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OPINION

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An integrative environmental pollen diversity assessment and its importance for the Sustainable Development Goals

Thomas Hornick[1,2] | Anett Richter[3,4,2] | William Stanley Harpole[1,2,5] | Maximilian Bastl[6] | Stephanie Bohlmann[7] | Aletta Bonn[2,4,8] | Jan Bumberger[2,9] | Peter Dietrich[9,10] | Birgit Gemeinholzer[11] | Rüdiger Grote[12] | Bernd Heinold[13] | Alexander Keller[14,15] | Marie L. Luttkus[13] | Patrick Mäder | Elena Motivans Švara[2,16,17] | Sarah Passonneau[1,2,16] | Surangi W. Punyasena[18] | Demetra Rakosy[2,17] | Ronny Richter[2,19,20] | Wiebke Sickel[3] | Ingolf Steffan-Dewenter[21] | Panagiotis Theodorou[16] | Regina Treudler[22] | Barbora Werchan[23] | Matthias Werchan[23] | Ralf Wolke[13] | Susanne Dunker[1,2]

[1]Department of Physiological Diversity, Helmholtz-Centre for Environmental Research (UFZ), Leipzig, Germany

[2]German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig, Germany

[3]Thünen-Institute of Biodiversity, Braunschweig, Germany

[4]Department of Ecosystem Services, Helmholtz-Centre for Environmental Research (UFZ), Leipzig, Germany

[5]Martin-Luther University Halle-Wittenberg (MLU), Halle, Germany

[6]Research Group of Aerobiology and Pollen Information, Department of Oto-Rhino-Laryngology, Medical University of Vienna, Vienna, Austria

[7]Atmospheric Research Centre of Eastern Finland, Finnish Meteorological Institute, Kuopio, Finland

[8]Institute of Biodiversity, Friedrich Schiller University Jena, Jena, Germany

[9]Department Monitoring and Exploration Technologies, Helmholtz-Centre for Environmental Research (UFZ), Leipzig, Germany

[10]Center for Applied Geoscience, Eberhard Karls University of Tübingen, Tübingen, Germany

[11]Botany, University Kassel, Kassel, Germany

[12]Institute of Meteorology and Climate Research Atmospheric Environmental Research (IMK-IFU), Karlsruhe Institute of Technology (KIT), Garmisch-Partenkirchen, Germany

[13]Department Modelling of Atmospheric Processes, Leibniz Institute for Tropospheric Research (TROPOS), Leipzig, Germany

[14]Department of Bioinformatics, University of Würzburg, Würzburg, Germany

[15]Center for Computational and Theoretical Biology, University of Würzburg, Würzburg, Germany[16]General Zoology, Institute for Biology, Martin-Luther University Halle-Wittenberg, Halle, Germany

[17]Department of Community Ecology, Helmholtz-Centre for Environmental Research (UFZ), Leipzig, Germany

[18]Department of Plant Biology, University of Illinois Urbana-Champaign, Urbana, Illinois, USA

[19]Systematic Botany and Functional Biodiversity, Institute for Biology, Leipzig University, Leipzig, Germany

[20]Geoinformatics and Remote Sensing, Institute for Geography, Leipzig University, Leipzig, Germany

[21]Department of Animal Ecology and Tropical Biology, Biocenter, University of Würzburg, Würzburg, Germany

[22]Department of Dermatology, Venerology and Allergology, LICA-Comprehensive Allergy Centre, University of Leipzig Medical Center, Leipzig, Germany

[23]German Pollen Information Service Foundation (PID), Berlin, Germany

Correspondence
Thomas Hornick and Susanne Dunker, Department of Physiological Diversity, Helmholtz-Centre for Environmental Research (UFZ), Permoserstr. 15, 04318, Leipzig, Germany.
Email: thomas.hornick@ufz.de; susanne.dunker@ufz.de

Present address
Patrick Mäder, Data-intensive Systems and Visualization Group (dAI.SY), Technische Universität Ilmenau, Ilmenau, Germany

Faculty of Biological Sciences, Friedrich Schiller University Jena, Jena, Germany

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Societal Impact Statement
Pollen relates to many aspects of human and environmental health, which protection and improvement are endorsed by the United Nations Sustainable Development Goals. By highlighting these connections in the frame of current challenges in monitoring and research, we discuss the need of more integrative and multidisciplinary pollen research related to societal needs, improving health of humans and our ecosystems for a sustainable future.

Summary
Pollen is at once intimately part of the reproductive cycle of seed plants and simultaneously highly relevant for the environment (pollinators, vector for nutrients, or organisms), people (food safety and health), and climate (cloud condensation nuclei and climate reconstruction). We provide an interdisciplinary perspective on the many and connected roles of pollen to foster a better integration of the currently disparate fields of pollen research, which would benefit from the sharing of general knowledge, technical advancements, or data processing solutions. We propose a more interdisciplinary and holistic research approach that encompasses total environmental pollen diversity (ePD) (wind and animal and occasionally water distributed pollen) at multiple levels of diversity (genotypic, phenotypic, physiological, chemical, and functional) across space and time. This interdisciplinary approach holds the potential to contribute to pressing human issues, including addressing United Nations Sustainable Development Goals, fostering social and political awareness of these tiny yet important and fascinating particles.

