mentions overpopulation, lack of food, soil depletion, and ecological imbalance (internal causes), before discussing climate change as a possible external cause of the decline [11].

Against the backdrop of the complexity of a great civilization, we cannot expect a one to one connection between climate change and collapse. The combination of different factors is more realistic. However, climate change has the potential to be the driving force for the downfall of the Maya civilization since many other possible causes such as environmental degradation, lack of food, and outbreaks of diseases are probable consequences of shifting climatic conditions. The following scenario might be possible: As a consequence of a long period of sufficient rainfall during the Preclassic and Classic Maya periods, the population increased significantly. To cope with the increased demand for food, agriculture had to be expanded by deforestation, which changed the local climate (less rainfall) and caused soil erosion. This initiated a downward spiral, which was significantly amplified then by the external factor of a shifting climate. This in turn caused a massive political disintegration (civil war, inter-city-conflicts) and the power of the kings vanished. There was no longer an authority for the water management, leading to more hunger, followed by epidemics. Taken together, the Maya “ran out of options” [12]. Beginning around 1050, the Maya abandoned the inland regions and their exodus may have been caused by hunger. When the European colonists entered Central America in the early 1500s, the towering limestone cities were already being reclaimed by the jungle and the population was no longer living in large cities.

The past climate changes were mainly caused by natural forces, but future changes will increasingly be dominated by anthropogenic intervention. Climate is one of the key controlling factors in agriculture, since most crops are highly responsive to their surrounding environment. Not surprisingly, agriculture and food security have become main topics of current climate change research [13–15]. The gradually rising average global temperature is anticipated to affect agriculture all over the world. The ancient Maya can deliver a historic experiment of how (anthropogenic or natural) climate change might impact a complex society. But the Maya civilization is not the only one that came to fall during a period of exceptional climatic conditions. The Akkadian empire in Mesopotamia, the Old Kingdom civilization of Egypt, the Harappan civilization of the Indus valley, the Anasazi in

North America as well as the Moche and the Tiwanaku civilization in South America collapsed in periods of severe drought [16].

The study of the ancient Maya tends to reflect the interests and preoccupations of contemporary society. We have to consider that climatological concerns of today might be influencing an interest in these topics for the ancient past. The anthropological understanding of “collapse” has also become more nuanced and the discussion about the Classic Maya has matured in such a way that the relevance of climatological factors has become more accepted. Current climate change research focusing on human made global warming is trying to understand past climate, in order to be able to predict future climate. Therefore, various techniques for consulting paleoclimatic data have been developed. The recent global warming discussion may absolutely have tempted researchers to discuss a multitude of effects as a result of natural or anthropogenic climate change (as for example the decline of ancient civilizations).

The highly dynamic climate change research could indeed deliver the preconditions to solve the mystery of the Maya collapse. The methods applied until now are based (1) on appropriate materials serving as climate archives (lake or ocean sediment cores, cave stalagmites, wood); (2) on dedicated dating techniques (isotope based dating using carbon-14 or uranium/thorium concentrations, tree ring dating); and (3) on suitable indicators for the amount of rainfall (composition of isotopes like oxygen-18, chemical elements like titanium, compounds like gypsum). A detailed overview on the methods is given by Douglas et al. [17]. But we have to keep in mind that “documenting past droughts relies on proxy indicators for rainfall, which are preserved in natural archives . . . Each archive and proxy has inherent strengths, but also weaknesses . . . Our current understanding of the relationship between climate and Maya cultural change during the Terminal Classic therefore remains fuzzy” [18] (p. 45).

This bibliometric analysis aims to quantify and visualize the scientific discourse about the role of climate change in the collapse of the Maya civilization. Although narrative reviews on this discourse are available, this study is the first with a quantitative, i.e., bibliometric approach. First, we selected a publication set of papers dealing with the decline of the Maya civilization and analyzed the time-evolution of the publications as well as the amount of climate-specific keywords. Second, we visualized co-authorship patterns of the publications, the amount of co-citations of the papers from the various authors, and the citation network of major contributors. Third, we analyzed the references cited within the publication set with regard to their specific role in the scientific discourse about the collapse of the Maya civilization. We analyzed the number of citations to study the scientific impact within the relevant community. Fourth, news counts were used to reveal the impact of the papers in our set beyond the scholarly context.

## 2. Materials and Methods

### 2.1. Dataset Used

Initially, we were interested in the time-evolution of the overall Maya literature covered by the Web of Science (WoS, Clarivate Analytics, formerly the IP and Science business of Thomson Reuters). We searched for publications with the terms “Maya”, “Mayas”, “Mayan”, or “Mayans” appearing in the titles and also in the topic search field (i.e., with abstracts and keywords included). Note that topic searching with abstracts included is not possible in the WoS before 1991, because the abstracts of the database records of the earlier publication years are still not available. However, we assume that a topic search with the abstracts and keywords included would deliver a similar picture before 1991 as the title word searching.

We established a more sophisticated search query to select the publications specifically dealing with the collapse of the Maya civilization. The complete WoS search query is given in Appendix A (Table A1). This topic-based search retrieved in particular research articles published since around 1990 as complete as possible. The multi-meaning of some search terms, however, caused a certain amount of non-relevant papers (approximately 10%) within the resulting data set. For getting a more

focused publication set, we iteratively refined the publication set of the first search step by excluding WoS research areas with irrelevant records. A few less relevant or some non-relevant publications may be still included in the final publication set, but we do not expect any significant influence on the overall picture. Finally, we narrowed down to those publications, which specifically discuss climate impacts on the Maya decline. At the date of search (January 17, 2017), we retrieved 433 publications dealing with the collapse of the Maya civilization published between 1923 and 2016 (#3 of the search query), with 207 papers discussing the impact of climate on the decline of the Maya (#4 of the search query). Since the initial publication set is comparatively small (433 papers) and as we focus here on the role of climate in general and not specifically on anthropogenic climate change, only few climate relevant search terms are needed, in contrast to the search query applied in [19].

The publications retrieved do not comprise the complete publication set covering any relevant paper. There are presumably more publications, which appeared in journals not covered by the WoS, or which cannot be retrieved by our search query. Reference [20] is a good example of a paper not retrieved by our search query (and therefore not included in the set of 433 papers). The term “collapse” or one of the searched synonyms do not appear in the title or abstract; instead, the authors speak of “discontinuities of Maya cultural evolution” (abstract). However, we assume that we have included most of the (journal-based) key papers. We are aware of the fact that our publication set is incomplete in particular with regard to books and book chapters, which play a major role in the humanities [21]. Therefore, we have considered in some analyses the complete list of references cited by the papers of our publication set for visualizing the citation network as well as for detecting the historical origins and the most important works within the discourse. The cited references are not restricted to certain document types.

## 2.2. Visualization of the Research Topic

We used the VOSviewer software 1.6.5 [22,23] for mapping the authors and keywords of the literature dealing with the collapse of the Maya civilization. We analyzed co-authorship and co-citation patterns in the dataset. The co-authorship map and the co-citation map of the first-authors are based on concurrent occurrence (co-occurrence) for positioning the nodes (i.e., the authors) on the maps. The distance between two authors is approximately inversely proportional to the amount of co-authorships or the number of co-citations. Hence, authors who have frequently co-authored or whose papers have often been co-cited tend to be found closer to each other. The size of the nodes is proportional to the number of papers or the number of co-cited references, respectively. The nodes on the maps are assigned by VOSviewer to clusters based on a specific cluster algorithm (the clusters are highlighted in different colors). These clusters identify closely related nodes, where each node is assigned to only one cluster [22]. The method, which we used for revealing the thematic content of our publication set, is based on the analysis of all keywords (author keywords and “keywords plus”, allocated by the database provider). The keyword map is based on co-occurrence for positioning the corresponding keywords on the map. The distance between two keywords is approximately inversely proportional to the similarity of the keywords (relatedness in terms of co-occurrence). Hence, keywords with a higher rate of co-occurrence tend to be closer to each other. The size of the nodes is proportional to the number of papers with a specific keyword.

