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OPINION PAPER

Early Career Researchers advocate for raising the profile of bryophyte ecological research

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ABSTRACT

Bryophyte research is severely underrepresented compared to vascular plant research, even though we know that bryophytes are crucial components of ecosystems and contribute significantly to ecosystem functions and processes, and thus to ecosystem services. This underrepresentation creates many hurdles and barriers that Early Career Researchers (ECRs) must first overcome to establish in this field, which significantly hinders research now and in the future. Therefore, this work deals with the future of bryophyte research, and bryophyte ecology in particular, which is reflected in the perspectives of ECRs in this scientific field. By listing the many barriers that bryophyte researchers and especially ECRs face, including underrepresentation, funding and publishing, but also possible solutions, we want to raise awareness for and advocate to raise the profile of bryophyte research. We here identify multiple barriers that bryophyte-focused ECRs face and what is needed to overcome them. We address different structural and institutional levels, ranging from early education in schools to academia, funding and publishing. Raising the profile of bryophyte research works on many different levels simultaneously. To improve the prospects of bryophytes and thus increase scientific interest in, and ultimately understanding of, this important group of plants, we need to raise awareness now.

Bryophytes are essential organisms to numerous ecosystem processes and services (Eldridge et al., 2023). Their contribution ranges from soil biodiversity and functional attributes, such as nutrient cycling and carbon sequestration, to water cycling, bioindication, and net primary productivity (Eldridge et al., 2023; Hupperts et al., 2021; Porada et al., 2018; Elbert et al., 2012). However, even though bryophytes in some systems are the dominant vegetation and despite their key role in ecosystem functions, processes, and services, bryophytes are often overlooked and underrepresented in ecological research. From the curriculum in school and at university to a taxonomic bias in assessments of biodiversity, funding and publishing, the underrepresentation of bryophytes results in serious gaps in our knowledge of how anthropogenic factors affect biodiversity and ecosystem functioning. As Early Career Researchers (ECRs) pursuing a bryophyte-focused research agenda, we want to advocate for raising the profile of this important group by identifying barriers to overcome and possible solutions to how we as an ecological community can overcome them.

The importance of bryophytes

Bryophytes, which comprise mosses, liverworts, and hornworts, are ubiquitously distributed and are integral components of numerous ecosystem processes and services (Eldridge et al., 2023). In particular, non-vascular plants, including bryophytes among others, can increase

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rainfall interception by >12 times and global evaporation by on average 61 %, thus contributing substantially to global water cycling (Porada et al., 2018). By efficiently resorbing and retaining nitrogen (N) from senescing tissue, and increasing soil N, phosphorous, and magnesium content, bryophytes act as a substantial N sink and strongly influence the nutrient cycle (Liu et al., 2020; Hupperts et al., 2021; Eldridge et al., 2023). Their contribution of 7 % of terrestrial net productivity and half of biological N fixation on land (Martin & Adamson, 2001; Elbert et al., 2012), the ability to sequester up to 6.43 Gt more carbon than bare soils, and their comparably slow decomposition rate makes bryophytes key organisms in environments where they are abundant (Eldridge et al., 2023). Moreover, they serve as sensitive bioindicators for environmental conditions such as air quality, climate change impacts, and ecosystem resilience (Lindo et al., 2013; Parmar et al., 2016; Thiemer et al., 2018), making them valuable subjects for studies on environmental change (Becker Scarpitta et al., 2017). Despite this key role in ecosystem functions, processes, and services, bryophytes are still overlooked and underrepresented, and receive much less attention than vascular plants, both in public awareness, funding and publishing.

Bryophytes are not the only underrepresented group in research. Other key cryptogam groups, such as lichens, face similar challenges. Yet, as the second largest group of land plants with roughly 20,000 described species, bryophytes receive disproportionally little attention in ecology, especially considering their abundance in and importance for ecosystems. For instance, in deserts and tundra ecosystems, they reach a comparable cover to vascular plants and exceed them by far in Antarctica (Eldridge et al., 2023; Walshaw et al., 2024). In boreal and Arctic environments, bryophytes dominate ground cover, and northern peatlands can be shaped by one single moss genus, namely Sphagnum, making them key ecosystem engineers (Rydin & Jeglum, 2013). Within the context of climate change these ecosystems are crucial as boreal peatlands contain ca. 25 % of the global carbon stock, while only taking up 3 % of the land area (Loisel et al., 2021). Specifically in these environments, it is crucial to determine to a higher taxonomic level than just "bryophyte" to obtain precise results on ecological interactions and functional roles. This requires researchers who are trained in species identification, starting already with ECRs. However, there are numerous barriers to overcome for ECRs to be able to pursue a bryophyte-focused research agenda.