KEYWORDS
aerobiology, allergy, diversity, environmental monitoring, food safety, paleoecology, palynology, pollination

1 | INTRODUCTION

Pollen is an intimate part of plant reproduction, being the microscopic carrier of the sperm to the ovules of other, or sometimes the same, individual plants. Pollen represents the evolutionary solution that allows plants to sexually mix their genetic material with spatially distant members of their species because plants themselves are essentially stationary and cannot move. To do this requires a vector, to move the pollen, which can be the wind or animals or occasionally water. Because the chances of an individual pollen grain reaching a suitable partner are small, plants must produce a lot of pollen, and this quantity has consequences beyond plant reproduction (Figure 1). The sheer amount of pollen produced during the growing season has significant effects on the environment, transporting nutrients and micro-organisms (Dharampal et al., 2019; Filipiak, 2016; Keller et al., 2021). Pollen serves as important food source for insects to meet their nutritional requirements providing carbohydrates, proteins, lipids, and micronutrients, thus impacting insect health directly (Filipiak et al., 2017; Moerman et al., 2017) or indirectly, for example, by increasing their tolerance to pesticides (Barascou et al., 2021).

Pollen triggers allergic immune responses in humans (Linneberg et al., 2016; Zuberbier et al., 2014) and can even influence the weather (Fröhlich-Nowoisky et al., 2016; Steiner et al., 2015). Information about pollen diversity is central for understanding prehistoric ecosystems and their climates (Matthias et al., 2015; McElwain, 2018). Pollen provides essential information for fields such as food safety and authenticity control (Bogdanov & Matin, 2002; European Commission, 2002), material science (Katifori et al., 2010; Zhao et al., 2020), or forensics as crime scene telltale sign, for example, by analyzing pollen composition in a forensic sample in order to determine the time of the year or place when and where the pollen was deposited (Coyle, 2004).

In addition to these far-reaching indirect consequences of plants fulfilling their reproductive cycles are the many ways that pollen connects to the United Nations' Sustainable Development Goals (Figure 1). The Sustainable Development Goals are the blueprint to achieve a better and more sustainable future for all humans. They address the global challenges we face, including those related to poverty, inequality, climate change, environmental degradation, peace, and justice (https://www.un.org/sustainabledevelopment/sustainable-development-goals/).