## 2.3. Cited References Analysis

We used CitNetExplorer [24,25], a bibliometric tool to visualize the citation network of an ensemble of papers including their references. The tool builds on Eugene Garfield’s work on algorithmic historiography and the corresponding program HistCite (the program is no longer in active development or officially supported). CitNetExplorer was used to analyze the development of the research dealing with the collapse of the Maya civilization over time.

Questions regarding the historical context of research fields or specific research topics can be answered by using a bibliometric method called Reference Publication Year Spectroscopy (RPYS) [26]

in combination with a recently developed program named CRExplorer [27–29]. In this study we determined, which references have been most frequently cited by the papers in our publication set and whether comparatively highly-cited early references (citations classics) exist. RPYS analysis aims to mirror the knowledge base of the relevant research topic (here: research dealing with the collapse of the Maya civilization). It is an advantage of RPYS that the seminal papers are detected on the basis of the references cited by the relevant community without any further assumptions. However, the results should be interpreted preferably by experts with substantial insights into the topic.

The analysis of the publication years of the references cited by all papers in a specific research field shows that (earlier) publication years are not equally represented. Some years occur particularly frequently among the cited references. The years appear as pronounced peaks in the distribution of the reference publication years (i.e., the RPYS spectrogram). The peaks are frequently based on single early publications, which are highly-cited compared to other early publications. The highly-cited papers are, as a rule, of specific significance to the research field in question and often represent its origins and intellectual roots [26]. RPYS has the advantage that it is based on cited references; it is thus less dependent on restrictions of literature coverages by databases. In recent years, several papers have been published, in which RPYS is basically described and applied to examine the historical roots of various research fields [30–34].

In this study, we performed the reference analysis by importing the publication data including the cited references (downloaded from the WoS) into the CRExplorer. The first step in RPYS was to select the publications of the research field and to extract all references cited therein. The second step was to establish the distribution of the frequencies of the cited references over the reference publication years and to determine the reference publication years cited rather frequently. The third step was to analyze these reference publication years for frequently referenced publications. The RPYS revealed the most frequently referenced papers within specific reference publication years. In contrast to usual bibliometric analyses in research evaluation, RPYS does not identify the most highly-cited papers of the publication set under study (which is based on the WoS times cited information).

The publication years of the references ( $n_r = 19544$ ) cited by the papers of our publication set ( $n_p = 433$ ) range from 1923 to 2016. CRExplorer offers the possibility to cluster and merge variants of the same cited reference [27,28]. Automatic clustering (without considering volume and page numbers due to the large portion of cited books) and subsequent merging of 2084 variants of the same cited references provided the initial data basis (for more information on using the CRExplorer see its handbook at [27]). Due to the many possible errors in cited references, the automatic clustering and merging procedure of the CRExplorer may not unify all possible variants. Therefore, the CRExplorer offers the possibility to cluster cited references manually. But the manual cleaning is only practically manageable with a small number of cited references. We do not expect significantly different results with a manually corrected set of cited references.

After automatic clustering and merging of our dataset we applied a threshold to identify substantial cited references: To focus the RPYS on the most-pronounced peaks, we removed all references with reference counts below 10 (resulting in a final number of 203 cited references published between 1931 and 2014) for the detection of the most frequently cited works. A minimum reference count of 10 has proved to be reasonable in particular for early references [26].

The occurrences of cited references determined by RPYS reflect the citation impact of the cited publications within the publication set dealing with the collapse of the Maya civilization. Thus, a kind of normalization of citation impact is ensured by the RPYS: the selection of the publication set, on which citation impact is measured exclusively. All citing publications focus on the collapse of the Maya civilization. However, the cited references have been published throughout a large time period and thus within quite different publication and citation cultures. Therefore, the frequencies of cited publications from different years are not comparable with each other.

## 2.4. News Counts

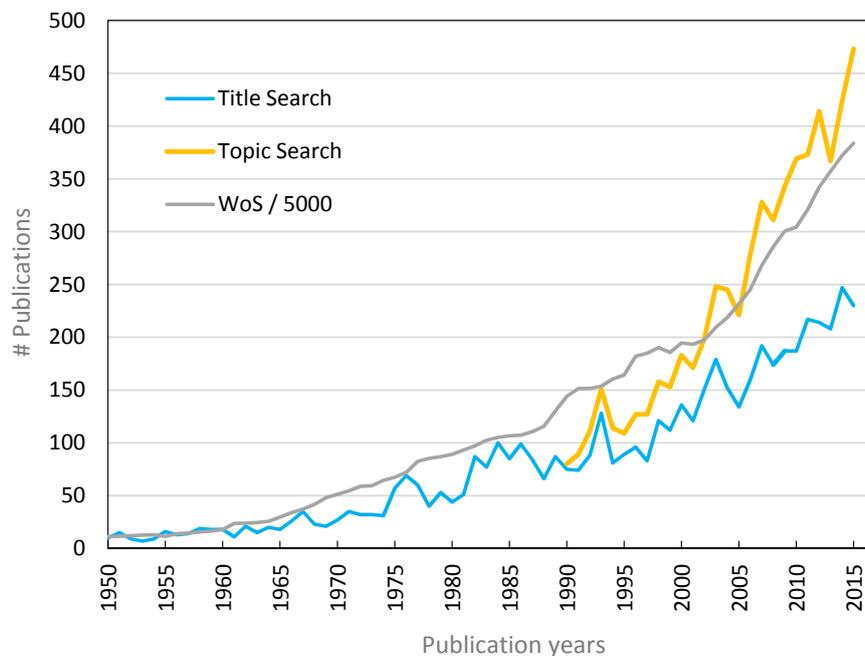
Since citations measure the impact of papers within science, we considered in this study news counts to identify papers with a broader impact (beyond science). Books cannot be included here, however, books typically don't receive many news mentions. Therefore, most of the news counts are dominated by journal articles. News impact is mainly linked to papers by using direct links or unique identifiers, such as DOIs [35,36]. Providers (e.g., Altmetric [37] or Plum Analytics [38]) of alternative metrics (altmetrics) track mentions of scientific works in online media, among them news outlets (e.g., BBC or The Times) [39]. Altmetric shared with us a snapshot of their data on 4 June 2016. We imported this snapshot into a database locally maintained at the Max Planck Institute for Solid State Research in Stuttgart. This database was used to analyze how often a publication in our set was found to be mentioned in a news report.

The datasets include various variants of author names (e.g., one or more first name initials) and keywords (e.g., complex terms with and without hyphen). Basically, the variants could be unified. However, this is only possible by comparing each single paper with the corresponding original article. A clear assignment is difficult or can be misleading in many cases. Therefore, we decided to create the presented maps based on the bibliographic information as provided by the Web of Science database.