Early career researchers as the future of science

ECRs represent the future of science. In biodiversity research and ecosystem ecology, elucidating patterns of how organisms contribute to ecosystem services and functions and respond to environmental change is a pressing priority, as this understanding is crucial for predicting and mitigating the impacts of global change. A comprehensive understanding of biodiversity and how it links to ecosystem functioning can only be achieved by incorporating all aspects of biodiversity. However, doing so requires a diversity of skills for different organisms within the scientific community. For example, for an ecologist working on bryophytes, a profound species knowledge, assessment of habitat conditions, knowledge of how to plan and conduct field surveys and subsequent data analysis are some of the skills required. On the one hand, a scientifically underrepresented group of organisms, such as bryophytes, may offer a compelling niche for research. On the other hand, research niches also pose serious challenges and create barriers that can be hard to overcome for ECRs. Barriers that ECRs in bryophyte ecology face include the challenging process of gaining strong identification skills, biases in taxonomy, and funding and publication, all of which we discuss in more detail below. As ECRs are the future generation of scientists, it is necessary to overcome these barriers now to avoid a serious shortage of scientific skills, and hence of bryophyte-related research. Therefore, as a group of ECRs working on bryophytes, we advocate here for raising the profile of bryophyte research, with a main focus on bryophyte ecology, across regions and thematic disciplines by identifying barriers and possible solutions on how we as an ecological community can overcome them.

Barriers to overcome

Even though the number of studies on bryophytes and their functional traits has slightly increased in the last few decades (Coe et al., 2024; St. Martin & Mallik, 2017), bryophytes still receive much less attention than vascular plants in ecological research. This is evidenced by the taxonomic bias in large databases, such as the Global Biodiversity Information Facility (GBIF), with, for example, a taxonomic coverage of 83 % for pteridophyte species, but only 28 % for bryophyte species (Meyer et al., 2016). Furthermore, there is a geographical bias due to differences in bryophyte sampling density based on accessibility and logistical challenges, leading to a sparse sampling in the Arctic north of the treeline: just a third of specimens that are databased in GBIF were collected above 60°N, compared to adjacent southern latitudes (50°N-60°N), leading to an undercollection in these regions (Lewis et al., 2017). Similarly, many bryophyte specimens sampled decades ago are stored in herbarium collections but are yet to be digitised, which currently hinders their inclusion in scientific studies (Lewis et al., 2017). Additionally, <10 % of all known moss species have available information on functional traits, compared to >70 % of vascular plants (TRY database v6.0, Kattge et al., 2020). There are more than twice the records for response traits covering mainly morphology, physiology, and nutrient cycling than traits related to water cycling, reproduction or the function as boundary layer (Coe et al., 2024), showing both research successes and gaps that should be addressed by future research.

From our viewpoint as ECRs, these biases are not surprising. The barriers one faces when wanting to pursue a career that is centred around bryophytes are numerous, intertwined, and start early. Bryophytes are insufficiently, or not at all, included in school textbooks and teaching curricula. In our undergraduate courses, bryophytes were at best mentioned as part of the evolution of vascular plants or as a prominent example of cryptogams. This is far from enough to provide an understanding of the crucial role that bryophytes play in many ecosystems. Furthermore, moss-related thesis topics are often only offered by supervisors who are specialized in the matter, which are few in our experience. Much of the bryophyte-related expertise seems to be distributed among senior colleagues both within and particularly outside academia. There is a breadth of expertise to be found within local and regional botanical societies, and among amateur bryologists with extensive taxonomic and ecological knowledge. However, exchanges between academia and non-academic colleagues are not streamlined.