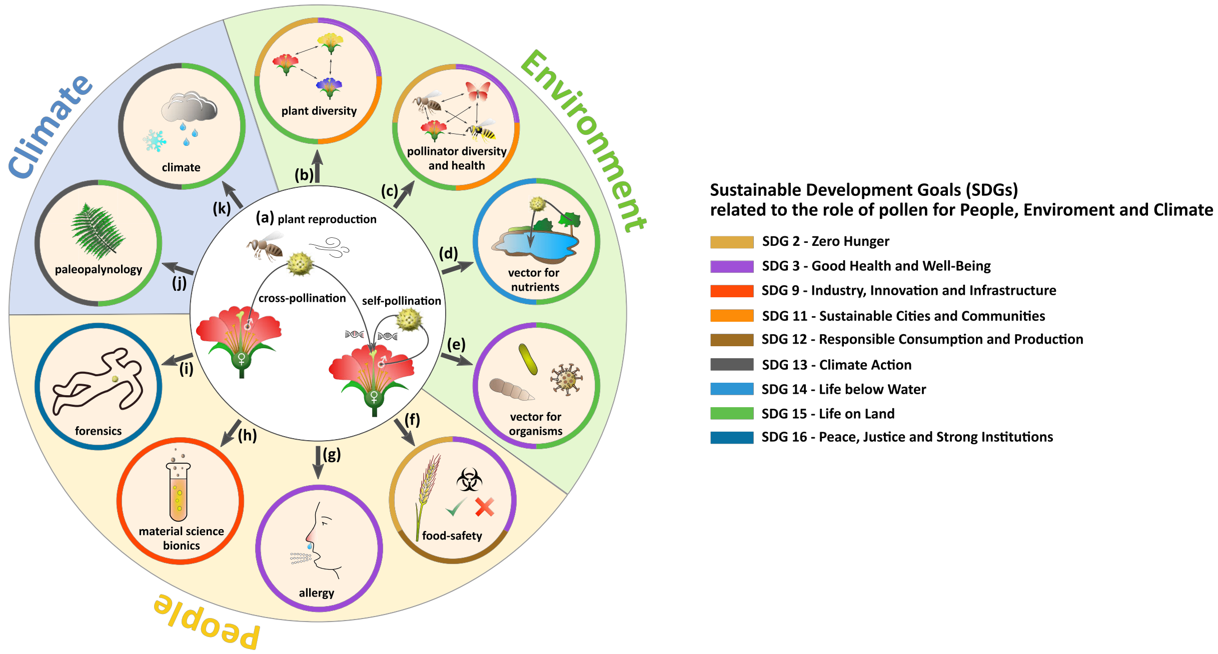

FIGURE 1 **(a–k) The multifaceted roles of pollen for the environment, people and climate beyond plant reproduction and how they link to the sustainable development goals (SDGs).** Coloring of the outer smaller circles refers to the respective most relevant SDGs which are related to the individual facets of pollen. *Note*: The size of color coding does not rate the importance of the single SDGs. *Environmental implications of pollen diversity:* Pollen grains are microscopic two- or three-celled structures containing the reproductive cell (male gametophyte) which are mainly transferred by wind (anemophily), animals (zoophily), and sometimes water (hydrophily) (Figure 1a—central circle) to prevent self-pollination which has long-term risks of inbreeding and loss of genetic diversity (Figure 1b—plant diversity). The size and structure of pollen grains is adapted to their mode of transfer and vary to different degrees among plant taxa. Because pollen grains are small in size, produced in large numbers and possess a resistant outer wall that protects the male reproductive cell from environmental damage, they are almost ubiquitous in the environment. The number of pollen grains produced by each plant, their relationship to the number of ovules, as well as the number and type of pollen found on a plant's stigma determine the reproductive system of plants and impact on stability and resilience of plant populations. A huge variety of pollen morphologies reflect plant–pollinator co-evolution in the about 87.5% of the currently 226.000 angiosperm plants that require an animal pollinator (Ollerton et al., 2011). Pollinator nutrition and health depend on pollen chemical composition and diversity (Figure 1c—pollinator diversity and health) (Filipiak et al., 2017; Moerman et al., 2017; Vaudo et al., 2015). If pollen are transported over long distances, they may influence terrestrial (e.g., epiphyte communities) and aquatic food webs by supplying nutrient-rich resources to detrivores (Filipiak, 2016) (Figure 1d—vector for nutrients) or serve as vector for organisms (bacteria and fungal spores) (Dharampal et al., 2019) (Figure 1e—vector for organisms) across spatial scales. *The role of pollen diversity for people:* As food-security is dependent on animal-pollination (IPBES, 2019), plant–pollinator interactions are highly relevant to maintain food security (Figure 1f—food safety). Pollen is used in food safety and authenticity control (Bogdanov & Matin, 2002; Teufer, 2011). Pollen can interact with the human immune system, causing allergy symptoms in approximately 23% of humans, which are associated with tremendous costs for national health systems and socio-economic consequences (Linneberg et al., 2016; Zuberbier et al., 2014) (Figure 1g—allergy). Nature-inspired design could be explored in material science, fostering industry and innovation (Figure 1h—material science and bionic). Especially morphological and chemical characteristics and the use of the outer pollen wall (exine) and its forming biopolymer (sporopollenin) are in focus of applied research due to its light shielding, antioxidant, elastic, and resilient characteristics (Katifori et al., 2010; Mackenzie et al., 2015; Zhao et al., 2020). Forensic palynologists are using pollen as crime scene telltale sign (Coyle, 2004) (Figure 1i—forensic). *Pollen diversity and climate:* The tough outer shell of pollen can be preserved for millions of years, providing a record of past vegetation and climate (Matthias et al., 2015; McElwain, 2018) (Figure 1j—paleopalynology). Airborne pollen grains are a part of primary emitted bioaerosols (PBAs). The interaction of pollen with radiation, photo-oxidants, pollutants (e.g., NOx), and clouds makes pollen a key player for both climate and weather (Steiner et al., 2015; Wozniak et al., 2018) (Figure 1k—climate). Due to aging, humid conditions, or certain meteorological conditions, pollen can rupture releasing subpollen particles, which are efficient cloud condensation nuclei impacting reflectivity (albedo), lifetime of clouds, and precipitation (Steiner et al., 2015; Wozniak et al., 2018)

Here we begin by (i) briefly providing the background necessary to appreciate the many additional roles that pollen plays beyond its central role in plant reproduction (Figure 1). (ii) We outline how monitoring and measuring pollen diversity can contribute to implementing the agenda for sustainable development. Finally, (iii) we discuss aims in pollen research, which can leverage new integrative pollen monitoring networks with the future aim that better information on pollen diversity in our environment can contribute to improving human health and well-being, as well as the health and functioning of our natural and managed ecosystems.

2 | MONITORING AND MEASURING POLLEN DIVERSITY TO SUPPORT SUSTAINABLE DEVELOPMENT GOALS

Although biodiversity monitoring is an obligatory component of many international agreements (CBD, 2010; European Commission, 2020), its implementation is often challenging. In addition to estimating species abundances, diversity monitoring concepts need to embrace variation in composition, structure, and function at several levels of biological organization in order to address global biodiversity loss and to quantify the value of its manifold services (Walters & Scholes, 2017). A holistic view of pollen diversity, comprising monitoring of species diversity, phenotypic, genotypic, chemical, and physiological variability, as well as functional diversity across space and time, can lead to new insights of the impact pollen diversity has for ecosystems, people and climate.