## 3. Results

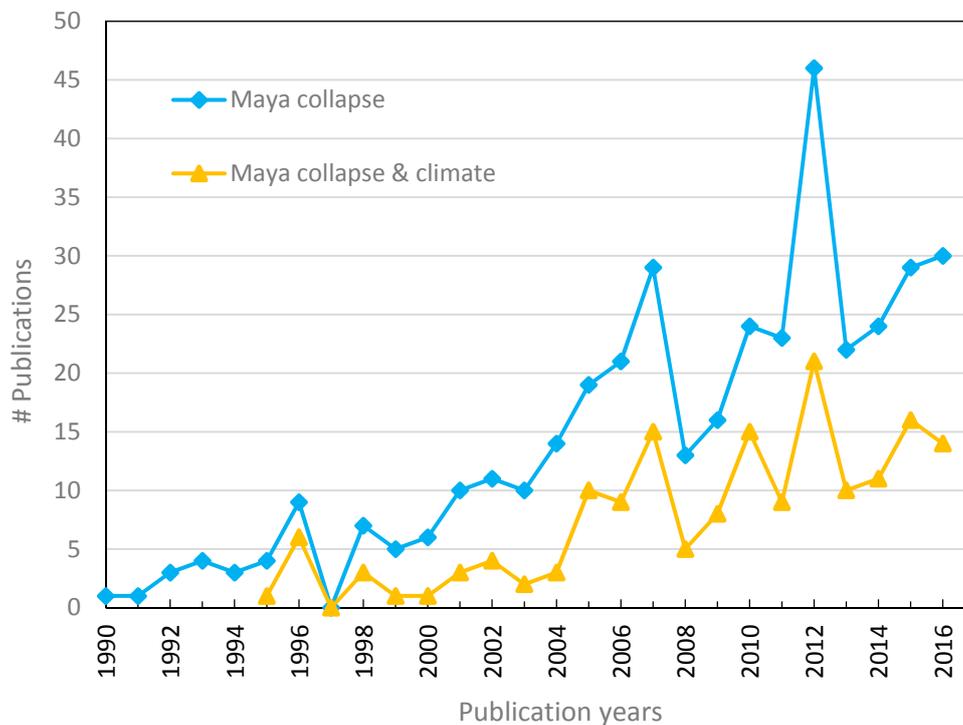
### 3.1. Growth of the Overall Maya Literature

First, we show the time-evolution of the overall Maya literature covered by the WoS (Figure 1). The time-evolution of the publication rates evolves exponentially and doubles approximately every 10–15 years since 1990. To put this into perspective, we compare our results with the growth rate of the overall science: According to Bornmann and Mutz [40], the total volume of publications covered by the WoS between 1980 and 2012 doubled approximately every 24 years. Hence, the growth rate of Maya related publications is comparatively high. However, the Maya literature increases less quickly than the literature on climate change, which doubles every five to six years [19].



**Figure 1.** Number of publications per year with the title words “Maya”, “Mayas”, “Mayan”, or “Mayans”. For comparison, the time curve of the overall number of publications in the database divided by 5000 is included. Source: WoS.

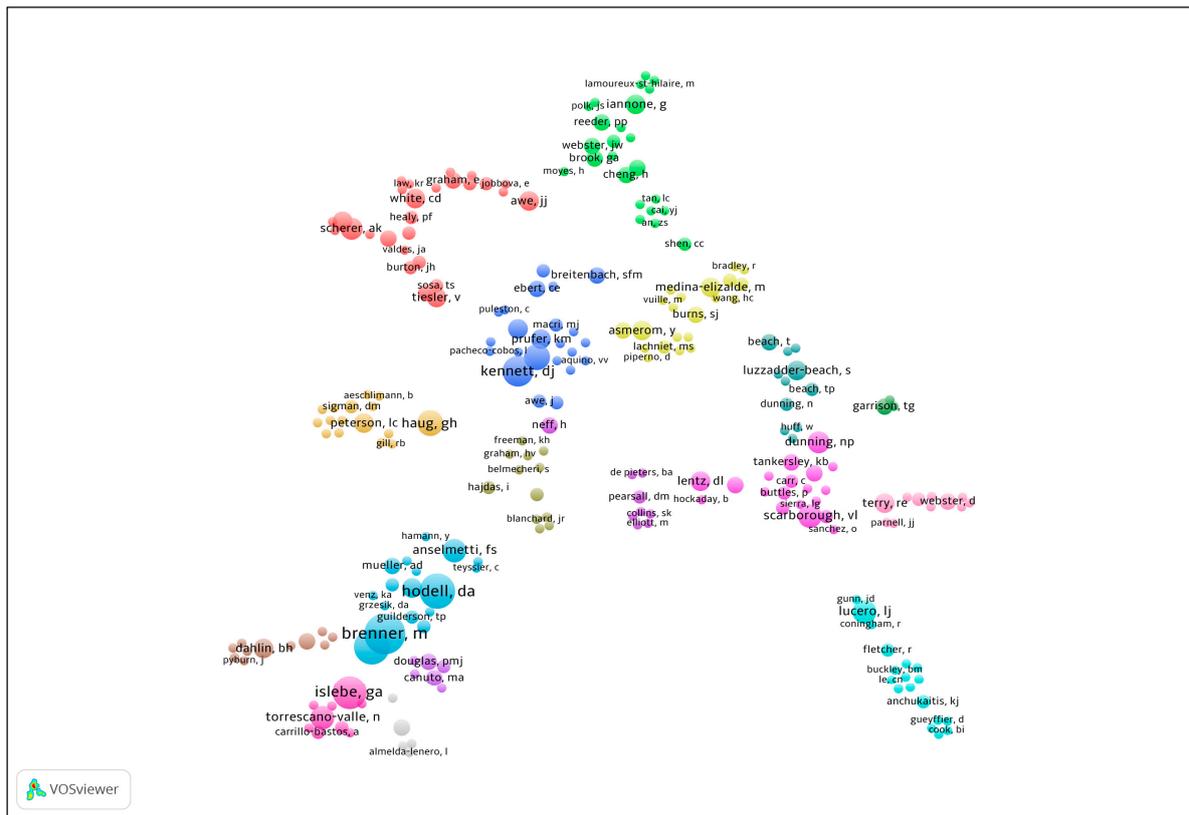
Second, we show in Figure 2 the time curves of the publications in our set related to the Maya collapse and to the collapse in combination with climate (#3 and #4 of the search query in Appendix A (Table A1)). The publications show a significant increase since 1990 and reached about 30 papers per year at present. About half of the publications deal with climate impacts and are predominantly assigned to one of the WoS geosciences subject categories. The pronounced peak in 2012 could be due to the Maya calendar-related prediction that the world would end on 21 December 2012. This might have renewed interest in Maya culture and calendar as well as the Maya collapse.



**Figure 2.** Number of publications per year related to the Maya collapse and to those in combination with climate. Source: WoS.

### 3.2. Visualization of Co-Authors and Co-Citations

The co-authorship map based on 433 papers dealing with the collapse of the Maya civilization is presented (Figure 3). The figure visualizes the most-productive authors within our publication set. We see at the bottom left Mark Brenner, Jason Curtis, and David Hodell at the University of Florida. Their co-authored paper from 1995 initiated the application of methods from geoscience, which had proved valuable in modern climate change research, into research activities dealing with the fall of the Classic Maya civilization [5]. The authors of the Hodell group and Gerald Islebe at the University of Amsterdam are located nearby. The paper by Islebe on the vegetation history of the Maya Lowlands is based on cooperation with the Hodell group [41]. We find Gerald Haug (ETH Zurich) and Larry Peterson (University of Miami) above the authors around David Hodell. Their 2003 paper on sediments from Cariaco Basin of the Caribbean Ocean indicates a severe drought at the end of the Classic Maya civilization [7], thereby confirming the findings of the Hodell group.