Another barrier to sparking interest of ECRs in bryophyte ecology is that bryophytes initially appear less eye-catching. In contrast to vascular plants, which are more conspicuous due to their size and flower formation and likely represent the imagination of typical plants for most, bryophytes can appear as rather unimpressive and unspectacular. Given that botanical teaching tends to concentrate on vascular plants, it is likely that the lack of focus on bryophytes will continue. Without the guidance of a mentor, it is challenging for students to develop an interest in this relatively inconspicuous group, which in turn leads to a reduction in the number of ECRs with the necessary knowledge and skills to conduct bryophyte research.

Even if and when one discovers an interest in bryophytes, several hurdles remain. Species identification is key. For the most common species, field determination with a good magnifying glass or hand lens is possible. However, it might be necessary to take samples and examine them microscopically. This can be both a financial and a methodological hurdle. Additionally, species determination literature is essential, but it can be expensive and hard to obtain. Gaining species knowledge is certainly a valuable skill. Yet, due to the underrepresentation of the discipline, this skill seems inferior to gaining other more highly regarded skills, which hinders entry into bryophyte research. Confronting

multiple generations of ECRs with these uncertainties and obstacles might lead to a loss of researchers, followed by a loss of species knowledge and thus the ability to keep generating bryophyte ecological research. Ultimately, bryophyte research suffers, with these repercussions leading to a negative feedback loop. If someone overcomes the odds and finds themselves researching bryophytes, they will find that developing expertise in both bryophyte taxonomy and ecology can be difficult. Linking these two fields is essential but there seems to be a general trend where taxonomists tend to not participate in ecological research, and vice versa for ecologists and taxonomical research.

A key part of academia is publishing new findings. However, publishing high-impact bryophyte studies might be challenging, particularly considering the current emphasis on publishing metrics, since this taxonomic group is often considered less relevant in ecological research. Many more projects have been funded in the past ten years focusing on plants in general compared to research on bryophytes only (at least 23–52 times more, depending on the funding agency; Fig. 1A). This pattern was the same for different regional scales, from country- to continent-wide scales (Germany, USA, Europe). However, it remains unknown if this is a result of bryophyte project proposals being rejected or if just few proposals were submitted as a result of institutional and structural hurdles. Yet, we think that this difference in magnitude reflects the underrepresentation of bryophytes in academia quite well. Additionally, bryophyte studies are also less frequently published in high impact journals, compared to other plants (Fig. 1B). In the journals of three high impact publishers (AAAS, NAS, and NaturePortfolio), only one study on bryophytes was published for every 147, 66, and 64 studies on other plants, respectively, in the last decade (the full list of studies is provided in Appendix A: Table 1). There were differences across fields of research with the majority of studies on bryophytes being ecological. Molecular studies had a relatively large share showing that in recent years, bryophytes, such as *Physcomitrella patens* or *Marchantia polymorpha*, have been increasingly used as model organisms in molecular biology studies (Yadav et al., 2023). Yet, the overall difference between bryophyte and vascular plant studies demonstrates the significant underrepresentation of bryophytes in research. This is likely to result in reduced motivation to conduct further bryophyte research given that it yields lower career benefits than working with vascular plants.

We acknowledge that there are roughly 20 times less described bryophyte species than vascular plant species, so a certain difference in funded projects and conducted studies is to be expected. However, accounting for species number, i.e., multiplying the number of bryophyte studies with the factor of species number difference between bryophytes and all other vascular plants (ca. 18.45), we still see an underrepresentation of bryophyte studies in high impact journals: for every bryophyte study, between 3.5–8 vascular plant studies are published. Regarding funding, the underrepresentation also is still noticeable when taking into account the difference in number of species, even if it is less severe than for publishing (i.e., 1.27–2.8 times less funding to bryophyte studies than vascular plants). This might seem less severe but a 27 % lower chance of getting funding could easily discourage researchers from developing and applying for grants focused on bryophytes. Given the importance of bryophytes for specific biomes and ecosystems such as peatlands, boreal systems or the alpine and Arctic tundra, where bryophytes are key dominant functional groups, we believe that this group should receive more attention in ecological research.