2.1 | Pollen diversity and ecosystems: Relevance of pollen diversity monitoring in maintaining healthy ecosystems

Pollen diversity monitoring can effectively complement existing biodiversity monitoring of plants (e.g., forestry or plant inventories) by tracking plant phenology (time of flowering), establishing species absence/presence, censusing community composition, and capturing changes in trait variation and physiology. With adequate sampling strategies at a range of spatial and temporal scales and supplemented by monitoring of indicators for environmental pressures, pollen diversity monitoring can help to determine and understand causes for change in status and trends of plant populations and ecosystems. Assessment of genotypic pollen variability can foster our understanding on plant diversification and ploidy (Knight et al., 2010). Pollen morphological and chemical variability might leverage new insights into plant–pollinator co-evolution (Moreira-Hernández & Muchhala, 2019; Pyke, 2016; Roulston et al., 2000).

Pollen can help to build a detailed picture of plant–pollinator networks at various spatial scales (Bosch et al., 2009; Pornon et al., 2016). Plant–pollinator visitation networks can be expanded by adding pollen transfer, pollinator activity, and flower specializations in an ecosystem-level context to learn more about which insects pollinate which plants (Dunker et al., 2020). In this way, it would be possible to see how communities are influenced by warming, shifts in phenology, land-use change, invasive species, and accompanying biodiversity loss—all factors, which are commonly referred to as "global change" (Forrest, 2015; IPBES, 2019).

Detailed information on pollen chemical composition might lead to a better understanding of the roles of pollen quantity and quality on insect physiology (Danner et al., 2017; Di Pasquale et al., 2013; Moerman et al., 2017).

In this context, we might better understand how insects depend on the availability of pollen to meet their nutritional requirements and how the impact of agriculture and land-use intensification impact on insect nutrition and health, resilience of pollinators, and species richness. The chemical composition of pollen can help to understand how specialist (oligolectic) and generalist (polylectic) pollinators might respond to the spread of invasive plant species or how appropriate suits of plant species can benefit threatened pollinators while supporting stable or expanding ones (Moerman et al., 2016). Ritchie et al. (2016) raised the need for better chemically characterizing highly rewarding plant species for simplifying the compositional requirements for restoration to support native pollinator diversity in human-dominated landscapes. Rather than considering habitat plant diversity and pollen amount alone, the chemical composition of pollen (e.g., sterols, essential amino acid concentration, and toxic plant substances) as a key factor for pollinator development needs to be suggested with attention for future conservations strategies (Moerman et al., 2017).

2.2 | Pollen diversity and people: Relevance of pollen diversity monitoring to achieve food security, good health, sustainable cities, and innovations

Pollen analyses can help to determine how ecological threats like global wild pollinator declines may affect food security and economy (Woodcock et al., 2019). Monitoring of pollen genotypic and chemical variability gives us a tool to assess genetically modified organisms (GMOs) and to analyze honey-based products for food safety, food fraud (e.g., aduleration), and authenticity control (e.g., botanical source and geographical origin) (Bogdanov & Matin, 2002; Teufer, 2011).

Monitoring of allergenic pollen online or with high spatial and temporal coverage can foster our understanding on health relevant issues when linked to clinical data of allergy sufferers. In addition to leading to tailored recommendations with options for spatio-temporal risk mapping information to avoid contact with potential allergenic pollen, this also might help understanding how the diversity of pollen present in the environment relates to allergies and their cross-reactivities (e.g., food allergies) in the frame of global change, air pollution, adherents (e.g., fine dust and microflora), rural–urban gradients, and genetic as well as social-economic factors (Eisenman et al., 2019; Treudler et al., 2018; Ziska et al., 2019). Information on pollen genotypic, physiological, and chemical variation could leverage new specific therapies and understanding of immunological responses at plant species level (e.g., grass pollen) (Brennan et al., 2019). An effective monitoring and understanding of the sensitization and allergy to low abundant pollen of allergenic invasive but also native plants is crucial.

By 2050, two thirds of humanity will live in urban areas (https://www.id.undp.org/content/indonesia/en/home/sustainable-development-goals/goal-11-sustainable-cities-and-communities.html). Planting trees and deploying green infrastructure will be essential to cool urban areas, to reduce air pollution and to use urban space for food production (Grote, 2019). To achieve sustainable cities, we need to transform the way we manage urban biodiversity and species which emit allergenic pollen. Fine-scaled pollen monitoring and pollen distribution models could provide essential information for urban greenspace managers, giving plant taxa recommendations to reduce allergenic pollen, developing allergy risk projections, and at the same time increase pollinator abundance and health for urban farming and food production.

