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Aerobiology in the International Journal of Biometeorology, 1957–2017

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Abstract Aerobiology and biometeorology are related fields. Here we provide a broad review of aerobiology articles published in the International Journal of Biometeorology (IJB) over the past 60 years. We consider how the quantity of such work has varied over this period as well as which regions and countries have been the focus of such work, and where there is a relative paucity. We then focus on a number of highlights and themes in this research, including aerobiology and climate change and aerobiological modelling and forecasting. While much of the article focusses on airborne pollen research, we also discuss the extent to which other airborne organic particles such as fungal spores and bacteria have been the focus of research published in IJB. Also considered are knowledge gaps and research needs and priorities with respect to the field of aerobiology. While the IJB has been one of the main platforms for presenting aerobiological research over recent decades, the article highlights the need for the field of aerobiology to embrace new sampling technologies such as spectral analysis and next-generation sequencing to identify and quantify airborne biological particles.

Keywords Climate change · Forecast · Fungal spore · Model · Phenology · Pollen

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Introduction

Aerobiology studies the identity, behaviour, movement and survival of airborne organic particles passively transported in the atmosphere (Gregory 1961), both outdoors and indoors (Lacey and West 2006). More specifically, from an allergy perspective, Burge (2002) describes the science of aerobiology as dealing with disease agents (pollen and fungal spore aerosols), the processes of aerosolisation, the aerosol itself and, to some extent, exposure and response. Importantly, aerobiology seeks to understand interactions between biological aerosols and the atmosphere including the role of weather and climate in what has been described as the aerobiology pathway—from release to dispersal to deposition (Cox 1987).

It is clear, therefore, that aerobiology and biometeorology are related fields. Indeed, there is overlap in scope and some topics could, in theory, be equally considered aerobiology or biometeorology or both (Fig. 1). Biometeorology is the broader of the two fields, being the study of the relationships between the atmospheric environment and all living organisms. The timing of the rise of the two fields is also similar, with, for example, the International Society of Biometeorology (ISB) being established in 1957 and the International Association for Aerobiology being founded in 1974 and aerobiology being a panel and integrated research program in the International Biological Program prior to this in the 1960s and early 1970s (National Academy of Sciences 2017).

Although this article will focus on aerobiology articles in the *International Journal of Biometeorology* (IJB), it is important to acknowledge other journals that have also contributed significantly to aerobiology. Two of special note are *Aerobiologia*, the official journal of the International Association for Aerobiology, which has been published since 1985; and *Grana* that has been published since 1954 (formerly known as *Grana Palynologica*). The interdisciplinary

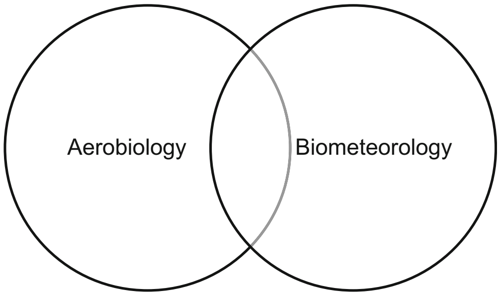

Fig. 1 Conceptual diagram of the fields of aerobiology and biometeorology including their relationship (overlap) with each other

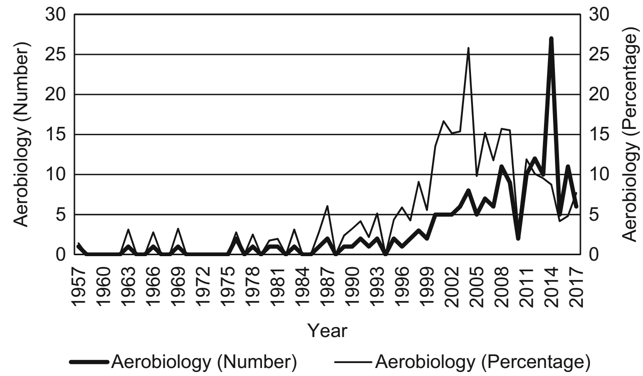

Fig. 2 The number of IJB documents per year with pollen, spore, or aerobiol* in their title, abstract or keywords from 1957 to 2017. Also shown is the number of such aerobiology articles published in IJB per year expressed as a percentage of total articles published in IJB per year (based on a Scopus® (Elsevier B.V.) search as of 28 March 2017)

nature, importance and universal relevance of aerobiology has also meant that aerobiological research has made its way into many other journals, both general and specific.

