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Co-authorship analysis of the speleothem proxy-climate community: working together to tackle the big problems

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Abstract: Understanding the environmental context of speleothem palaeo-climate proxies is fundamental to their interpretation. We analyse four methodological approaches to accomplish this: stalactite discharge analysis, proxy/process tracer studies, discharge modelling, and geophysics. Datamining produced citation data sets that reflected these methodological sub-disciplines. Social network analysis is used to examine co-authorship within and between these sub-disciplines, and between the joint methodological community and the broader speleothem proxy climate community. Members of the sub-disciplines have become more connected to one another over time, and to members of the other sub-disciplines. High degrees of connectivity between and within communities allows for the rapid and efficient adoption of new ideas and methods, and will enable the community to effectively tackle emerging complex problems.

Keywords: paleoclimatology, co-authorship, speleothem

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INTRODUCTION

The speleothem-derived palaeo-climate proxy community (SPCPC) seeks to improve understanding of past climates through the interpretation of climate sensitive proxies in stalagmites. This necessitates better understanding of the environmental context, including climate impacts (from the micro-scale (cave environment) to the macro-scale (large weather systems and climate patterns)) and groundwater hydrology (McDermott, 2004; Fairchild et al., 2006a; Lachniet, 2009; Fairchild & Baker, 2012). We analysed four methodological approaches to achieve this, which are broadly grouped into; stalactite discharge analysis, proxy/process tracer studies (hereinafter “tracer studies”), discharge modelling, and geophysics (Table 1). Nonetheless, the SPCPC faces ongoing challenges related to the common assumption of stationarity in how the proxy data respond to changes in climate, i.e. that the proxies will exhibit the same behaviour in response to changes in climate over time (Gedalof, 2002; Jones & Mann, 2004; Bradley et al., 2010; Baker et al., 2013; Moerman et al., 2014).

As systems-based approaches have become prevalent in the environmental sciences, many disciplines have

advocated inter-, trans- and multi-disciplinarity (Steele & Stier, 2000; Klein, 2008; Bark et al., 2016). Choi and Pak, (2006) note that while ‘inter-’, ‘trans-’, and ‘multi-disciplinarity’ are commonly used terms, they are poorly defined, applied ambiguously, and used interchangeably. Here, we use the term “*inter-disciplinary*” to refer to any instance of co-authorship between scientists from different disciplines, where co-authorship is defined as collaboration between unique authors in a published piece of work.

Social network analysis methods have been developed to measure collaborative behaviour. These methods are based on the study of social structure using graph theory, and originate in sociology (Scott, 1988). Co-authorship networks have been used to represent acquaintanceship and research collaboration effort, and thereby the sharing of ideas (Newman, 2001, 2004; Huang & Chang, 2011). Co-authorship social network analysis (C-SNA) has been used for strategic planning of research and development (Morel et al., 2009), to investigate the relationship between co-authorship and h-index (McCarty et al., 2013), to study inter-disciplinarity (Huang et al., 2011), and to investigate the structure of different fields of study (Grossman, 2002; Newman, 2004; Zare-Farashbandi

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et al., 2014). At the individual level, McCarty et al. (2013) showed that scientific impact as measured by the h-index increases when authors collaborate with as many co-authors as possible.

We use C-SNA to investigate co-authorship within methodological sub-disciplines of the SPCPC, between these sub-disciplines, and across the whole community from 1996 to 2017. This has implications for the capability of the community to identify and

address emerging complex problems. We address three specific questions:

- 1) Have the populations of the methodological sub-disciplines become more connected over time?
- 2) Have the methodological sub-disciplines become more connected to one another? Is there a trend towards inter-disciplinarity?
- 3) Has the whole speleothem palaeo-climate community moved towards inter-disciplinarity?

Table 1. Strengths and weaknesses of methods used to contextualise stalagmite proxy climate records.