The morphological, chemical, and physical characteristics of pollen offer a wide range of potential applications for applied science and industry, including the use of pollen as natural microparticles and microcapsules, for example, for drug delivery and oral immunization, micro-reaction vessels for enzymes and inorganic reactions, reinforcing filters, micromotors or for the engineering of sustainable, and eco-friendly and biocompatible pollen-inspired materials (e.g., microgels and self-actuating pollen-based paper) (Mackenzie et al., 2015; Zhao et al., 2020). Better assessment, characterization, and screening of the astonishingly divergent morphological and chemical structures of pollen can accelerate the quest for more cost-effective materials from renewable natural sources. The geometrical and mechanical principles of pollen wall structure and folding pathways may provide quantitative structure–function relationships inspiring bionics (Katifori et al., 2010).

2.3 | Pollen diversity and climate: Relevance of pollen diversity monitoring to understand past climate trends and to improve atmospheric models

During this century, human activity will lead to an unprecedented increase of atmospheric carbon dioxide concentration not observed during the past 50 million years according to plant fossil records (McElwain, 2018). Associated disruptions in global carbon cycling and ocean acidification threaten diversity and life on land and water (Reichstein et al., 2013; Riebesell & Gattuso, 2015). Paleobotanical records of pollen can offer insights into vegetation responses to past global warming events, predicting analogs for Earth's climatic future (McElwain, 2018).

In atmospheric models, the processing of primary emitted bioaerosols and its impact on other compartments within the Earth system are very intricate. Models of varying complexity in combination with advanced monitoring systems are required for analyzing the related processes, their interactions, and feedback effects on weather, climate, or water and element cycles. However, global and regional model estimates for pollen production and emission, transport and atmospheric effects (e.g., aging, chemical, and physical processes) are still subject to considerable uncertainties (Fröhlich-Nowoisky et al., 2016). High spatial and temporal resolved pollen monitoring improves knowledge of pollen emission, dispersion, and transformation during transport, which will greatly benefit the model representation of primary emitted bioaerosols (PBAs). In addition, information on pollen phenotypic and chemical variation at species level can yield better parameter estimation of models, for example, to estimate how different pollen act as cloud condensation nuclei (Steiner et al., 2015).

3 | SAFEGUARDING POLLEN RESEARCH'S CONTRIBUTIONS TO THE SUSTAINABLE DEVELOPMENT GOALS

The culture and distinctiveness of different fields of pollen research restricts the potential of total pollen monitoring and research in