Aerobiology has been an important topic within biometeorology since the very first days of what was, in 1957, the International Society of Bioclimatology and Biometeorology and the *International Journal of Bioclimatology and Biometeorology*. The first issue of the journal included short reports for presentations delivered at the First Bioclimatological Congress held in Vienna, Austria, 23–27 September 1957. Amongst these were the report by Barkai-Golan (1957) of a study of airborne fungi in Israel and the report by Canto Borreguero (1957) of the influence of climate and weather on the pollen, spores and allergic diseases in Spain.

The introduction of an IJB Aerobiology Field Editor in 2014 signalled the continued growth of aerobiology manuscripts being submitted to the journal and the journal's desire to more explicitly acknowledge this field as a part of biometeorology. Dr. Matt Smith has filled this role since it was created. Also significant is the inclusion of a number of other accomplished aerobiologists on the IJB's Editorial Advisory Board, most notably, Dr. Carmen Galán.

This article provides a broad review of aerobiology articles published in the IJB over the past 60 years. Our aim is to focus on a number of highlights and themes in this research rather than to describe and discuss all aerobiological articles published in the journal over this period. We do, however, consider some aspects of the latter.

Aerobiology articles in the IJB

Based on a Scopus® (Elsevier B.V.) search for IJB documents with pollen, spore or aerobiol* in their title, abstract or keywords, approximately 6% (180) of the 3220 articles published in IJB have had an aerobiology component or focus (as of 28 March 2017). The number of such articles published per year (Fig. 2) has increased exponentially, with 0, 1 or 2 articles being published per year from 1957 to 1997 and then the number of articles per year increasing to a maximum of 27 in 2014. Figure 2 shows the number of aerobiology articles published in IJB per year expressed as a percentage of total articles published in IJB per year. This also increases exponentially over time but reaches a peak in 2004 of a quarter of all articles (8/31) and has since decreased to around the overall/long-term average over the past few years. The year 2010 saw an anomalously low number (2) and corresponding percentage (3%) of aerobiology articles published in IJB.

Europe has been the source of much of this aerobiological research (Fig. 3). Spain is the top country represented in the IJB's aerobiology articles, with the next most prominent European countries being the UK, Poland, Austria, Italy and Switzerland. North America is the next most represented region in IJB aerobiology articles, which is dominated by the USA—the second highest country overall after Spain. While the other four major populated regions of the world (Africa, Asia, Oceania and South America) all have some representation in this literature, it is minimal compared to especially the volume from Europe, and many countries in these regions have no representation at all in this literature. There is no aerobiological research from Antarctica published in the IJB.

The most prolific authors of articles in this area in the IJB have been Carmen Galán (16 articles), Matt Smith (12 articles), Carsten Skjøth (11 articles) and Hermínia García-Mozo, Francisco Rodríguez-Rajo and Eugenio Domínguez-Vilches (8 articles each). Accordingly, the top institutions/affiliations have been Universidad de Cordoba, Cordoba, Spain (Galán, García-Mozo, Domínguez-Vilches and others); University of Worcester, Worcester, UK (Emberlin, Skjøth, Smith and others); Adam Mickiewicz University, Poznan, Poland