Method	Strengths	Weaknesses	Key Applications	References
Stalactite discharge analysis	Common method; Rugged technology; capable of long-term and remote deployment; information about physical (drip) hydrology.	Without tracer data can't quantify impact of subsurface processes on proxy record.	Commonly used to support palaeo-climate reconstructions. Includes discharge response to precipitation, effective infiltration, etc.	Baldini et al., 2006; Fairchild et al., 2006a; Genty & Deflandre, 1998; Hu et al., 2008; Mahmud et al., 2016; Markowska et al., 2015
Proxy/Process tracer studies	Quantitative results: event times, mixing, transmission time.	Can be conservative; false breakthrough signatures; approvals and social licence for using artificial tracers; natural variability of isotope input; karst complexity complicates signal.	Landscape-scale karst hydrology and small scale karst drip hydrology; tracer studies – including stable isotopes, radio isotopes, trace element concentrations and processes such as source –precipitation-infiltration-drip discharge; dissolution processes and disequilibrium/kinetic isotope fractionation.	Bottrell & Atkinson, 1992; Bradley et al., 2010; Callow et al., 2014; Cuthbert et al., 2014; Fairchild et al., 2006b; Friedrich & Smart, 1982; Fuller et al., 2008; Gunn, 1974; Jex et al., 2012; Kogovsek & Petric, 2014; Pitty, 1966; Polk et al., 2012; Poulain et al., 2015; Treble et al., 2013, 2005
Discharge modelling	Extend limited observational records; infer subsurface processes that affect dripwater behaviour and chemistry.	Simplify reality, may not capture complexity of the physical system; not always physically-based.	Commonly used in association with drip monitoring and tracer experiments, recently a greater emphasis on modelling isotopic values in dripwaters.	Arbel et al., 2010; Bradley et al., 2010; Cuthbert et al., 2014; Fairchild, et al., 2006b; Tooth & Fairchild, 2003; Treble et al., 2013; Wackerbarth et al., 2010
Geophysics	Non-invasive, high spatial resolution (incl. 3D); image physical structure.	Cannot image at the pore-scale; limited resolution at depth; artefacts caused by (for example) large cavities limit resolution.	Limited applications at stalactite-scale settings.	Al-fares et al., 2002; Campbell et al., 2017; Carrière et al., 2013; Roth & Nyquist, 2003; Valois et al., 2010; van Schoor, 2002; Zhou et al., 2000

METHODS

We apply CSNA to citation data obtained by data mining the Web of Science – Core Collection (26th of May 2017) using keywords (Morel et al., 2009). Keyword searches were applied for the four identified methodological approaches; stalactite discharge analysis (“speleothem AND hydrology NOT model”, n = 48), tracer studies (“speleothem AND tracer”, n = 20), geophysics (“karst AND geophysics”, n = 76) and discharge modelling (“speleothem AND hydrology AND model”, n = 27). Methodological approaches and keywords were chosen through a review of the literature, and to capture a sufficiently large portion of the community in order to make analyses possible (respectively). Consequently, a broader search term for geophysics was used as “speleothem AND geophysics” only returned one article. The databases are used to attribute sub-disciplines to the authors, and authors are assumed to have published in multiple disciplines if they are found in multiple databases. There was just one paper which appeared in two databases, and those authors were attributed to (at least) two disciplines. We also extracted a broader community set using “speleothem AND climate” (n = 860), and this was combined with the citations sourced to investigate the methodological approaches to form an overall SPCPC community database (duplicates between the two datasets were included but classified

as part of the methodological subset). The Web of Science – Core Collection was chosen over other archives as it does not contain unpublished papers. Citations were exported in “.bib” file format. Citation data were analysed cumulatively at time-steps of 5 years between 1996 (the earliest entry for any of the search terms in the Web of Science- Core Collection) and 2017. Note that the final time step was 6 years. Bin size was a parsimonious choice to reflect change over time. The decision was made to present data in cumulative time-steps because discrete time windows do not adequately reflect the nature of the collaboration networks, in that they become more connected over time. The choice of bin size also impacts the analysis of discrete time windows. If authors were to collaborate extensively in the first time period, but not the second, it would appear as if they are not connected (or even present in the network) in the second time period, when in reality they may still be collaborating on unpublished work during this time. See [Supplementary Figure 1](#) for an analysis of co-authorship in the sub-disciplines in discrete time windows.

Data analysis and network construction were undertaken in R using the *bibtex* and *igraph*, packages (Csardi & Nepusz, 2006; Francois et al., 2017; R Core Team, 2017). Files were parsed to extract the unique author name, and names were considered to consist of one first initial and a surname. The term ‘unique

author' refers to the unique authors present in the database. Efforts were made to ensure correct attribution of authorship to each parsed unique author. Instances of co-authorship between unique authors were recorded in an adjacency matrix, which was then converted into a graph of co-authorship. All network graphs were rendered in Gephi (Gephi, 2016), see Fig. 1 for an example of network components and how to interpret them.