**Figure 3.** Co-authorship map of all authors from the 433 Maya collapse papers (the minimum number of papers containing a specific author is one). Source: WoS, VOSviewer.

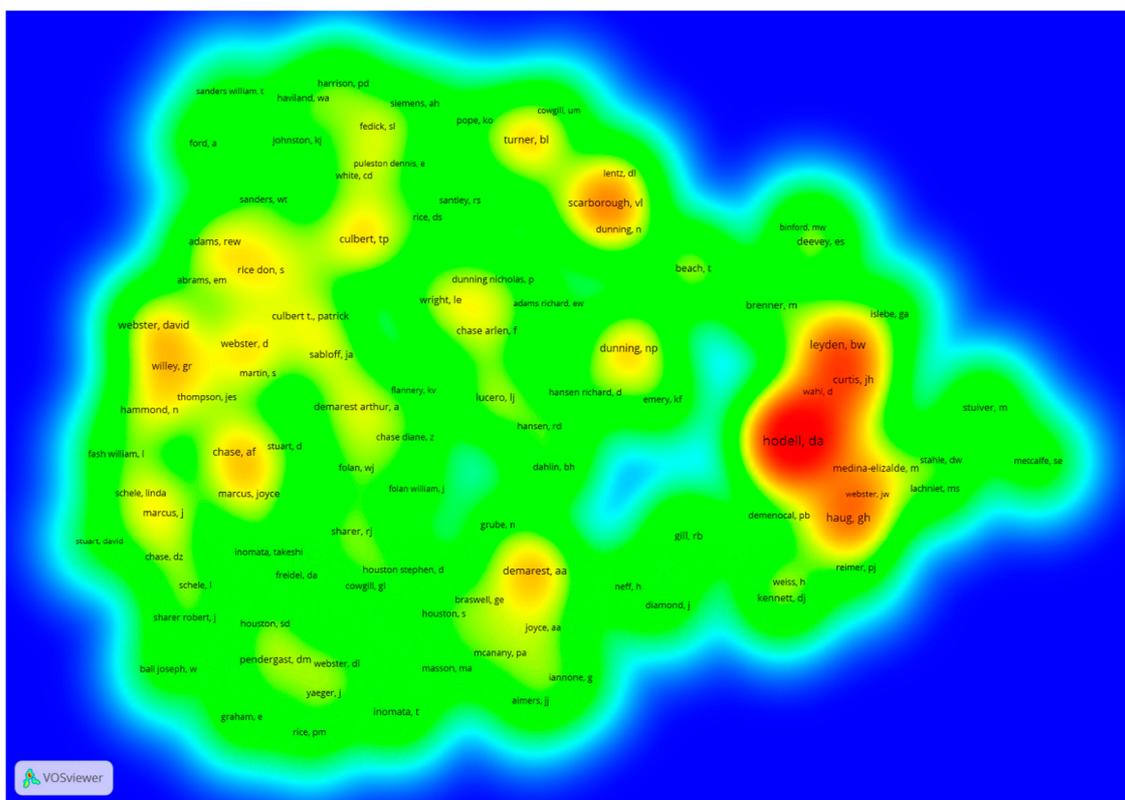
Douglas Kennett from the Pennsylvania State University appears in the center of Figure 3. His 2012 paper (co-authored by Gerald Haug and analyzing the influence of drought on the disintegration of the Maya political systems) correlated precisely dated paleoclimatic records of the past 2000 years with the active times of urban Maya centers (based on stone calendar inscriptions and radiocarbon dating) [4]. According to their results, a second period of drought in the 11th century had caused the collapse of the Maya in the north, after they had suffered a decline during the first wave of droughts about 200 years earlier. The 11th century brought the worst drought for the region within 2000 years, a real mega-drought. After this second wave of drought the Maya civilization never recovered.

Some authors in Figure 3 can be seen as predecessors of Hodell, Haug, and Kennett: Bruce Dahlin at the University of Colorado (bottom far left) discussed drought and its effects on soil and vegetation in late Preclassic Maya civilization already in 1983 [42]. Vernon Scarborough (center right) at the University of Cincinnati discussed the Pre-Hispanic water management and water storage in well-planned reservoirs in the Maya Lowlands in a paper from 1991 [43].

Further major authors appearing in the map are (in alphabetical order and each with the title of the most-frequently cited first-author paper in our publication set): Flavio Anselmetti (“Late quaternary climate-induced lake level variations in Lake Peten Itza, Guatemala, inferred from seismic stratigraphic analysis”) [44] at bottom left, Timothy Beach (“Impacts of the ancient Maya on soils and soil erosion in the Central Maya Lowlands”) [45] at center right, Nicholas Dunning (“Kax and kol: collapse and resilience in Lowland Maya civilization”) [46] at center right, Gyles Iannone (“The rise and fall of an ancient Maya petty royal court”) [47] at center top, David Lentz (“Tikal timbers and temples: ancient Maya agroforestry and the end of time”) [48] at center, Lisa Lucero (“The collapse of the Classic Maya: a case for the role of water control”) [49] at bottom right, Sheryl Luzzadder-Beach (“Wetland fields

as mirrors of drought and the Maya abandonment”) [50] at center right, Martin Medina-Elizalde (“Collapse of Classic Maya civilization related to modest reduction in precipitation”) [51] at center, Andrew Scherer (“Bioarchaeological evidence for social and temporal differences in diet at Piedras Negras, Guatemala”) [52] at top left, and James Webster (“Stalagmite evidence from Belize indicating significant droughts at the time of Preclassic abandonment, the Maya hiatus, and the Classic Maya collapse”) [53] at center top.

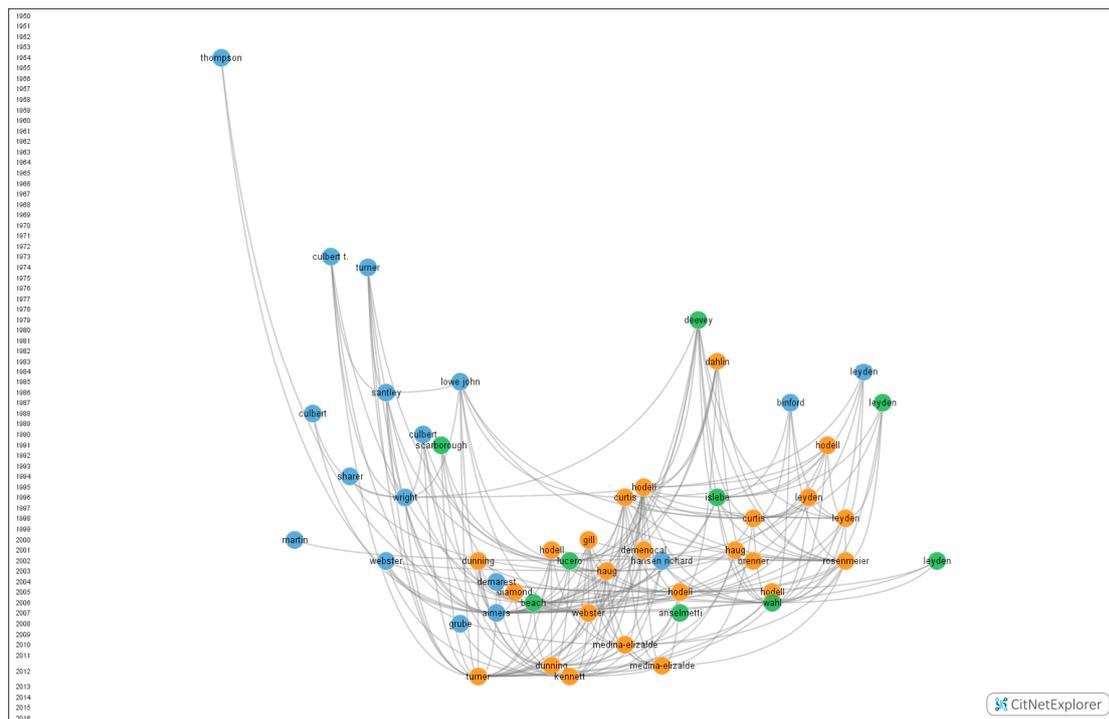
The co-citation map of the first authors from the Maya collapse papers is presented, here in the form of a density map (Figure 4). The figure illustrates a clear separation between (1) the authors from the geosciences and paleoclimatology who focused on the impact of climate change, appearing on the right (Hodell, Curtis, Haug, et al.); and (2) the authors from archeology and anthropology (Culbert, Demarest, D.L. Webster, et al.) located in the center and on the left. The red-colored area around Hodell, Curtis, and Haug indicates the high citation impact of their works in the form of (co-cited) references, and by this the significance of their contributions for the current Maya research.