Recently, interest has grown in using identification apps such as Flora Incognita, iNaturalist, and Pl@ntNet to identify plants. By now, those softwares and apps contribute to (mostly) reliable identification of vascular plant species across most realms of the world. However, none of these are able to reliably identify bryophytes to species level or include them at all (J. Wäldchen from FloraIncognita, H. Grasse from Pl@ntNet, pers. comm.). The reasons for this are certainly linked to the small characteristics and strong similarity of many species or even genera such as *Bryum, Grimmia* or *Orthotrichum*. Although modern cameras produce high-resolution images, tiny characteristics such as glass hairs or middle

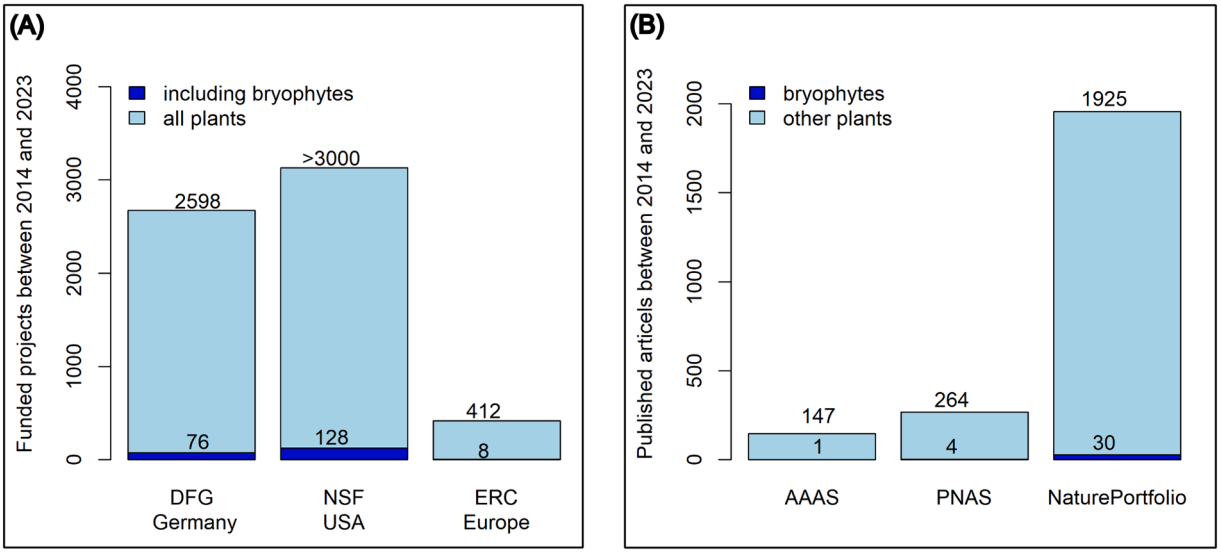

Fig. 1. Database queries on the funding and publishing figures of bryophyte projects and projects on plants in general, respectively. (A) Number of projects being funded between 2014 and 2023 which focus on bryophytes and plants, respectively, by the ERC (European Research Council, www.dashboard.tech.ec.europa.eu, accessed 31.05.2024), DFG (Deutsche Forschungsgemeinschaft, www.gepris.dfg.de, accessed 31.05.2024) and NSF (U.S. National science foundation, www.nsf.gov, accessed 05.06.2024). Our search terms were "bryophyte", "moss", "liverwort", "hornwort", and "plant". The keywords were screened in the abstracts (ERC), in abstracts and titles (NSF), and in the project descriptions and final reports (DFG), depending on the data provided by the databases. We filtered out projects which used these terms in an unrelated way, and further selected data for the ten most recent years (2014–2023). We summarized the number of projects containing the keywords "bryophyte", "moss", "liverwort" or "hornwort" as bryophytes. Projects which contained more than one of these keywords were counted once and duplicates were removed. Note that funded bryophyte projects here represent a share of all funded plant projects. (B) The number of publications for bryophytes and other plants between 2014 and 2023, respectively, in the journals of three high impact publishers including the American Association for the Advancement of Science (AAAS; Science journals), the National Academy of Sciences (NAS; PNAS journals), and NaturePortfolio (Nature journals). The query was carried out using the Europe PMC database (www.europepmc.org; access: 17.06.2024) for the search terms "bryophyte*", and "plant*" specifically excluding all bryophytes. All publications from journals belonging to one of the above publishers were then grouped in the appropriate category and summed.

rips may still be difficult to discern, thus challenging the identification algorithms. In many cases, even reproductive structures or cross-sections of leaves or stems are required to determine individuals to species level. Consequently, one or a few images captured at a single point in time might not be sufficient, hence creating significant challenges for algorithms.