Networks were evaluated using the average degree and the presence or absence and relative size of a giant component. The average degree is the mean number of co-authors that each unique author has, where higher average degree means that information propagates more readily through the network (Newman, 2001). The term 'giant component' refers to the largest subgraph (connected part of the network) (Holme et al., 2002). Here, we further restrict the definition to exclude subgraphs which are only comprised of the unique authors of one paper. Therefore, in Fig. 1, which shows two example networks and their key features, 1A does not include a giant component as the largest subgraph is the product of just one instance of collaboration (i.e. all of the authors who collaborated on one paper are connected). Figure 1B includes a giant component made up of unique authors collaborating in several different instances. Not all unique authors in the giant component are directly connected by co-authorship, but as members of the giant component they may still benefit from the easier sharing of ideas through the connected part of the network.

The full citation dataset and R scripts are in the [Supplementary Material](#). Analysis was conducted on each: a) method database (see Section *By discipline*), b) the combined method database (see Section *Combined discipline*), and c) the overall SPCPC community database (see Section *Whole community*).

RESULTS AND DISCUSSION

By discipline

The CSNA identifies that the SPCPC methodological sub-disciplines have grown in both the number of unique authors and their level of connectivity, as shown by the increase in the average degree over time (Fig. 2), though some subtle but important differences are evident between the sub-disciplines. The stalactite discharge analysis sub-community is the second largest network, growing exponentially from 10 unique authors in 2001 to 213 in 2017. The discharge analysis network became more connected during this time, as the average degree increased from 4.8 to 7.47 between 2001 and 2017. The average degree of the discharge analysis network in 2017 was second only to that of the discharge modelling community. By 2017, 177/213 (83%) unique authors were part of the giant

Fig. 1. An example of network features. Nodes represent authors, and connecting lines (edges) indicate that authors have collaborated. 1A does not include a giant component, as the largest connected subgraph is the product of a single publication. 1B shows a giant component (circled) which is made up of unique authors collaborating over >1 publication/s. The red circle in 1B denotes a 'linking author' who is the only connection between different parts of the network. The position of nodes in the graph and the length of edges do not signify anything.

component, this is an increase from 58/249 (23%) in 2011, when the giant component was first observed.

The tracer study community is the youngest and smallest sub-community. The first citation found in the Web of Science Core Collection database was published in 2004, but the discipline has grown consistently from 13 authors in 2006 to 80 in 2017. Co-authorship has not been as pronounced within the tracer community, although it has increased over time. A small giant component had formed by 2011 (10/42 authors) but by 2017 this giant component comprised just 18 of the 80 authors (22%). However, these 18 are very well connected which reflects the relatively high average degree which increased from 4 in 2001 to 5.25 in 2017. Although members of the giant component were in the analysis in 2006, the giant component was not observed until 2011.

The discharge modelling community grew from 3 authors in 2001 to 107 in 2017. During this time co-authorship also increased - the average degree grew from 3.1 to 8.15 (the highest observed average degree of any of the disciplines). By 2011 a giant component was observed (12/30 authors), and by 2017 the giant component included 38/107 authors and a secondary subgraph had formed which included 29/107 authors. In both the giant component and the subgraph there are linking authors (two in each) who act as the only link between different groups of authors in the network (see also Fig. 1B). These linking authors clearly have a role as influencers, and are likely established members of the community.

The geophysics community is the largest and least well-connected community, although its size is an artefact of the broader search terms applied. Despite this, the average degree is consistently low relative to the other disciplines (4.17 in 2017). A giant component had formed by 2011, although it included just 9% of the community (12/137). By 2017 this had increased to 12% (27/232). Due to the relative lack of connectivity in the geophysics community there are no standout linking authors until 2017 when one member of the giant component had published with every other member.

Fig. 2. Co-authorship networks for each methodological sub-community over time, where N is the number of publications, A is the number of unique authors, and AD is the average degree (the mean number of co-authors that each unique author has).

Combined disciplines

Since 2001, the four sub-disciplines have become increasingly connected, as shown in Fig. 3 and by the increase in the average degree.

A giant component was present in 2001, which included 9 of 33 authors (27%). This remained stable through to 2006 (although the percentage of total authors in the giant component had fallen to 9%). By 2011 the giant component included 95 of 275 authors (34%), and by 2017 it included 269 of 563 authors (48%). The stalactite discharge analysis and discharge modelling disciplines are the most inter-disciplinary. In 2001, all authors from these two disciplines were part of either the giant component or a multi-disciplinary subgraph. In 2017 they continued to represent the largest proportion of the giant component, with 253 of the 268 authors in the giant component publishing in stalactite discharge analysis, discharge modelling, or both. There is a growing trend towards authors publishing in multiple

sub-disciplines. In 2001, four authors had published in two sub-disciplines, this increased to five in 2006, 22 in 2011 and 46 in 2017. By 2011, one author had published in three sub-disciplines. This increased to 11 by 2017.