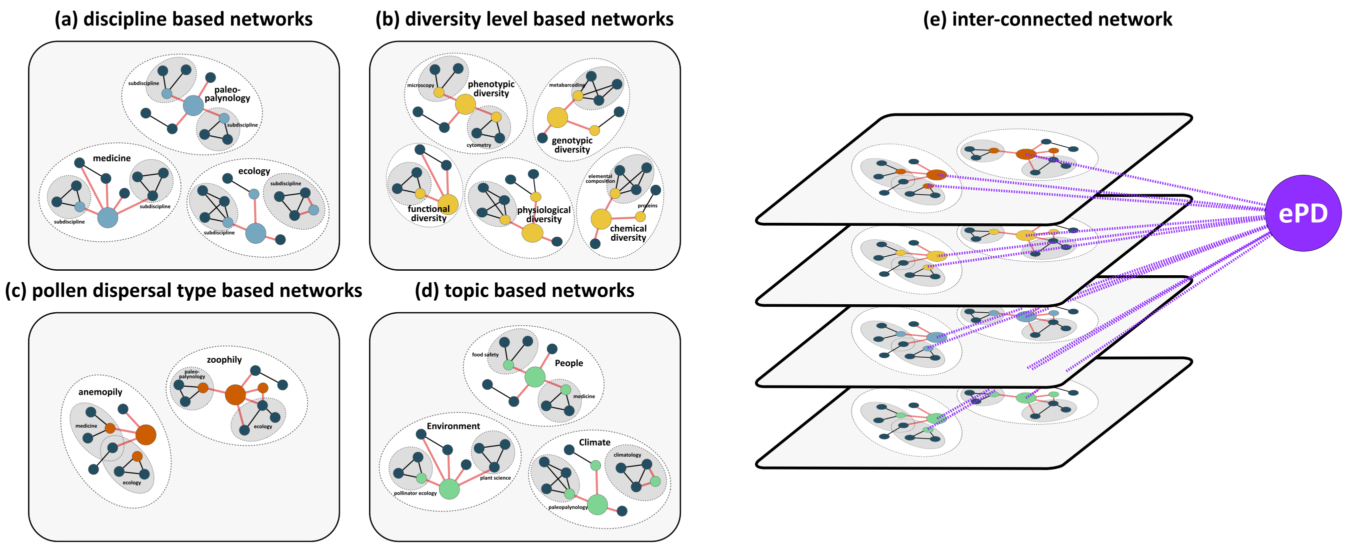

FIGURE 2 Complexity and interdisciplinarity gradients of pollen research networks. Dark blue nodes represent individuals, groups, or institutions which can collaborate within networks. Within each domain, synthesis nodes collect standardized pollen data for different research disciplines (colored nodes). Currently, pollen research is mainly performed in (a) discipline-based networks or (b) diversity level-based networks, focusing either on the respective discipline (e.g., medicine, ecology, or paleopalynology) or on certain diversity levels (e.g., phenotypic or genotypic diversity). A higher level of connectivity and interdisciplinarity between individuals, groups, or institutions is achieved by (c) dispersal-type-related networks or (d) topic-based networks. The environmental pollen diversity monitoring we suggest should (e) interconnect across such networks of different research disciplines, diversity levels, pollen dispersal types, and topics, establishing synthesis nodes, exchanging domain expertise, and facilitating common workflows

TABLE 1 Components of environmental pollen diversity (ePD)

ePD component	Measure	Methods	Possible data types	Pollen research disciplines	Reference(s)
Genotypic	Diversity measure (e.g., richness, evenness, β-diversity, etc.), metagenome, genotyping of genetic markers	Next-generation sequencing/ metabarcoding	Digital sequence information, operational taxonomic units (OTUs)	Aerobiology, agriculture, bioinformatics, ecology, forestry, medicine, paleopalynology	Bell et al. (2016), Brennan et al. (2019), Danner et al. (2017), and Keller et al. (2015, 2021)
	Genotyping of genetic markers	Polymerase-chain-reaction (PCR), next-generation sequencing/ metabarcoding	Presence/absence of genetic marker(s), digital sequence information	Agriculture, ecology, food safety control (GMO detection)	Hofmann et al. (2014) and Stewart et al. (2003)
	Genome size, DNA content, ploidy	Microscopy, cytometry, next-generation sequencing	Chromosome number, DNA content, digital sequence information, number of alleles	Agriculture, ecology, forestry	Altmann et al. (1994) and Kron and Husband (2012)
Phenotypic	Morphology feature, anatomic measure	Microscopy, electron microscopy, cytometry, imaging flow cytometry	Images, image features (e.g., length, diameter, area), thickness of, for example, exine	Aerobiology, bioinformatics, climate science, ecology, food safety control, paleopalynology	Dunker et al. (2020) and Erdtman (1986)
Physiological	Gene expression, transcriptome, proteome	Real-time (RT)-PCR, next-generation sequencing, microarray, western blot	Presence/absence of genetic markers/protein, digital sequence information	Aerobiology, ecology, medicine	Rutley and Twell (2015)
	Viability, germination	Viability tests (e.g., acetocarmine glycol jelly test or in vitro germination)	Abundance or concentration of viable or germinating pollen	Aerobiology, agriculture, ecology, forestry, medicine	Marks (1954) and Rodriguez-Riano and Dafni (2000)
Phylogenetic	Phylogeny-based diversity	Next-generation sequencing		Ecology, agriculture	
Chemical	Elemental concentration, stoichiometry, chemical fingerprint, isotope analysis; concentration of primary metabolites (e.g., macromolecule composition); concentration of secondary metabolites (e.g., sterols, flavonoids, alkaloids, terpenoids)	Standard chemical analytics, fourier transform infrared spectroscopy (FTIR), high performance liquid chromatography (HPLC), isotope ratio mass spectrometry (IRMS)	Concentration, ratio, stoichiometry, emission- and absorption spectra	Aerobiology, agriculture, ecology, forensics, forestry, food safety control, climate science	Bogdanov and Matin (2002), Filipiak (2016), and Filipiak et al. (2017)
	Allergenicity	Immunoassay (e.g., ELISA)	Antigen concentration	Medicine	Sousa-Silva et al. (2020)
Physical	Physical property (e.g., density, sinking velocity, ice nucleation efficiency)	Digital holography, ice nucleation array (e.g., LINA/INDA-assays)	Physical measure (e.g., of density, ice nucleation)	Aerobiology, climate science, ecology	Huang et al. (2021), Kanji et al. (2017), Knackstedt et al. (2018), and Van Hout and Katz (2004)

Note: Measures and methods of single cell and bulk measurements and possible data types of different pollen research disciplines beyond taxonomic count data revealed by standard microscopy. Ideally, several of these components will be combined to get a more holistic view on ePD in a certain temporal and spatial scale, however, being probably limited by financial and methodological constraints.