**Figure 4.** Co-citation map of the first-authors from the 433 Maya collapse papers (the minimum number of co-citations is 30). Source: WoS. VOSviewer.

In addition, we produced a keyword map for the content analysis of the papers on the Maya collapse (Figure 5). As expected, our basic search terms *Maya* and *collapse* appear in the map as pronounced keywords (center), surrounded by related keywords (*civilization*) and geographical terms (*Mexico*, *Mesoamerica*, *Lowlands*). More important, however, is a second category of major keywords associated with climate: *climate*, *climate change*, *drought*, *precipitation*. A third category of terms (more specific and less pronounced) is associated with methods specifically applied in the field of paleoclimatology (*records*, *sediments*, *pollen*, *isotope*). Altogether, most keywords point to research dealing with climate change in connection with the downfall of the Maya civilization.





**Figure 6.** Citation network of the 50 most-frequently cited references out of 433 Maya collapse papers (including the non-matching cited references) with a minimum frequency of 10. Light blue: publications with no focus on climate. Light green: publications with a more indirect relation to climate change, dealing for example with agriculture, soil erosion, deforestation, and vegetation history. Orange: publications with a direct relation to climate as a driving force, mostly based on paleoclimatic records. The classification is based on content analysis of the papers and the coloring has been performed by the corresponding software function. Source: WoS, CitNetExplorer.

The evolution of the scientific discourse on the causes leading to the collapse of the Maya civilization is visualized by the citation network of the most-frequently cited papers (Figure 6). Until around 1990, many controversial theories about possible causes have been discussed in the subject-specific literature (e.g., civil war, invasion, epidemics, overpopulation, and environmental sins). Only few earlier papers focus on the impact of climate change on Maya culture. The works of Deevey on soil erosion [54], of Leyden on climate history in the Maya Lowlands [55], and of Scarborough on water storage adaption in the Maya Lowlands [43] introduced climate as an important factor for the evolution and the fall of the Maya civilization. Dahlin already discussed drought and its effects on soil and vegetation in the late Preclassic Maya period and can be seen as a forerunner of the climate-oriented community [42]. The earliest work in Figure 6 was published by Sir John Eric Thompson, a great historical overview (“Rise and fall of Maya civilization”) [56]. The publication by Martin and Grube [57] relies on chronicles of the Maya kings, which play a major role in the correlation of archeological and paleoclimatic data by Kennett [4].

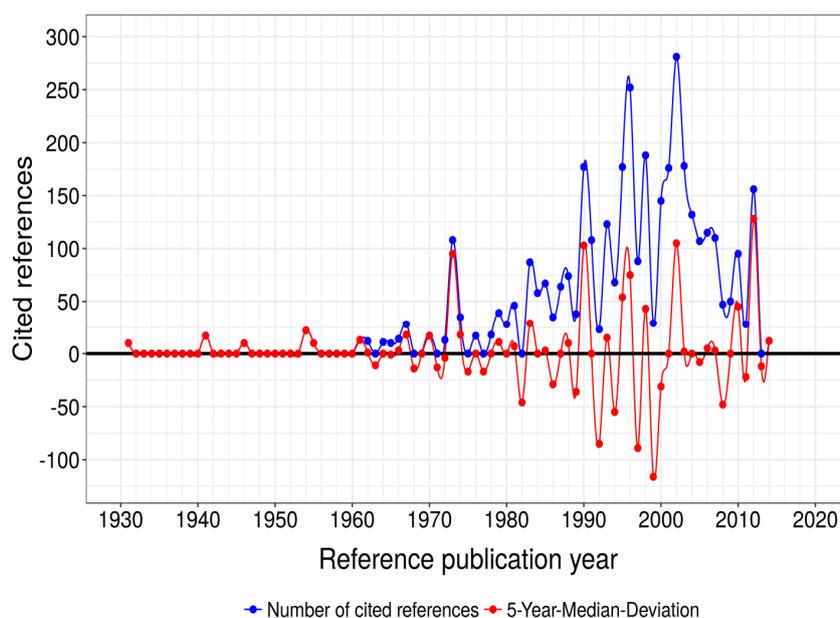
In 1995, David Hodell initiated a series of paleoclimatic papers based on records from ocean and lake sediments as well as from cave stalagmites (in diverse collaborations with Brenner, Curtis, Haug, Medina-Elizalde, and Rosenmeier). Five years later, the book by the independent archeologist Richardson Gill entitled “The great Maya droughts” presented an enormous amount of information and stimulated the discussion and the following research [3]. Meanwhile, many indicators supported this picture: James Webster presented a paper entitled “Stalagmite evidence from Belize indicating significant droughts at the time of Preclassic abandonment, the Maya hiatus, and the Classic Maya collapse” [53]. The 2012 paper by Kennett can be seen as an important example for the increasing inter-disciplinary collaboration to solve the mystery on the causes of the Maya downfall [4].

This paper represents only one of many other inter-disciplinary collaborations. According to Kennett, we have to distinguish two waves of drought; after the second wave in the 11th century, there was no real recovery for the Maya. Both papers [4,53] conclude that a long lasting mega-drought seems to be a decisive factor for the fall of the Maya civilization. Against the backdrop of these contributions from the geosciences and paleoclimatology, Heather Pringle speaks of “a new look at the Maya’s end” [58].

The idea that the Maya may have changed the environment of some of their city-states by massive deforestation followed by soil erosion was popularized by the environmental historian Jared Diamond in his 2004 book “Collapse” [59]. A rapidly growing population at the city of Copan (a major Maya site in western Honduras) made the Maya cut trees to plant cornfields and use the wood as fuel for cooking and heating limestone for the plaster of their buildings. As a consequence of the changing local climate and the soil erosion, agriculture became increasingly difficult and the population decreased rapidly (about 99% of the population in the southern Maya areas was no longer living in large cities). Diamond discusses the findings of Hodell [5]; he assumes that similar to the demise of the Anasazi civilization in New Mexico (USA), the frequently occurring drought was the decisive external force. The Maya society became extremely vulnerable because of a rapidly growing population, the soil erosion as a consequence of deforestation, and the generally irregular rainfall in combination with an increasingly complex society.