The aforementioned barriers are undoubtedly intertwined. A lack of awareness is connected to a lack of funding and high-impact publishing, which in turn creates a research gap that negatively impacts education and perpetuates a feedback loop. These issues also extend to the public and stakeholders, further impacting the perception of bryophytes, and decreasing their interest outside of academia. Consequently, the integration of bryophytes into conservation plans and decision-making is impeded. Given that these barriers operate at numerous levels, their overcoming requires simultaneous action at all levels of the scientific process.

Overcoming barriers

In order to increase the amount, breadth and depth of ecological bryophyte research, we provide a series of suggestions aimed at different parts of the scientific process (Fig. 2).

Research: We encourage administrators to create more teaching/research positions with a focus on bryophyte research at universities and research centres. Similarly, PIs and supervisors could offer more undergraduate, master's and PhD projects on bryophyte research, which would also ensure full training of the next generation of scientists. In order to overcome the wide bryophyte data gaps, we encourage all bryophyte researchers to establish, expand and participate in collaborative networks of bryophyte research across countries and institutions, and share data through open science portals and databases. The exchange of knowledge and collaboration between disciplines, especially between taxonomists and ecologists, bridges knowledge gaps and thus paves the way for excellent bryophyte ecology research. Including bryophytes in vegetation studies as functional groups is another way to incorporate their significant ecological roles at a coarser taxonomic resolution level (Lett et al., 2022). Successful initiatives for data sharing include the recently compiled comprehensive databases on bryophyte functional traits such as Bryophytes of Europe Traits (Van Zuijlen et al., 2023) and BryForTrait (Bernhardt-Römermann, Poschlod, & Hentschel, 2018), and the herbarium database Consortium of Bryophyte Herbaria that makes millions of herbarium specimens available online. However, just because a trait is available for a species, it does not mean that these are the most relevant traits for specific contexts and research aims. We currently see room for improvement in DNA databases that should also increase focus on including bryophytes, since e-DNA sampling will undoubtedly be part of future biodiversity monitoring. This would not only enhance further research but will be key for ecosystem monitoring and establishing trends of biodiversity over time. Further interdisciplinary collaboration between researchers should be encouraged to get the full picture of ecosystems, such as partnerships between different academic disciplines (e.g., soil sciences, remote sensing and bryophyte ecology, taxonomists and ecologists, academia and industry, etc.). We encourage scientists to engage in informal discussion too: a great forum to participate in and follow international discussions is Bryonet-L, the mailing list of the International Association of Bryologists, which regularly discusses topics and questions in an email forum. Finally, stronger links between academia and amateur botanists and botanical societies will certainly strengthen our pool of available knowledge and data, and contribute to further training.

Education: More bryophyte identification courses are certainly needed to set a basis for bryophyte ecological research. These can be guided tours, e.g., through bryological societies that hold extensive knowledge, both from amateurs and from professionals, or (online) identification courses to facilitate inclusivity. Since time is often limited, courses could combine both taxonomy and ecology to directly bridge the gap between these two fields of research. Partly this is already done by some organisations focusing on bryophytes such as The British Bryological Society (BBS) or the Bryologisch-lichenologische Arbeitsgemeinschaft für Mitteleuropa e.V. (BLAM). They offer informative websites and events revolving around bryophytes on a regular basis. Events include basic identification courses, excursions and workshops and welcome all interested people which is a great way to share scientific knowledge and combine taxonomy and ecology. Another great