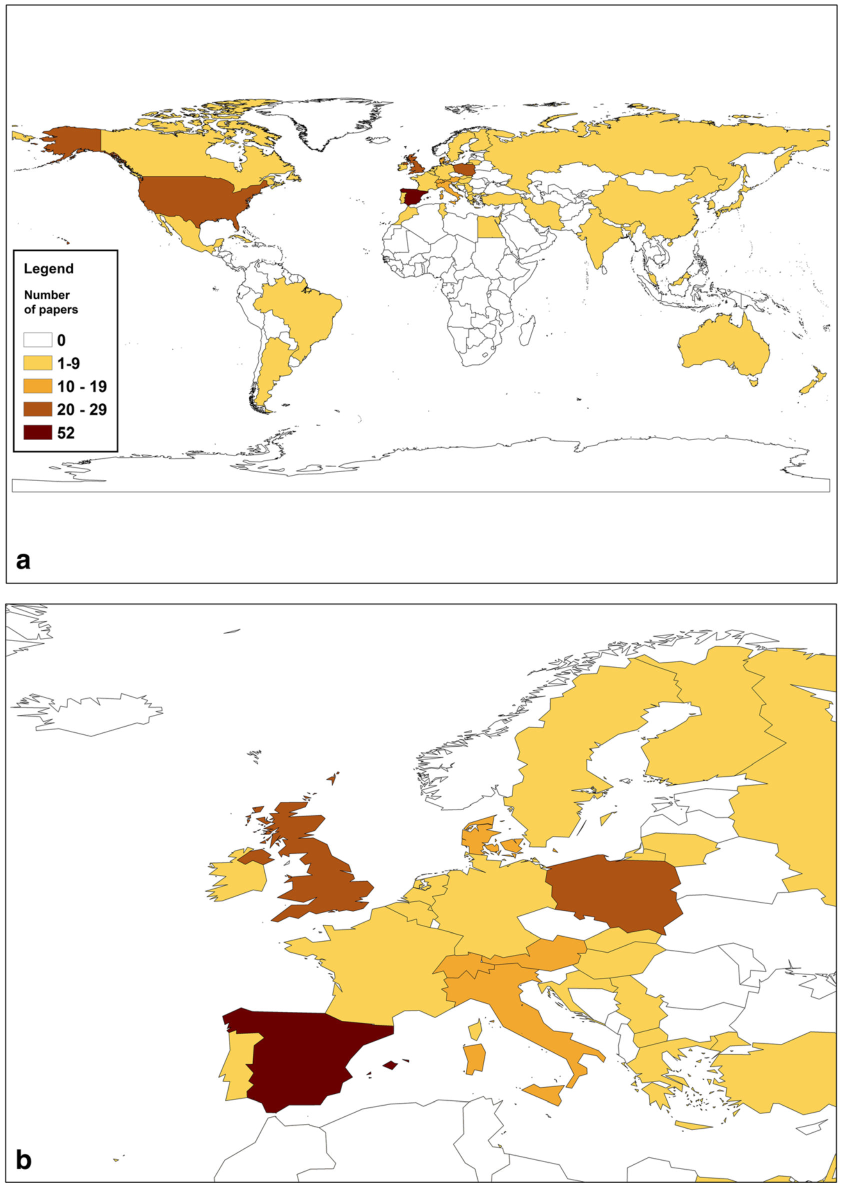

Fig. 3 The number of IJB documents per country with pollen, spore, or aerobiol* in their title, abstract or keywords from 1957 to 2017 **a** globally and **b** detailed for Europe (based on a Scopus® (Elsevier B.V.) search as of 28 March 2017)

(Grewling, Smith and Stach) and Universidad de Vigo, Vigo, Spain (Rodríguez-Rajo and others).

When considering the most impactful aerobiological research that has been published in IJB, four articles stand out from the rest. Based on citations, the most impactful article has been that by Emberlin et al. (2002) on responses in the start of *Betula* (birch) pollen seasons to recent changes in spring temperatures across Europe (153 citations, approx. 10/year). Following this article are those by Galán et al. (2005) (114 citations, approx. 10/year), Sofiev et al. (2006) (111 citations, approx. 10/year) and Burch and Levetin (2002) (102 citations, approx. 7/year). The following sections discuss two of these articles in detail, with this providing context for (an introduction to) a broader discussion of two broad themes in aerobiological research in recent decades: aerobiology and climate change (Emberlin et al. 2002) and aerobiology and numerical forecasting of atmospheric pollen (Sofiev et al. 2006).

Aerobiology and climate change in IJB

In 2002, climate change was firmly on the scientific and political agenda. The Third Assessment Report of the Intergovernmental Panel on Climate Change had been released the previous year (IPCC 2001) and several important papers were published relating to ecological and phenological responses to climate change (Ahas et al. 2002; Fitter and Fitter 2002; Walther et al. 2002). Against this backdrop, several studies came out that investigated the impacts of changing temperatures on pollen season characteristics over the latter decades of the twentieth century (i.e. Emberlin et al. (2002), Frenguelli (2002), Rasmussen (2002) and van Vliet et al. (2002)).