In 2017 geophysics dominated outside of the giant component (221 authors), followed by tracer studies (34 authors), then stalactite discharge analysis (19 authors), and modelling (12 authors). Although outside the giant component, inter-disciplinary still occurred in subgraphs, with 33 authors publishing either across different disciplines or with co-authors from different disciplines. This includes six authors who themselves published across two different disciplines and an additional author who published across 3 different disciplines.

While authors publishing across different sub-disciplines are not necessarily linking authors as per our definition, it is likely that they may have been linking authors in the past and have played

Fig. 3. Combined co-authorship network, with unique authors colour-coded by the sub-discipline they published within. Stalactite discharge analysis is dark blue, tracer studies is orange, discharge modelling is light blue, and geophysics is red. Authors that have published within two sub-disciplines are yellow, and those that have published within three sub-disciplines are green.

key roles in sharing information and methods, owing to their central positions in the giant component, and their experience in applying different methods. Since collaborating implies acquaintanceship and the communication of ideas, by publishing with co-authors from different disciplines, authors are exposed to different methods, approaches, and ideas (Huang et al., 2011; Newman, 2001, 2004).

Whole community

The rate of publication, and by inference, the broader SPCPC continues to grow. While the proportion of publications in the method-derived citation database which was used for the analyses in sections *By discipline* and *Combined disciplines* ("the subset") has not increased relative to the whole community (Fig. 4), co-authorship analysis shows that the authors in the subset are linked to the broader community, and that the broader community is itself highly connected (Fig. 5). Of 2433 unique authors in the broader community, 563 (23%) of them were found in the subset. A giant component included 2122 (87%) of the total unique authors, and authors from the subset made up 417/2122 (20%) of that giant component. Therefore, while co-authors in the subset database are well connected to one another (see section *Combined disciplines*), they are not as well-connected to the broader speleothem climate community. Note that the broad search terms used to define the broader community is likely to have included authors that have referred to the applications of speleothems in palaeo-climate science as a general comment. As such, the shortfall between the proportion of the subset in the whole community and in the giant component is not surprising.

Fig. 4. Citations data-mined from the web of science. The citations that make up the method-based subset are orange and the whole citation network is red.

CONCLUSIONS

Since 2001, the methodological sub-disciplines identified in this analysis have become more connected. This is most notable in the stalactite discharge analysis, tracer studies, and discharge modelling disciplines. Increasing levels of co-authorship has implications for the propagation of information through the community, and the growth of the community, as authors with high levels of co-authorship are statistically more likely to add new co-authors to the network (Barabási & Albert, 1999).

The methodological sub-disciplines have become more connected to one another over time. Again this

Fig. 5. The methodological subset (black) and its connections with the broader community (blue). Figure 5B is an enlargement of the giant component in the network.

behaviour was most common in the discharge analysis, tracer studies and discharge modelling disciplines. There was also an increase in the number of authors publishing across multiple disciplines. The high level of cohesiveness and inter-disciplinarity means that the community has improved scope to tackle complex problems, and is able to quickly adopt and share new technologies and methodologies. The absence of geophysics from the giant component until after 2011 is surprising considering that the method is broadly applied in karst science, and that geophysicists were consistently well represented in the database. Its addition to the giant component of the network after 2011 is an indicator that this technology has begun to be adopted by the community. We may expect the use of geophysics to become more common due to the high levels of co-authorship in the broader SPCPC, and therefore easy pathways of knowledge sharing.

The broader SPCPC is highly connected, and the sub-disciplines are represented in the giant component. This means that, while many of the citations in the broader palaeo-climate community were not represented in the analysis of inter-disciplinarity, it is likely that they have access to the knowledge and expertise to adopt a diverse range of methods.

The speleothem palaeo-climate proxy community has become increasingly well-connected, and increasingly inter-disciplinary. While there remains a large part of the community that has not adopted any of the common methods to contextualise speleothem proxy climate records, the high degree of co-authorship between the members of the methodological sub-disciplines and the community at large indicates that it is likely that the broader community will a) adopt these approaches, and b) become more interdisciplinary over time, or c) become aware of these approaches through enhanced dissemination of ideas through a more integrated speleothem palaeo-climate proxy community. An interesting subject for future research is the speleothem palaeo-climate proxy community's self-perception of collaborative behaviour between different sub-disciplines. This could use social science methods (such as interviews and surveys) to establish the methodological approaches of these sub-disciplines and where authors position themselves within or across them.

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