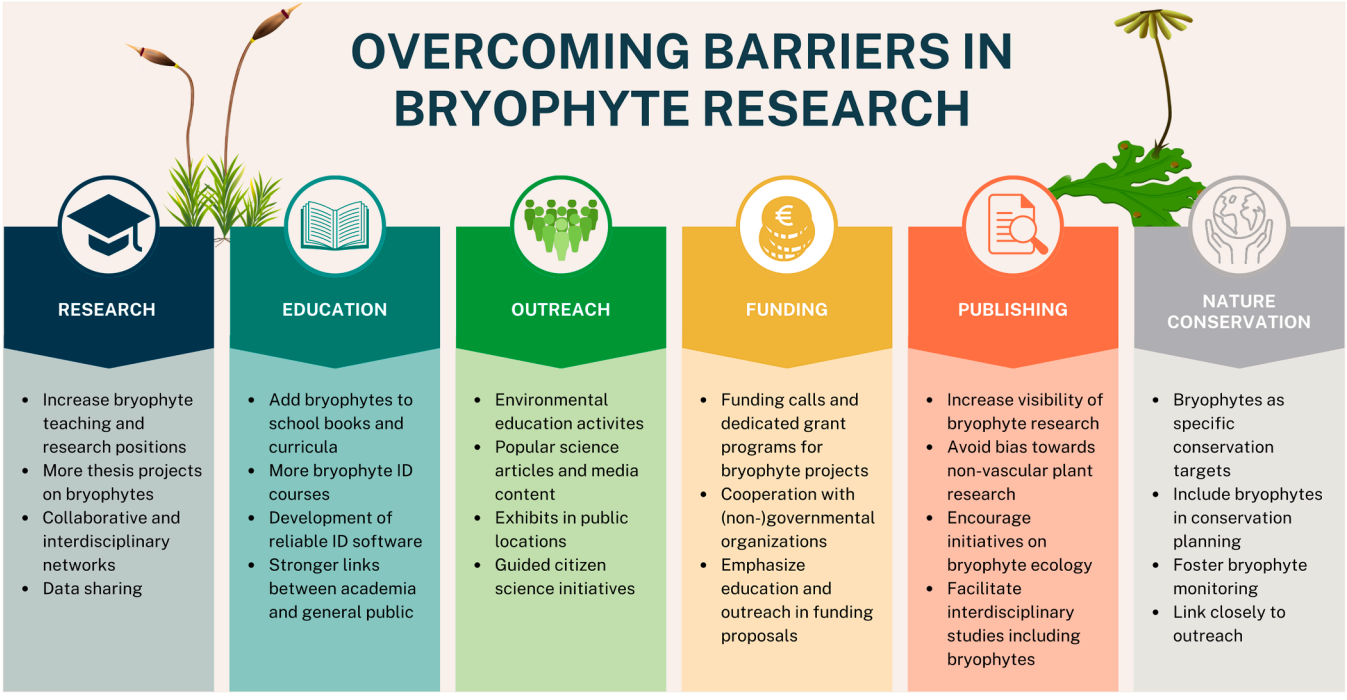

Fig. 2. Summary of the proposed ways to overcome the barriers that Early Career Researchers face when working on bryophyte research. We categorize our recommendations between different relevant parts of the scientific process, several institutions and levels in society. ID = Identification.

example is the annual bryology summer school by the Daugavpils University in Latvia where expert knowledge on bryophytes is shared with young researchers including both taxonomy and ecology. This is a good starting point but stronger links between academia and the general public through e.g., citizen science initiatives, would facilitate further outreach, education and data generation at the same time. Learning about bryophytes and their importance to ecosystems at an early age, and including them in school curricula and entry-level university courses, would help to raise awareness and interest in bryophyte research. Here, we as ECRs and scientific community can help as well by introducing biologically interested people in our social surroundings to the fascinating world of bryophytes, or offer excursions for e.g., schools and other educational institutions.

Outreach: Including bryophyte activities in environmental education activities would generate public awareness of this species group to a wide variety of audiences. These can include Open Door Days at universities and research centres, but also field activities and workshops. The latter are offered by some organisations such as the BBS or BLAM (see above) but often have small numbers of participants. To increase demand, popular science articles and multimedia content such as documentaries or social media campaigns can increase the outreach potential. The BBS and BLAM are already announcing a bryophyte of the month or year including species portraits on their websites which can be a first step to raise public awareness of these species but also of bryophytes in general. Exhibits that focus on bryophytes in botanical gardens, museums, or other public venues can also help raise awareness of the diversity and importance of bryophytes. We recommend that interested individuals and collectives extend and improve their social media presence to enhance their outreach potential. Additionally, guided citizen science initiatives help fill in data gaps and may increase public interest and outreach.