ecological, medical or paleoecological research fields (e.g., the European-wide approach of harmonized allergy-related pollen monitoring [EUMETNET—AutoPollen]; Clot et al., 2020) (Figure 2). Thus, the multiple implications of pollen, their interlinkages, and the importance for the UN global goals are often not recognized by the scientific community and society at large nor sufficiently acknowledged by decision makers. In order to achieve a holistic view on pollen-related impacts, we want to encourage cross-sectoral cooperation in monitoring, technological development, and implementation of workflows for data sharing (Box 1). To achieve a better interdisciplinary connection, we suggest defining the term "environmental pollen diversity" (ePD) expressing the total phenotypic, genotypic, chemical, physiological, and functional variability of pollen and dispersal types (anemophilous and zoophilous and occasionally hydrophilous) in a range of different social and scientific contexts. ePD monitoring and data sharing integrate all environmental pollen across space and time and inspire technologies and research fields. This would require new integrated monitoring and sampling strategies, connecting data from different research fields, for example, with locally connected device networks (Figure 2). By promoting various pollen diversity measures on an ecological scale, we want to highlight also the need for and diversity in scientific research related to pollen. Instead of using the concept of ePD as a strategy for unifying all scientific disciplines to standardized measures, the ePD framework rather aims to nurture cooperation across scientific disciplines promoting standardization and integration of data and metadata from different disciplines (Table 1). The data management should be interoperable, standardized, and accessible via machine-readable interfaces and repositories in order to meet current and future information technology and research-related requirements, for example, oriented on FAIR (Findable, Accessible, Interoperable and Reusable) and open science principles (Gallagher et al., 2020; Wilkinson et al., 2016).

Box 1: Recommendations for future pollen research

i. Defining commonalities in pollen research for coordinated monitoring programs, technological development and data sharing

Pollen research is inherently diverse and found in different scientific disciplines that are not well connected. Research communities, methods, and technological development are yet separated (Figures 1 and 2). The question arises, how these communities might better inform each other in order to implement an overarching strategy for long-term oriented pollen research, technological development, and data sharing that contribute to humanity pressing issues. Commonalities across research sectors need to address (a) common variables and metadata, (b) the linkage of data and metadata fulfilling requirements necessary for syntheses (e.g., taxonomy, temporal, and spatial resolution of metadata), and (c) sharing of infrastructure and technologies. The intention here is not to "equalize" the scientific disciplines but rather to achieve a meaningful cross-fertilization and use of existing beneficial methods and knowledge in order to positively support the progress of the respective disciplines.

ii. Current protocols of pollen monitoring need to overcome methodological limitations and assure comparability of results.

For methodological advances the need and prospects for automatization and real-time monitoring in pollen research have been proposed several times. Although alternative methods have been developed, time-consuming and labor-intensive manual microscopy is still the gold standard (for reviews see (Buters et al., 2018; Holt & Bennett, 2014; Stillman & Flenley, 1996)). While ex-situ measurements are already performed in Core Facilities (Microscopy, Metabarcoding, and Cytometry), however, limited by sampling effort, in-situ measurements are mostly limited by high costs for precise quantitative data. To further increase sample throughput, more frequent combinations, exchange, and transfer of sampling strategies and technology developed in the respective fields are crucial. One suitable combination of methods could be to merge semiquantative metabarcoding or chemical fingerprinting (Kenđel & Zimmermann, 2020; Pornon et al., 2016) with quantitative, image-based single cell approaches (e.g., imaging cytometry; Dunker et al., 2020) as complementary tools to benefit from the huge effort of past sequence databases or development of chemical analytics and herewith providing more reliable outcomes for large datasets. Usage and merging of data of different methods and technologies should assure intercalibration of results. If suitable, standards, calibration laboratories, and intercalibration campaigns need to be established to ensure reproducibility of results and the comparability of measurement systems for the emerging field of pollen data acquisition.

iii. Coordinating a FAIR-home of data

Data integration and its interoperability with other data stores need harmonized data and standardized metadata and its mapping to other catalogs. Sequencing data are, for example, already standardized and required to fulfill FAIR principles including public repository deposition and standardizing metadata for almost any publication. Other data types, however, still need harmonization and standardization in order to link different data types and locations (e.g., imaging data). Many excellent databases for depositing processed data already exist, which is on the one hand probably much more useful than raw data for further use and on the other hand may be the foundation for an integrating database for pollen-related measures.

A strategically designed pollen-specific registry of datasets is needed that encompasses, in addition to pollen counts and taxonomic identities, abundance, and variability of pollen traits including morphological, genetic, chemical, and medical traits (e.g., allergenicity) alongside geographical and temporal distribution (Table 1). In order to estimate taxonomic richness independent of evenness or turnover rates, pollen measures and metadata should also allow to take into account pollen accumulation rates, rarefaction measures, and sampling effort (e.g., Van der Knaap, 2009). We suggest to integrate these data in an existing database for plant measures, for example, using the TRY databases, which compiles plant trait data from the different aspects of plant functioning on a global scale to make the data available in a consistent format through one single portal (Kattge et al., 2011). Also appealing to researchers and journal editors for the necessity to make pollen data public (Gallagher et al., 2020), the resulting possibilities are then to integrate further spatial–temporal environmental, biodiversity, or health data from observations, remote sensing, and simulation runs of models in order to develop, for example, operational information systems. Such data integrations are also necessary to achieve standards for data collection in monitoring networks, to identify gaps in data acquisition processes, and to effectively relate biological variables to other data.

iv. Raising societal awareness of pollen research to increase the outreach of global goals

First assessments of pollen with the aid of volunteers have been established in some regions (e.g., pollen radar, CSI pollen; Brodschneider et al., 2019). We suggest standardized pollen collection programs that could be easily employed by citizens across large geographic gradients or at very fine-scale cover (e.g., in a selected urban area) by equipping them with cheap personal samplers or passive pollen samplers. Involvement of citizen scientists can also help in gaining data, which may give more accurate measures of air quality by using personal monitors in daily life, gaining a better relationship of symptoms to pollen concentration, or accounting for higher spatially resolved sampling in biodiversity monitoring to support local as well as global monitoring initiatives and assessment mechanisms (e.g., IPBES).