#### 3.4. Spectrogram of the Cited References

The results of the cited reference analysis are shown as RPYS graph (Figure 7). The spectrogram presents the distribution of the number of cited references across their publication years within the time period 1931–2014. The blue curve shows the number of cited references per reference publication year. In order to identify those publication years with significantly more cited references than in other years, the deviation from the five-year median, i.e., the deviation of the number of cited references in each year from the median of the number of cited references in the two previous, the current, and the two following years ( $t - 2$ ;  $t - 1$ ;  $t$ ;  $t + 1$ ;  $t + 2$ ), is also visualized (red curve). This deviation from the five-year median provides a curve smoother than the one in terms of absolute numbers. We used both curves for the identification of peak references.



**Figure 7.** Annual distribution of the references cited in the publication set of 433 papers across their reference publication years 1931–2014. Blue curve: number of cited references; red curve: deviation from the median. Source: WoS, CReXplorer.

The RPYS spectrogram shows 13 (more or less) pronounced peaks in the following reference publication years: 1931, 1954, 1973, 1983, 1990, 1995, 1996, 1998, 2001, 2002, 2003, 2010, and 2012 (Figure 7). CRExplorer enables the identification of highly-cited references via the table of references presented alongside the spectrogram. The references mainly responsible for the peaks are listed in Table 1.

**Table 1.** The most frequently cited references from specific reference publication years cited by papers dealing with the collapse of the Maya civilization. For each reference, the corresponding reference publication year (RPY) and the number of cited references (NCR) within our publication set are listed (note that these are not the total citation counts according to the WoS times cited numbers). The publication years of the paleoclimatic papers are in bold. Source: WoS.

RPY	Reference	NCR
1931	C.W. Cooke: Why the Mayan cities of the Petén district, Guatemala, were abandoned. <i>Journal of the Washington Academy of Sciences</i> 21(13), 283–287. [60]	10
1954	J.E.S. Thompson: The rise and fall of Maya civilization. University of Oklahoma Press, USA. [56]	22
1973	P.T. Culbert (Editor): Classic Maya collapse. School for Advanced Research Press. [61]	44
<b>1983</b>	B.H. Dahlin: Climate and prehistory on the Yucatan Peninsula. <i>Climate Change</i> 5(3), 245–263. doi:10.1007/BF00140183 [42]	19
1990	P.T. Culbert (Author): Precolumbian population history in the Maya Lowlands. University of New Mexico Press. [62]	31
<b>1995</b>	D.A. Hodell, J.H. Curtis, & M. Brenner: Possible role of climate in the collapse of Classic Maya civilization. <i>Nature</i> 375(6530), 391–394. doi:10.1038/375391a0 [5]	135
<b>1996</b>	J.H. Curtis & D.A. Hodell: Climate variability on the Yucatan Peninsula (Mexico) during the past 3500 years, and implications for Maya cultural evolution. <i>Quaternary Research</i> 46(1), 37–47. doi:10.1006/qres.1996.0042 [6]	74
<b>1998</b>	J.H. Curtis, M. Brenner, & D.A. Hodell: A multi-proxy study of holocene environmental change in the Maya Lowlands of Peten, Guatemala. <i>Journal of Paleolimnology</i> 19(2), 139–159. doi:10.1023/A:1007968508262 [63]	31
<b>2001</b>	D.A. Hodell, M. Brenner, J.H. Curtis, & T. Guilderson: Solar forcing of drought frequency in the Maya Lowlands. <i>Science</i> 292(5520), 1367–1370. doi:10.1126/science.1057759 [20]	71
2002	D.L. Webster: The fall of the ancient Maya: Solving the mystery of the Maya collapse. Thames & Hudson Ltd. [64]	59
<b>2003</b>	G.H. Haug, D. Günther, L.C. Peterson et al.: Climate and the collapse of Maya civilization. <i>Science</i> 299(5613), 1731–1735. doi:10.1126/science.1080444 [7]	117
<b>2010</b>	M. Medina-Elizalde, S.J. Burns, D.W. Lea et al.: High resolution stalagmite climate record from the Yucatan Peninsula spanning the Maya Terminal Classic period. <i>Earth and Planetary Science Letters</i> 298(1–2), 255–262. doi:10.1016/j.epsl.2010.08.016 [65]	32
<b>2012</b>	D.J. Kennett, S.F.M. Breitenbach, V.V. Aquino et al.: Development and disintegration of Maya political systems in response to climate change. <i>Science</i> 338(6108), 788–791. doi:10.1126/science.1226299 [4]	35

According to Figure 7 and Table 1, we distinguish between forerunners (Cooke, Dahlin), subject-specific textbooks (Culbert, Thompson, D.L. Webster), and many recent publications by paleoclimatologists (Curtis, Haug, Hodell, Medina-Elizalde, Kennett, and their co-authors). Independent of the view on the role of climate, the textbooks deliver valuable information for any kind of Maya related research. For example, Culbert [62] has been cited by Haug [7] and Kennett [4], who both rely on Culbert’s population numbers. RPYS informs about the historical origins and the comparatively highly-cited references within the subject-specific research articles. In agreement with

the analyses above, the dominance of the paleoclimatic papers with regard to their number and impact within the relevant community is clearly visible.

The increasing importance of paleoclimatology in Maya research is demonstrated via citation time curves (Figure 8). The figure shows the annual citation rates of four key papers. The citation time pattern of these four key papers deviates significantly from the overall publication set: According to the WoS, the time-dependent citation rate of the complete publication set shows a maximum of annual impact about three years after publication, the citation history of the majority of scientific papers. Obviously, the interest for the paleoclimatic contributions within the research on the downfall of the Classic Maya civilization is still growing.

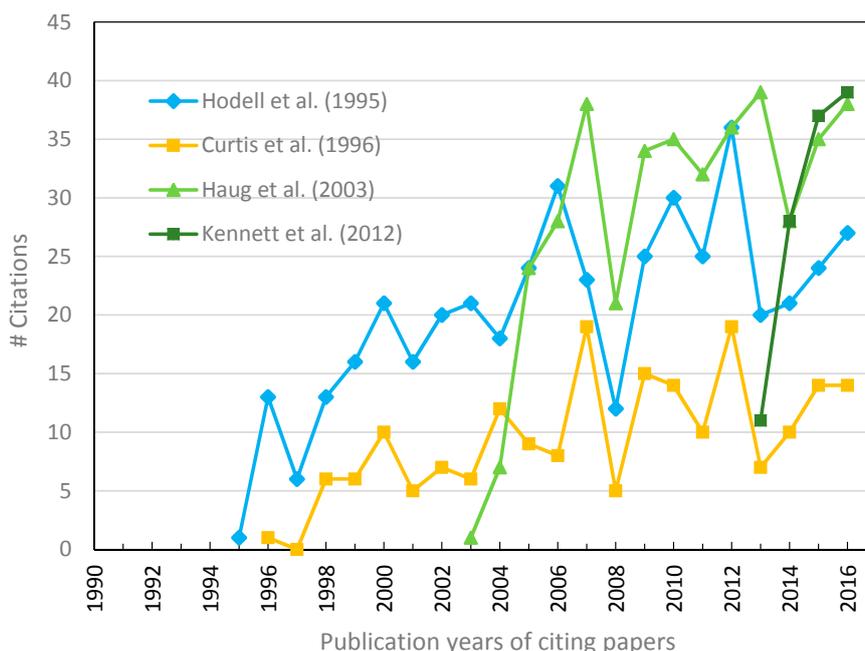


Figure 8. Time-evolution of the number of citations per year of four key-papers. Source: WoS.