For example, Emberlin et al. (2002) examined birch (*Betula*) pollen records from six sites representing a range of biogeographical situations from just within the Arctic Circle through to North West Maritime and Continental Europe: Kevo, Finland; Turku, Finland; London, UK; Brussels, Belgium; Zurich, Switzerland and Vienna, Austria. These pollen records were compared to spring temperature records from the same locations. The analyses showed regional contrasts, with one of the sites showing a trend towards later birch pollen season starts (associated with a trend towards cooler springs), one of the sites exhibiting a cyclic pattern in start dates, and the other four locations showing trends towards earlier birch pollen season starts (Emberlin et al. 2002, 2003). The prominence of this work in the context of climate change impacts on allergens and allergic diseases has been recently noted by Beggs (2014).

Other research on the impacts of climate change on pollen season characteristics has subsequently been published in IJB, including Galán et al. (2005), Frei and Gassner (2008), Newnham et al. (2013) and Sofia et al. (2017), to name but a few. As noteworthy as the IJB contribution to this area of research has been, it has not been the sole domain of such work. For instance, Ziska et al. (2011) published an impactful study in the *Proceedings of the National Academy of Sciences of the United States of America* showing recent warming was associated with increased length of the ragweed pollen season in central North America.

Aerobiological modelling and forecasting in IJB

Modelling and forecasting of the pollen season was reviewed in the publication *Allergenic Pollen* (Scheifinger et al. 2013) produced under the auspices of European COST Action ES0603 for the "Assessment of production, release, distribution and health impact of allergenic pollen in Europe" (EUPOL) that was conducted during the period 2007–2011. Models for airborne pollen concentrations can be separated into those that are based on observations and those based on knowledge of the sources, emissions and calculations of diffusion (Scheifinger et al. 2013). Traditional observation-based models employ a number of different methods to relate records of airborne pollen or phenological observations to one or more variables that can be measured or predicted, usually meteorological data. Examples in IJB include regression models (Laaidi et al. 2003; Smith and Emberlin 2006; Sabariego et al. 2012), time series models (Fernández-Rodríguez et al. 2016; Silva-Palacios et al. 2016), computational intelligence techniques (Puc 2012; Navares and Aznarte 2017) and process-based phenological models (Schaber and Badeck 2003; Kasprzyk 2009). The main drawback of such models is that they are generally specific to a particular site, although there are some exceptions (e.g. García-Mozo et al. 2008, 2009).

There is now a large body of evidence showing that atmospheric transport can result in high atmospheric pollen concentrations and modify pollen season characteristics such as start date and duration (Sofiev et al. 2006, 2013a), including a number of papers published in IJB on the subject (Damialis et al. 2005; Stach et al. 2007; Belmonte et al. 2008; Šikoparija et al. 2009; Skjøth et al. 2009; Hernández-Ceballos et al. 2011; Izquierdo et al. 2011; Kasprzyk et al. 2011; Fernández-Rodríguez et al. 2014; Grewling et al. 2016). It is argued that such atmospheric transport episodes cannot be predicted by the use of local or regional observations, and forecasts need to be constructed at the continental level and include the biological and meteorological mechanisms that control the release and subsequent dispersion of pollen to the atmosphere (Sofiev et al. 2006). In this respect, the seminal paper by Sofiev et al. (2006) is considered to be a game changer, especially coming as it did at the beginning of COST Action ES0603 that brought together experts from the modelling community with workers in the fields of aerobiology and allergology. The authors presented the results of a feasibility study, which used the Finnish System for Integrated modeLling of Atmospheric coMposition (SILAM) to estimate the scales of atmospheric birch pollen dispersion and determine whether its simulation was applicable to existing modelling approaches. The study confirmed that existing dispersion models were appropriate for the task of modelling pollen transport and provided some reference parameterisations of the key processes (Sofiev et al. 2006). There are now several source-orientated numerical forecast models extended to simulate the dispersion of pollen grains (Zink et al. 2017) and include CHIMERE (Bessagnet et al. 2008), CMAQ-pollen (Efstathiou et al. 2011), COSMO-ART (Vogel et al. 2008; Zink et al. 2012, 2017) and SILAM (Sofiev et al. 2006, 2013b; Prank et al. 2013; Siljamo et al. 2013).