Pollen interacts with humans in multiple ways, making ePD monitoring ideal for public participation in science. Citizen science has the added effect of raising awareness, for example, for the importance of stable plant–pollinator networks or good air quality in cities; "learning by doing" and thereby scientific literacy can help fostering civic participation and environmental stewardship (Bela et al., 2016; Turrini et al., 2018). Although airborne pollen and pollination monitoring are public services of general interest for society, in most countries, it is not financed by public funds (Baeker et al., 2019). Raising societal awareness can build support for state financed monitoring programs. Providing citizens with integrated knowledge products (e.g., biodiversity trends, species- and site-specific allergy forecasts, and pollen composition in honey) may support a social transformation towards greater sustainability and increase the outreach of global goals.

These challenges can only be adequately solved by interdisciplinary teams and a long-term orientation of research and funding. More frequent research practices across disciplines may consequently result in coordinated monitoring programs, databases, and conferences for scientific exchange addressing the pollen research community as a whole.

4 | CONCLUDING REMARKS

Interdisciplinary collaboration across scientific disciplines dealing with pollen data should take place on a much larger scale, fostering communication across traditional professional and academic boundaries and strengthening the particular importance of a holistic view on pollen diversity and all related facets. Here we emphasize that not only species diversity should be an integral part of ePD monitoring, but other levels of diversity as phenotypic, genotypic, chemical, physiological, and functional diversity should be similarly considered to provide better mechanistic insights in processes. Research and society could more effectively benefit from recent technical advances and achievements in automation, high-speed image recognition by artificial intelligence, miniaturized and/or low-cost sensors, and instruments if there would be a better exchange and integrative collaboration of separated research fields. A shift towards more integrated research practices creates new avenues for ePD monitoring and research, forcing further technological advancements. This must be accompanied by approaches in data science assuring updated protocols for data quality-control und data-sharing. At the same time, it is important to create a societal awareness of pollen-related aspects, in order to ensure a long-term, broad-based implementation of measures. To achieve all this, we have compiled appropriate recommendations in Box 1.

Once these steps are more and more implemented, society and policy makers will gain a better understanding of ecosystem services related to pollen biodiversity ecosystem functioning

(SDG15—Life on Land). ePD monitoring might be an efficient tool for quantitative and qualitative assessment of resilient and sustainable food production (SDG2—zero hunger and SDG12—Responsible production). A detailed assessment of rural–urban gradients of ePD can help to plan more sustainable urban environments (SDG11—sustainable cities and communities) as well as can help to investigate interregional ecosystem service flows (telecoupling) by transport of pollen and pollen-related products (Koellner et al., 2019). In addition, ePD monitoring opens up new directions for exploring pollen features for industrial applications (SDG9—Industry, Innovation, Infrastructure; SDG12—Responsible production), adapting patient-specific therapies (SDG3—health and well-being), and allowing for more precise climate forecast (SDG13—climate action). Engagement in public outreach should clarify that pollen-related ecosystem services are not self-evident, strengthening societal awareness to support necessary measures addressing anthropogenic environmental crisis.

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CONFLICT OF INTEREST

All authors have nothing to disclose.

AUTHOR CONTRIBUTIONS

SD had the original idea for the workshops and the manuscript. TH organized the workshops, did the main work of manuscript writing, drafted the manuscript, and designed the figures with close support of SD and conceptual advice by AR and WSH. All authors attended the workshop and with that helped shaping the research, participated in the writing process, provided text passages, and contributed editing suggestions to the manuscript. All authors contributed to the final manuscript. SD supervised the project.

DATA AVAILABILITY STATEMENT

This manuscript presents a conceptional framework; no data were used.

ORCID

Thomas Hornick https://orcid.org/0000-0003-0280-9260
William Stanley Harpole https://orcid.org/0000-0002-3404-9174
Stephanie Bohlmann https://orcid.org/0000-0002-1019-4692
Aletta Bonn https://orcid.org/0000-0002-8345-4600
Patrick Mäder https://orcid.org/0000-0001-6871-2707
Elena Motivans Švara https://orcid.org/0000-0002-2407-9564
Surangi W. Punyasena https://orcid.org/0000-0003-2110-5840
Demetra Rakosy https://orcid.org/0000-0001-8010-4990
Susanne Dunker https://orcid.org/0000-0001-7276-776X

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