Identification software: Plenty of species identification apps are available for vascular plants, insects and birds. These contribute to the general public's understanding of nature but are also incredibly valuable for data collection and research. Bryophytes can be difficult to identify, but with the increasing capability of AI techniques, it is worthwhile to train such algorithms in bryophyte identification. In fact, some softwares are already working on implementing bryophyte identification into their algorithms in the near future (J. Wäldchen from FloraIncognita, pers. comm.). The validation process is still challenging because it requires well-trained taxonomists or at least good microscopic images of correctly identified species. A promising approach would be to work with databases that contain many photographs with reliable information about bryophyte species and their characteristics but also we as bryophyte community can help by annotating pictures where possible Currently, digitisation is on the rise, AI is advancing rapidly, and the increasing availability of geo-referencing will help software to narrow down the options and exclude certain species from the results. In addition, algorithms function in a manner distinct from that of human visual inspection. Therefore, we believe that it is likely possible to further develop these technologies in the near future, provided that there is sufficient interest, and that it would be well worth the effort.

Funding: With this paper, we want to raise awareness specifically to funding bodies and review panels on the importance of funding bryophyte research. One impressive example is the NSF-funded herbarium digitisation project "North American Lichens and Bryophytes: Sensitive Indicators of Environmental Quality and Change" which made several million records of lichens and bryophytes available online. For bryophyte specimens, the Consortium of Bryophyte Herbaria (see above) is a paragon of what additional funding in this area of research can achieve. Additional funding calls and dedicated grant programs for bryophyte projects (from local to international scales) would increase the amount of research and the diversity of researchers working on bryophytes. Funders can cooperate with (non-)governmental organizations and cofund bryophyte-focused initiatives. When evaluating funding proposals regarding bryophyte projects, the educational and public engagement can be emphasized to further increase the outreach.

Publishing: We encourage journal boards and editors to increase the visibility of bryophyte research, particularly at more generalist and high impact journals. Journals should ensure that their editors are not potentially biased towards non-vascular plant studies, and encourage initiatives such as advertising more special issues on bryophyte ecology. Publishers can facilitate the publication of interdisciplinary studies that integrate multiple fields of research to create a more holistic understanding of bryophytes. Perspective and opinion papers and invited reviews synthesizing the current state of bryophyte research should also be encouraged on a regular basis to highlight current gaps in knowledge that can help guide and motivate future research.

Conservation policies: Concrete conservation targets for bryophytes are essential to establish biodiversity baselines and to monitor species trends over time at national and international levels. A key step is to separate bryophyte species from vascular plants in monitoring efforts, in order to untangle their different life histories and patterns. Periodic assessments of extinction risk (i.e., through the IUCN Red List) will be key to identify threatened bryophyte species under global change. Bryophytes should feature more strongly in conservation planning and decision-making processes, which would underline their importance as bioindicators and for ecosystem services and functions.

In conclusion, the essential ecological roles of bryophytes should be reflected in research efforts. In this perspective, we hope to pave the way for discussions within the scientific community about research, funding, and teaching priorities, hopefully leading to concrete changes and an increase of future bryophyte research agendas. As ECRs, we commit to play our part via pursuing a bryophyte-focused research agenda, spreading awareness via outreach and education, setting and maintaining collaborative networks and links outside academia, making our data and publications open access where possible, and advocating for bryophyte representation from academia to conservation and policy. We call on other ECRs, and the wider ecological research community, to join us in this effort.

CRediT authorship contribution statement

Till J. Deilmann: Writing – review & editing, Writing – original draft, Visualization, Project administration, Formal analysis, Conceptualization. **Ditte Marie Christiansen:** Writing – review & editing, Writing – original draft, Conceptualization, Visualization. **Mariana García Criado:** Writing – review & editing, Writing – original draft, Conceptualization, Visualization. **Theresa Möller:** Writing – review & editing, Writing – original draft, Conceptualization, Visualization. **Maren Schüle:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Conceptualization. **Alexander Täuber:** Writing – review & editing, Writing – original draft, Conceptualization, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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