### 3.5. News Mentions

The papers of our publication set with more than three news mentions are listed in Table 2. Kennett et al. [4] shows the highest number of news mentions. This paper made the theory of a shifting climate as the driving force for the collapse of the Maya civilization more convincing, and in addition discussed it in the context of its sociopolitical consequences (which is also the thematic focus of most other papers listed in Table 2).

Table 2. Papers with more than three news mentions and ordered by the number of mentions. The publication years of the paleoclimatic papers are in bold. Source: Altmetric.

RPY	Reference	# News
<b>2012</b>	D.J. Kennett, S.F.M. Breitenbach, V.V. Aquino et al.: Development and disintegration of Maya political systems in response to climate change. <i>Science</i> 338(6108), 788–791. doi:10.1126/science.1226299 [4]	18
<b>2015</b>	L.C. Tan, Y.J. Cai, Z.S. An et al.: A Chinese cave links climate change, social impacts, and human adaptation over the last 500 years. <i>Scientific Reports</i> 5, article number: 12284. doi:10.1038/srep12284 [66]	13
<b>2015</b>	T. Bhattacharya, R. Byrne, H. Boehnel et al.: Cultural implications of late holocene climate change in the Cuenca Oriental, Mexico. <i>PNAS USA</i> 112(6), 1693–1698. doi:10.1073/pnas.1405653112 [67]	12

Table 2. Cont.

RPY	Reference	# News
2013	D.H. Evans, R.J. Fletcher, C. Pottier et al.: Uncovering archaeological landscapes at Angkor using LIDAR. PNAS USA 110(31), 12595–12600. doi:10.1073/pnas.1306539110 [68]	11
1995	D.A. Hodell, J.H. Curtis, & M. Brenner: Possible role of climate in the collapse of Classic Maya civilization. Nature 375(6530), 391–394. doi:10.1038/375391a0 [5]	5
2016	J.A. Hoggarth, S.F.M. Breitenbach, B.J. Culleton et al.: The political collapse of Chichen Itza in climatic and cultural context. Global and Planetary Change 138(SI), 25–42. doi:10.1016/j.gloplacha.2015.12.007 [69]	5
2010	B.M. Buckley, K.J. Anchukaitis, D. Penny et al.: Climate as a contributing factor in the demise of Angkor, Cambodia. PNAS USA 107(15), 6748–6752. doi:10.1073/pnas.0910827107 [70]	4
2015	P.M.J. Douglas, M. Pagani, M.A. Canuto et al.: Drought, agricultural adaptation, and sociopolitical collapse in the Maya Lowlands. PNAS USA 112(18), 5607–5612. doi:10.1073/pnas.1419133112 [71]	4
2012	V.L. Scarborough, N.P. Dunning, K.B. Tankersley et al.: Water and sustainable land use at the ancient tropical city of Tikal, Guatemala. PNAS USA 109(31), 12408–12413. doi:10.1073/pnas.1202881109 [72]	4
2012	B.L. Turner II & J.A. Sabloff: Classic period collapse of the Central Maya Lowlands: insights about human-environment relationships for sustainability. PNAS USA 109(35), 13908–13914. doi:10.1073/pnas.1210106109 [73]	4

Between Table 1 (the most frequently cited references) and Table 2, there is an overlap of only two papers: Kennett et al. [4] and Hodell et al. [5]. This shows the different perspectives from the viewpoint of citations and news mentions. Factors that impact "media exposure" of publications are possibly unrelated to the scientific importance of the underlying research. Six out of the ten publications presented in Table 2 deal (in a mostly direct connection) with climate in the context of the decline of the Maya civilization. Four papers show only an indirect connection: Tan et al. [66] provide tests on relationships among paleoclimatic data, drought events, and societal crises based on ancient inscriptions and records from Central China. Evans et al. [68] and Buckley et al. [70] primarily discuss climate as a contributing factor in the demise of Angkor, Cambodia, mentioning the similarity with the Maya collapse. Scarborough et al. [72] deals with the water management of the ancient city of Tikal, Guatemala. Similar to the most-frequently cited references presented in Table 1, the papers with the highest number of news mentions are predominantly based on paleoclimatic methods.

The currently extensive scientific and political discussion on future climate change has made journalists and the general public sensitive with respect to this issue. Accordingly, papers depicting the massive consequences of climate change for ancient societies are highly significant for the current global warming discussion and thus of great interest for journalists. If a complex society really collapsed as a result of a natural climatic shift, the danger of an anthropogenic climate change for our much more complex society at present is obvious.

#### 4. Discussion

This bibliometric analysis deals with research on the collapse of the Maya civilization—a research topic with a long-lasting history, which has been boosted significantly by recent paleoclimatic research. The publications covered by the WoS show a significant increase of research papers since 1990 and reached about 30 papers per year at present.

We have mapped the authors and keywords of the literature dealing with the collapse of the Maya civilization. The co-authorship and the co-citation maps illustrate a clear separation between authors from the geosciences and paleoclimatology (who focused on the impact of climate change) and the authors from archeology and anthropology. The keyword map reveals a multitude of major keywords associated with climate change. Another set of keywords is associated with methods specifically

applied in the field of paleoclimatology. Most keywords point to research dealing with the downfall of the Maya civilization in connection with climate change.

We have visualized the citation network of our publication set and analyzed the network of the 50 most-frequently cited papers. We were interested in the evolution of the scientific discourse with regard to the causes of the collapse of the Maya civilization. Many influential papers show that the current discourse on the collapse of the Maya civilization is focused on the role of climate as a decisive factor for the demise of this ancient civilization. The 1995 paper by Hodell et al. [5] marks the entry of geosciences (in particular paleoclimatology focusing on the role of climate) into the traditional Maya research field.

RPYS informs about the historical origins and the comparatively highly-cited references within the subject-specific papers. In agreement with the analyses above, the dominance of the paleoclimatic papers with regard to their number and impact within the relevant community is clearly visible. According to RPYS, we can distinguish between forerunners (Cooke, Dahlin), subject-specific textbooks (Culbert, Thompson, D.L. Webster), and many recent publications by archeologists and in particular by paleoclimatologists (Curtis, Haug, Hodell, Medina-Elizalde, Kennett, and their co-authors). RPYS accentuates particularly the importance of Hodell et al. [5], Haug et al. [7], and Kennett et al. [4] for the research field in question. Altogether, the most-influential papers show that the current discourse on the collapse of the Maya civilization is focused on the role of climate as a decisive factor for the demise of the Maya civilization.

One should bear in mind that RPYS is not able to identify all influential publications in a paper set. Very recent influential publications can hardly be detected by RPYS, because they had not sufficient time for accumulating citations and therefore do not show up as distinct peaks in the spectrogram. Such publications can only be identified by browsing through the original publication set rather than the cited references. A good example is the paper by Frappier et al. [74], which presents annually resolved proxy data based on mud layers in stalagmites from caves suggesting that droughts during the Terminal Classic period were even more severe than previous estimates. The bibliometric study of Keeling's publications by Marx et al. on measurements of the atmospheric carbon dioxide concentration reveals that a scientific contribution can be more important than it seems from a citation perspective [10]. According to Douglas et al. [17], Cowgill et al. [75] undertook the first lake sediment studies in the Maya Lowlands. However, the corresponding publication received only 7 citations by the papers of our publication set and does not show up as a pronounced peak in the RPYS spectrogram. Presumably, there are other under-cited publications not detectable via bibliometric indicators.

