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Let research on subterranean habitats resonate!

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Abstract

Whereas scientists interested in subterranean life typically insist that their research is exciting, adventurous, and important to answer general questions, this enthusiasm and potential often fade when the results are translated into scientific publications. This is because cave research is often written by cave scientists for cave scientists; thus, it rarely “leaves the cave”. However, the *status quo* is changing rapidly. We analysed 21,486 articles focused on subterranean ecosystems published over the last three decades and observed a recent, near-exponential increase in their annual citations and impact factor. Cave research is now more often published in non-specialized journals, thanks to a number of authors who are exploiting subterranean habitats as model systems for addressing important scientific questions. Encouraged by this positive trend, we here propose a few personal ideas for improving the generality of subterranean literature, including tips for framing broadly scoped research and making it accessible to a general audience, even when published in cave-specialized journals. Hopefully, this small contribution will succeed in condensing and broadcasting even further the collective effort taken by the subterranean biology community to bring their research “outside the cave”.

Keywords

Bibliometric, Cave science, Citation analysis, Impact Factor, Jargon, Model organism, Natural laboratory, Scientific progress, Scientific writing, Temporal trend in citations

The model systems' roulette

Whether it is about birds or bugs, ants or antelopes, and no matter their ecology, systematics, or sexual behaviour, natural scientists tend to fall in love with the systems they study. This is nothing surprising considering how subtle and complex some eco-evolutionary patterns are, demanding the personal involvement of those seeking to unravel them. As this engagement increases, the distinction between work and passion often fades, promoting the idea of the stereotypical Stakhanovist scientist working tirelessly in the lab without realizing that the hours pass by. This hardworking attitude has blinded many scientists to the point of prioritizing their career over personal development and time with friends and family (Woolston 2017; Maestre 2018). Natural scientists might even take this engagement one step further, as the curiosity of a child, the passion for nature and collection, or simply the willingness of being outdoors is behind many successful careers. Have you ever taken advantage of a walk around your house or your family holidays to collect a few samples? Well, evidence suggests that you are not alone (Fontaneto et al. 2012).

Since most natural scientists share this very same passion for the natural world, how to explain the uneven impact of their research as individuals (Sinatra et al. 2016)? Well, different scientists concentrate their research efforts on different model systems (Ankeny and Leonelli 2011). And model systems are like a box of chocolate: *you never know what you're gonna get*. However, knowing the literature and playing well your cards may help to pick exactly that cherry-flavoured chocolate that you're dying for.

Selecting a natural organism or system might be seen as a trade-off between subjective features making it appealing to study (aesthetic characteristics, peculiar adaptations, etc.) and objective features making it a good model (ease to raise in the lab, generation time, genome size, etc.). And since many of these features are not obvious when selecting a new model organism (Hedges 2002; Maher 2009; Alfred and Baldwin 2015), we cannot deny a certain role of luck in this choice when, for example, a favourite organism turns out to be ideal to tackle an important question or to develop a new method. For example, the status of *Arabidopsis thaliana* as an anonymous flowering plant or of *Caenorhabditis elegans* as just-another-round-worm radically changed when pioneering researchers turned them into cutting-edge model systems in evolutionary biology (Mitchell-Olds 2001; Kaletta and Hengartner 2006). And while the love for a cavefish from Mexico probably came first, is the discovery that it can help curing type 2 diabetes that featured it on the front cover of *Nature* (Riddle et al. 2018).

Cave biologist as prisoners in the cave

Have subterranean biologists picked a tasty chocolate too? There are plenty of arguments suggesting that caves are amongst the appealing model systems (Itescu 2019). Humans' fascination for caves traces so deep in time that it is intertwined with the evolutionary history of *Homo sapiens*. Since the dusk of humanity, communities of hunter-gatherers have found shelter in the darkness of caves (Granger et al. 2015). Caves were the places where we buried our dead (Sealy 2006), accomplished rituals (Moyes 2012), and expressed our very first artistic manifestations (Valladas et al. 2001). Plato's Myth of the Cavern, Jules Verne's *Journey to the Center of Earth*, and even the overrepresentation of caves in modern cinema (Figueiredo 2013) are just a few examples illustrating how the underground world became a colliding point of several archetypical ideas forming the collective identity of our species (Campbell 1949).