Sofiev et al. (2006) reported that the most challenging part of numerical pollen forecasting was to determine the emission source. Several studies focusing on atmospheric pollen transport published in IJB have been conducted with the aim of identifying the locations of pollen sources (Stach et al. 2007; Šikoparija et al. 2009; Skjøth et al. 2009; Kasprzyk et al. 2011; Fernández-Rodríguez et al. 2014). Mapping sources of airborne pollen has been an important area of research and notable contributions include Skjøth et al. (2008) and Pauling et al. (2012). An alternative method, which combines land use data, annual pollen indices and local knowledge of species distribution, has successfully been used to produce a series of source inventories for *Ambrosia* pollen that now covers most of the main areas of *Ambrosia* infestation in Europe (Skjøth et al. 2010; Thibaudon et al. 2014; Karrer et al. 2015). These collaborations were aided by another European COST Action

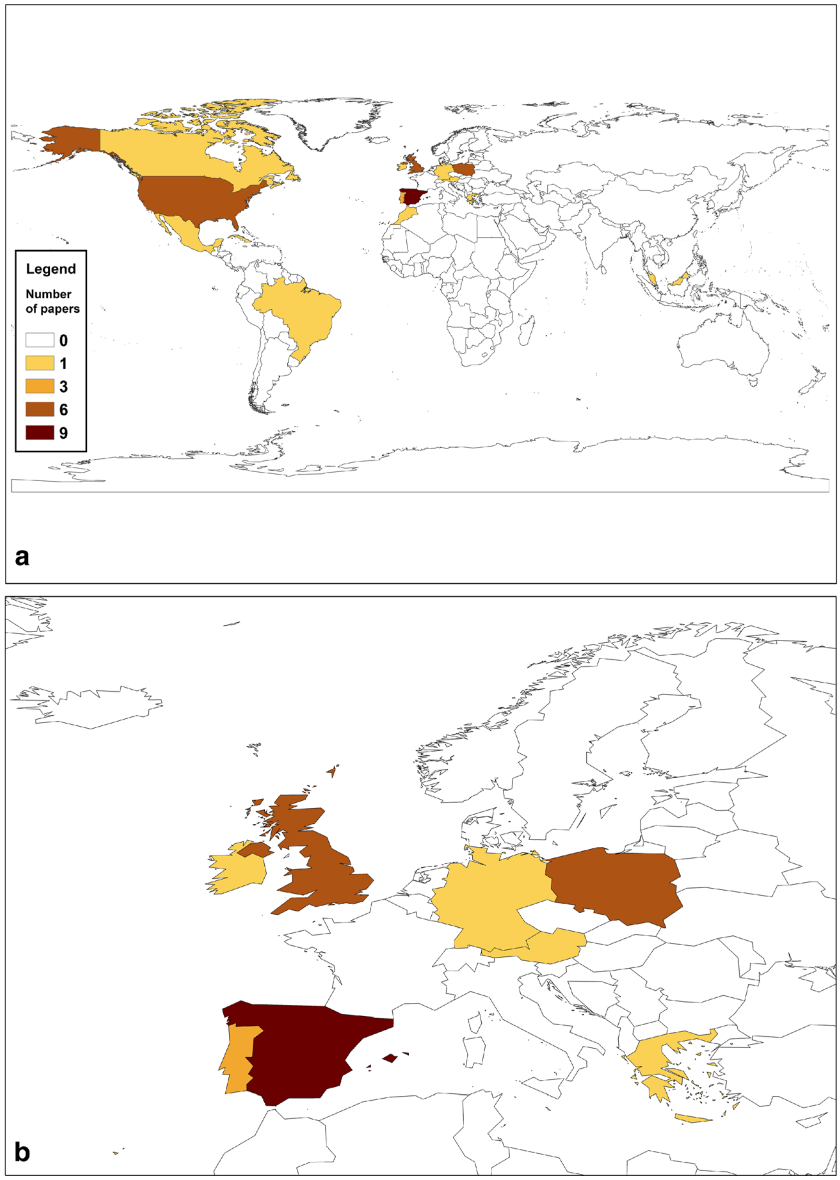

Fig. 4 The number of IJB documents per country with just spore and mold or mould or fungal in their title, abstract or keywords from 1957 to 2017 **a** globally and **b** detailed for Europe (based on a Scopus® (Elsevier B.V.) search as of 28 March 2017)

(FA1203 for the Sustainable Management of *Ambrosia artemisiifolia* in Europe - SMARTER) and the inventory for France (Thibaudon et al. 2014) has been shown to result in the best correspondence between observed and simulated airborne *Ambrosia* pollen concentrations when entered into COSMO-ART (Zink et al. 2017).