Similar to the most-frequently cited references, the papers with the highest number of news mentions are predominantly based on paleoclimatic methods. The comparatively high number of news articles mentioning Kennett (2012) illustrates the large impact of this paper about drought and disintegration of the Maya political systems within the media (e.g., see Los Angeles Times [76]). This is not surprising if we consider the far-reaching methods and results of the work: (1) The analysis is characterized by an intensive cooperation of archeology and the geosciences by correlating paleoclimatic records of the past 2000 years with the active times of urban Maya centers. (2) The data revealed that contrary to previous belief, also the north had suffered a decline in the 9th century and eventually collapsed in the Postclassic 11th century (as a result of the worst drought for the region within 2000 years). Against the backdrop of the increased explanatory power of the records (by analyzing samples from regions closer to the relevant Maya sites), these findings made the theory of a shifting climate as the driving force of the demise of the Maya civilization more convincing. The climate driven collapse of a complex society at that time was discussed in some news articles as a warning with respect to the risks of the anthropogenic climate change expected for the near future (e.g., see: National Geographic [77]).

## 5. Conclusions

The research topic analyzed in this study is a good example for how a discipline out of the natural sciences entered the research in the humanities (anthropology, archeology, history) and fertilized research around long discussed, but unsolved questions. New techniques in distinct fields are used to answer old questions. The situation can be compared, for example, with the application of modern physical methods like laser scanning technics (e.g., LIDAR = Light Detection and Ranging) for the detection of archeological artefacts, which deployed a similar effect.

The in-depth analysis of the relevant literature identified in this bibliometric study reveals: (1) The current discourse on the collapse of the Maya civilization is focused on the role of climate as a decisive factor for the demise of this ancient civilization. At least half of the papers deal with climate; (2) Paleoclimatic records become numerous and are increasingly better dated; (3) The explanatory power of the records has been significantly increased by analyzing samples from regions closer to the relevant Maya sites; (4) Interdisciplinary cooperation of the humanities (archeology, anthropology, history) with natural sciences (geoscience, ecology, paleoclimatology, meteorology) is highly promising. For example, Kennett et al. [4] is characterized by an intensive cooperation of archeological and paleoclimatic research groups and the correlation of their data (precisely dated paleoclimatic records versus the active times of urban Maya centers based on stone calendar inscriptions and radiocarbon dating). Against the backdrop of our bibliometric results, we can summarize the present state of knowledge by quoting Brian Fagan (also cited by Pringle [58]): “I don’t think that anyone is saying that drought is the only cause, but it clearly is a significant factor” (p. 456); see also [78].

But similar to the fall of the Roman Empire, we cannot expect a one-to-one correlation between a specific force and the downfall (see Peter Heather [79]). According to Andrew Scherer (quoted by Pringle [53]), “when you have something as complex as Classic Maya society, it’s going to take a complex string of events to bring that to an end” (p. 455). The search for one single cause might be wrong. According to the Anna Karenina principle, many factors are involved in such a process [80]. Certainly, the demise of the Maya society was a very complex process; however, climate change seems to be a major factor for the downfall, and this is what the paleoclimatic methods (i.e., the analysis and dating of paleoclimatic records) illustrate.

However, many Maya archeologists still argue that the mega-drought theory doesn’t fit their findings, mainly due to the complexity of the process and inconsistencies between the water supplies of different centers and the timing of their collapse (e.g., see James Aimers [81]). For many archeologists, the collapse of the Maya civilization is not a resolved issue: Most paleoclimatic proxy data do not come directly from the areas where the social collapse occurred. They are mostly far enough from the region that experienced the massive demographic decline and do not represent the patterns for the entire region. A majority of recent climatological studies (1) have coarser chronologies than archaeologists would want and (2) reveal that the drying period of the 9th and 10th centuries were often not the only ones in their entire recorded sequence. As a consequence, correlation doubts result from the first problem, while causation problems derive from the latter. The invention of new proxies providing better and more precise data might one day satisfy all.

Papers published by the experts in a specific field are in danger to be subjective based on their own background and interests. Even review papers can be biased depending on affiliations and collaborations. The bibliometric approach provides (as much as possible) an unbiased view of what the consensus opinion currently is regarding the collapse of the Maya civilization. This analysis aims to distinguish between ‘this is what caused the collapse’ and ‘this is what the current research suggests caused the collapse’. This paper provides a case study for the bibliometric analysis of a scientific discourse from a broader perspective, revealing the current status as well as the time evolution of the consensus and disagreement. The bibliometric methods and tools can well be transferred to other research fields.

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## Appendix A

**Table A1.** WoS search query, date of search: 17 January 2017.

#4	207	<b>TOPIC:</b> ((abandonment OR breakdown OR collapse OR decline OR demise OR doom OR downfall OR fall) SAME (maya OR mayas OR mayan OR mayans) SAME (climat* OR drought* OR rain* OR water*))
#3	433	<b>TOPIC:</b> ((abandonment OR breakdown OR collapse OR decline OR demise OR doom OR downfall OR fall) SAME (maya OR mayas OR mayan OR mayans)) <b>Refined by:</b> [excluding] <b>RESEARCH AREAS:</b> (WOMEN S STUDIES OR VETERINARY SCIENCES OR THEATER OR CHEMISTRY OR SURGERY OR PUBLIC ENVIRONMENTAL OCCUPATIONAL HEALTH OR PEDIATRICS OR NUTRITION DIETETICS OR OPTICS OR OBSTETRICS GYNECOLOGY OR PSYCHOLOGY OR LINGUISTICS OR LIFE SCIENCES BIOMEDICINE OTHER TOPICS OR PHARMACOLOGY PHARMACY OR FILM RADIO TELEVISION OR EVOLUTIONARY BIOLOGY OR DENTISTRY ORAL SURGERY MEDICINE OR ENGINEERING OR ACOUSTICS OR AUDIOLOGY SPEECH LANGUAGE PATHOLOGY OR ENERGY FUELS) AND [excluding] <b>WEB OF SCIENCE CATEGORIES:</b> (HOSPITALITY LEISURE SPORT TOURISM) AND [excluding] <b>PUBLICATION YEARS:</b> (2017)  Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan = All years
#2	436	<b>TOPIC:</b> ((abandonment OR breakdown OR collapse OR decline OR demise OR doom OR downfall OR fall) SAME (maya OR mayas OR mayan OR mayans)) <b>Refined by:</b> [excluding] <b>RESEARCH AREAS:</b> (WOMEN S STUDIES OR VETERINARY SCIENCES OR THEATER OR CHEMISTRY OR SURGERY OR PUBLIC ENVIRONMENTAL OCCUPATIONAL HEALTH OR PEDIATRICS OR NUTRITION DIETETICS OR OPTICS OR OBSTETRICS GYNECOLOGY OR PSYCHOLOGY OR LINGUISTICS OR LIFE SCIENCES BIOMEDICINE OTHER TOPICS OR PHARMACOLOGY PHARMACY OR FILM RADIO TELEVISION OR EVOLUTIONARY BIOLOGY OR DENTISTRY ORAL SURGERY MEDICINE OR ENGINEERING OR ACOUSTICS OR AUDIOLOGY SPEECH LANGUAGE PATHOLOGY OR ENERGY FUELS) AND [excluding] <b>WEB OF SCIENCE CATEGORIES:</b> (HOSPITALITY LEISURE SPORT TOURISM)  Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan = All years
#1	489	<b>TOPIC:</b> ((abandonment OR breakdown OR collapse OR decline OR demise OR doom OR downfall OR fall) SAME (maya OR mayas OR mayan OR mayans))  Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan = All years

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