At some point, human curiosity took this ancestral fascination one step further. This is how geologists turned anthropomorphic rocks into speleothems, taxonomists renamed puppet-dragons as *Proteus anguinus* (Aljančič 2019), and hydrologists explained Biblical miracles (*Exodus* 17: 1–7) as artesian wells (Owen and Fensham 2016). As reason prevailed upon mythology, caves became the arena for debating scientific ideas and ultimately good model systems for understanding the outside world (Poulson and White 1969). Yet, while we typically insist that our research is exciting, adventurous, and important to answer cutting-edge questions (Juan et al. 2010; Sánchez-Fernández et al. 2018; Mammola 2019; Mammola et al. 2019, 2020), this potential is often lost when the results are translated into scientific publications. Too often, the generality of our results remains unexpressed insofar as cave research is written by cave scientists for cave scientists. In other words, it rarely leaves the cave.

Escaping from the cave

However, this *status quo* is changing. Over the last decade or so, we have witnessed how more and more cave-based research resonates outside our specialized community. To show this, we here analysed the citations and impact factor of articles focusing on subterranean ecosystems, using a database of 21,486 research articles published between 1991 and 2019 (full details on data collection are in Martínez and Mammola 2020). We observed how, recently, there has been a steady increase in the annual average citations that cave-based papers receive (Figure 1a) and in the average impact factor of the journals in which they are published (Figure 1b). This pattern is seemingly due to a greater number of scientists publishing in general journals, given that the average citation over time is not increasing, but rather fluctuating, when considering papers published in cave-specific journals only (Figure 2).

A quick scrutiny of these highly cited papers shows that most of them used caves as systems to address general questions. The peculiarities of caves as simplified model systems in ecology and evolution have been summarized elsewhere (Mammola 2019), including their discrete nature, the partially stable conditions, as well as the presence of few, highly specialized organisms. Interestingly, some of these properties make caves useful in a broad range of scientific areas. The stable microclimatic conditions, for example, favour the preservation of fossils (Berger et al. 2015; Harvati et al. 2019) and makes caves natural laboratories for paleoclimatic reconstructions and global change biology studies (Yuan et al. 2004; van Hengstum et al. 2018; Mammola et al. 2019;

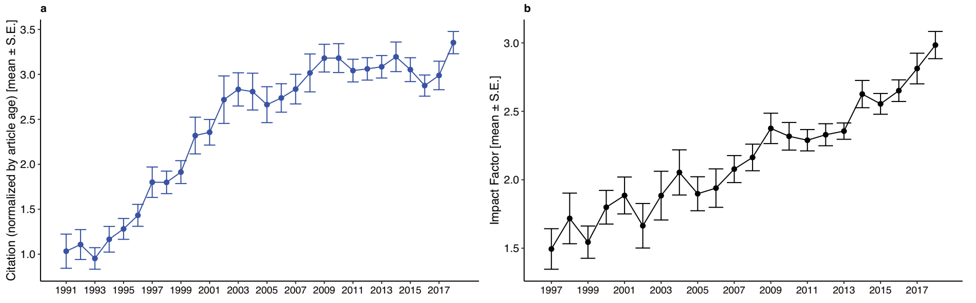

Figure 1. Variations in citations and impact factor of papers focused on subterranean systems over time. **a** Average ± standard error number of Web of Science citations to articles. Citation counts are normalized by the year of publication **b** Average ± standard error Impact Factor of the journals in which the papers are published. Graphs are based on a database of 21,486 research articles focused on caves and other subterranean habitats published between 1991 and 2018 (Martínez and Mammola 2020). The yearly Impact factor of journals is based on the periodical reports by the Journal Citation Reports of Clarivate. For this graph, the year 1997 was chosen as a starting point because around this date the use of Impact Factor started to become widespread (Archambault and Larivière 2009). Note also that the overall Impact Factor of scientific journals increased over the last 21 years, a feature that may have partly inflated this trend.