Fungal spore and bacteria aerobiology in IJB

It is noticeable that this article has to this point primarily focused on airborne pollen, particularly in relation to human health. It is important to remember, however, that this is only a small part of an extremely diverse field that is aerobiology. Some work has been conducted on fungal spores, and papers concerning relationships with meteorological data (Stephen et al. 1990; Grinn-Gofroń and Strzelczak 2008, 2009, 2011, 2013) and long-term trends (Damialis et al. 2015) have been published in IJB for some widespread and more easily identifiable fungal spore types. As for aerobiological articles, generally, most of this research has been from Europe (particularly Spain, Poland and the UK) and North America (again with most of this from the USA) (Fig. 4). Even fewer studies have been published concerning other airborne biological particles such as bacteria (e.g. Wu et al. (2012) and Harrison et al. (2005)).

Knowledge gaps and research needs/priorities

Most aerobiological studies published in IJB rely on airborne pollen and spore data collected by volumetric sampling using the method described by Hirst (1952). The Hirst type trap is widely considered the standard method for aerobiological monitoring, as it is robust enough for outdoor operation and enables continuous uninterrupted sampling. However, retrieval of data requires considerable amounts of time, effort and the expertise for examining samples by light microscopy (Galán et al. 2014) plus difficulties with calibration (Oteros et al. 2017). As a result, a degree of error is introduced into the data (systematic instrumental and random errors from operators) and a delay between sampling time and eventual data acquisition is inevitable, meaning that the "real-time" use of data cannot be achieved.

Real-time monitoring is not a prerequisite for understanding trends in plant phenology and the impacts of climate change. However, real-time airborne pollen concentration data are important for allergic individuals and medical workers exploring responses to allergen exposure, and assimilation of real-time data is necessary to increase the performance of atmospheric models as seen in the case of meteorology and airborne pollutants. The introduction of image processing, in particular spectral analysis, to identify and quantify airborne particles of biological origin is expected to overcome the limitations of Hirst type devices with respect to the temporal resolution of samples (currently, Hirst data are usually in the form of daily averages or at best hourly data). Increasing the temporal resolution should reveal dependences hidden in the averaged data, such as peak exposure levels and the onset and intensity of allergic symptoms. There are currently a number of systems being developed with the aim of producing real-time (or almost real-time) aerobiological data (e.g. Kawashima et al. (2007), Oteros et al. (2015), Perring et al. (2015), Crouzy et al. (2016) and Kawashima et al. (2017)) but there is still more scope to work in this area.

The high diversity in airborne biota is challenging with respect to identification of taxa. Classical biological approaches, i.e., culture and microscopy, are not able to give complete information about spectra of airborne particles, which is particularly wide for fungi and bacteria. In order to overcome this hurdle, new, molecular-based approaches are required. IJB has been able to address this aspect in studies that applied enzyme-linked immunosorbent assay (ELISA) and polymerase chain reaction (PCR) techniques to the identification and quantification of specific pollen allergens (Grewling et al. 2016), fungal spores (Tao et al. 2009) and bacteria (Harrison et al. 2005). There is a lot of potential for applying metagenomics and next-generation sequencing (NGS) in aerobiology (Núñez et al. (2016) and references therein). High-throughput sequencing is expected to enable identification and quantification of any organism from the sample, but this is novel methodology and requires additional research and standardisation to be applied in aerobiological studies.

Conclusions

The *International Journal of Biometeorology* has been one of the main platforms for presenting aerobiological research over recent decades, particularly concerning climate change impacts on airborne pollen and fungal spores and the modelling and forecasting of aeroallergens. These are exciting times and it is hoped that improvements in sampling and diagnostic techniques will result in more studies regarding other biological particles, like fungal spores, bacteria and viruses, where there is a paucity of data. There is a risk, however, that failure to embrace new technologies will result in stagnation of the discipline.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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