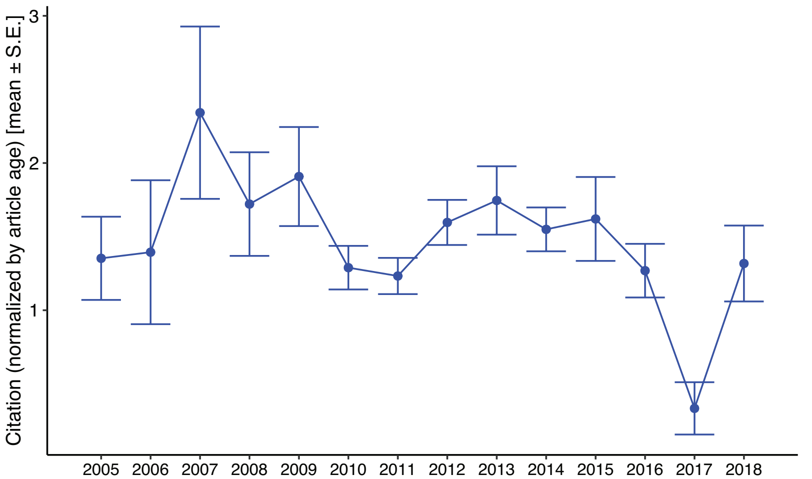

Figure 2. Variations in citations over time in papers focused on subterranean systems published in specialized journals. The average ± standard error number of Web of Science citations is based on a subset of articles published in *Acta Carsologica*, *International Journal of Speleology*, *Journal of Cave and Karst Studies*, and *Subterranean biology* (n= 969). Note that prior to 2005, no data was available for these journals in Web of Science.

Pipan et al. 2019). The stability of the underground is so even to cosmic radiation, making old mines as unique windows into quantum mechanics (Wolfendale 1968; Curceanu et al. 2017). For the very same reason, lava tubes are projected to host our first Martian and Lunar colonies (Sauro et al. 2020), whereas, in the domain of exobiology, cave microbiological studies are expected to bring important clues on the origin of extraterrestrial life (Northup et al. 2011; Popa et al. 2011). Not to mention, coming back on Earth, the role that cave organisms can play in the realm of medicine (Riddle et al. 2018; Yoshizawa et al. 2018) and pharmaceutics (Cheeptham et al. 2013; Ghosh et al. 2017; Genilloud 2018).

A return to the cave

Notably, darkness, isolation, and weirdness–the properties that constitute caves as excellent models to address timely questions in modern science–were also those that amazed our ancestors, symbolically rooting caves deeply in our human nature as a representation of our myths, tales, and pop-culture memes (Campbell 1956; Bassie-Sweet 1996; Ustinova 2009). Therefore, and even at the risk of over-romanticising these model systems, we argue that caves not only hold some of the clues of our past; but also, if used wisely, may help to unlock some of our hidden future scientific enigmas. However, to speak nature's most intimate secrets, caves need to be asked the right questions.

Encouraged by the inherent peculiarities of caves, we might have forgotten the importance of trying to address broad questions with our research, favouring the isolation of our research community and increasing our intellectual inbreeding. We believe that being aware of this potential is a fundamental step to frame broad-in-scope subterranean research (Mammola et al. 2020), regardless of the journal in which it will end-up published. Inspired by the writer and philosopher Umberto Eco (1997), we propose a few bullet-point ideas for improving the generality of the literature on subterranean habitats, including both tips for framing broad-scoped research and for writing texts accessible to a general audience (Box 1). These are just personal ideas, sometimes based on literature published on caves, sometimes borrowed from other disciplines, collected here

Box 1. Ideas for making research on subterranean habitats to resonate.

1. Try to identify general questions that are scalable to other systems (Mammola et al. 2020). Greeks brought philosophy into caves: we can also introduce our field into them.
2. Read and cite as many non-cave papers as possible. We say, baby, take a walk on the *bright side*.
3. It is advantageous to collaborate with non-cave scientists. They might even come up with good ideas...
4. Make your text understandable to a general audience (Plavén-Sigray et al. 2017; Barnett and Doubleday 2020). Facultative troglophiles, trogloxenes, and even accidental cave scientists should be able to grasp your wisdom (Martinez and Mammola 2020).
5. Don't overemphasize your findings with superlatives and exaggerations (Mammola 2020). By doing so, your research will turn out unique, remarkable, and ground-breaking!!!
6. When discussing the importance of your findings, don't appeal to authority. We say so.
7. Don't be jealous: data-sharing only brings you benefits (Piwowar et al. 2007; Piwowar and Vision 2013; Colavizza et al. 2020). Even the data supporting this study will be available *tomorrow* from the corresponding author upon a reasonable request.
8. And, well, don't forget to come back to good old cave literature from time to time. There is still a lot of wisdom in the Rock Art of our ancestors.

without any imperative intention. We do not want to tell anyone how to proceed, but rather encourage a debate around these topics with the ultimate hope of supporting the ongoing transition of our research from the darkness of caves out to the lighted world.

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Data and R code to generate the plot are available in Figshare (https://doi.org/10.6084/m9.figshare.13129604). Raw data can be obtained from the Web of Science using the search query and data cleaning procedure detailed in Martínez and Mammola (2020).

A.M. did the search on the Web of Science. S.M. plotted the graphs. Then, the idea came along, and both authors wrote and approved the text together.

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