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Review

BRYOPHYTES AND ENVIRONMENTAL CHANGE: A REVIEW OF BIOINDICATOR APPLICATIONS

Andrea Sass-Gyarmati

Eszterházy Károly Catholic University, Institute of Biology, Department of Botany and Plant Physiology; Eger, Pf. 43, H-3301 Hungary;
E-mail: sass.gyarmati.andrea@uni-eszterhazy.hu

Abstract: The aim of this review is to summarize the role of bryophytes as bioindicators of environmental change, highlighting their main areas of application and future research directions. Bryophytes (Bryophyta, Marchantiophyta, Anthocerotophyta) represent one of the most ancient groups of terrestrial plants, which, despite their small size, play a significant ecological and indicator role. Due to their simple structure, they are directly affected by environmental impacts and are therefore sensitive to changes in the chemical composition of air, water, and soil. Research in recent decades has confirmed their usefulness in monitoring air pollution, water quality, the state of forest ecosystems, and the effects of climate change. A classic example is the elimination of sulphur dioxide-sensitive epiphytic bryophytes from industrial areas, while heavy metal accumulation studies have also revealed spatial and temporal changes in atmospheric deposition. Aquatic mosses are important components of many European and Mediterranean biomonitoring programs, while forest and deadwood species indicate the naturalness and structural condition of habitats. Changes in distribution observed as a result of climate change indicate that mosses may be potential predictors of future biodiversity trends.

Keywords: bryophytes, bioindication, environmental monitoring, air pollution, water quality, forest ecology, climate change

INTRODUCTION

Bryophytes (Bryophyta, Marchantiophyta, Anthocerotophyta) represent one of the most ancient groups of terrestrial plants. Despite their small size and simple structure, they perform extremely important ecological functions: they contribute to soil formation, regulate water balance, and provide microhabitats for other organisms (Schofield 1985; Glime 2017). In recent decades bryophytes have become the focus of research not only because of their ecological importance, but also because of their applicability in environmental and nature conservation, particularly through their use as bioindicators (Longton 1992). Bryophytes are outstanding in this role because their bodies lack a developed transport tissue, so they directly absorb water and nutrients from their environment (Glime 2017) through their whole surface. Due to this characteristic, they react quickly and sensitively to changes in the chemical composition of the air, water, and soil, making them excellent indicators of various environmental impacts. ryophytes have been widely used for air pollution monitoring since the mid-20th century. A classic example of this is the decline of sulfur dioxide-sensitive epiphytic bryophytes in the vicinity of industrialized cities, which served as one of the early biological indicators of air pollution (Wielgolaski 1975). Starting in the 1970s, regular biomonitoring programs were launched across Europe, using the accumulation of heavy metals in bryophytes to study atmospheric deposition (Harmens *et al.* 2010; Zechmeister *et al.* 2004). Bryophytes are an important indicator group not only for air pollution but also for water quality. Aquatic and semi-aquatic species, such as *Fontinalis* and *Hygrohypnum*, are sensitive to changes in water chemistry, particularly eutrophication and heavy metal loading (Ceschin *et al.* 2012). As a result, they are used in many European and Mediterranean watercourse monitoring programs alongside macroscopic aquatic plants. In forest ecosystems, mosses function as indicators of naturalness and structural condition. Species living on dead wood (epixyl mosses) are particularly sensitive to forest management interventions, and their absence can often be considered an indicator of secondary forests or intensively managed forest areas (Vellak and Paal 1999). Bryophyte diversity is related to forest structural diversity and microclimatic stability, so their presence indirectly indicates the ecological condition of forests (Rydin 1997). Bryophytes have also become increasingly important in studying ecological responses to global climate change as they are particularly sensitive to changes in temperature and precipitation, as well as to the drying out of habitats (Gignac 2001). Changes in distribution patterns can be documented for both high-altitude and lowland bryophyte species (Bergamini *et al.* 2001). For this reason, mosses can be potential predictors of global biodiversity changes. Overall, this group of plants are excellent indicators for studying air pollution, water quality, forest management impacts, and climate change. The aim of this review is to summarize their role as indicators based on the available literature, to present their main areas of application, and to evaluate their significance in terms of environmental monitoring and nature conservation.

General characteristics of bryophytes as bioindicators

The basis for the use of bryophytes as bioindicators consists in their specific morphological and physiological characteristics, which clearly distinguish them from higher vascular plants. The fact that they absorb water, air and nutrients through their whole surface and are able repeatedly dehydrate and rehydrate, being poikilohydric results in bryophytes ability to regulate water and ion balance directly dependent on environmental conditions (Marschall and Mészáros 1994; Proctor 2000; Badacsonyi and Tuba 2001; Glime 2017). This close connection between the atmosphere and their tissues places them in an unique position to rapidly accumulate and store air pollutants (e.g., SO_2, NO_2, heavy metals) (Wielgolaski 1975). The rhizoid system of bryophytes primarily serves an anchoring function and has limited role in water and nutrient uptake. As a result, nutrients and pollutants are predominantly derived from the air and precipitation. This characteristic provides bryophytes with an unique ability to investigate atmospheric deposition and water-derived pollutants (Markert *et al.* 2003). The gametophyte is the dominant phase in the life cycle of bryophytes, being photo-synthetically active and in close relationship with the environment. This property facilitates the direct response of morphological and physiological characteristics to environmental stress, such as air pollution, water shortage, or acid deposition (Vanderpoorten and Goffinet 2009). The high cation exchange capacity of the protonema and leaves allows the efficient binding of metal ions, which forms the basis of numerous biomonitoring programs (Harmens *et al.* 2010). Their response to environmental stress is fast and susceptible. Some species may disappear completely from polluted areas, while other, more tolerant species may become dominant, resulting in a marked change in species composition (Rao 1982). At the same time, cellular processes also respond rapidly: for example, a decrease in the amount of photosynthetic pigments, changes in membrane permeability, and an increase in the activity of stress-related antioxidant enzymes can be detected (Giordano *et al.* 2013). Based on the above, bryophytes can be considered a plant group of particular importance in terms of environmental indication. Their morphological simplicity, physiological sensitivity, and fast response to environmental changes all contribute to their application in a wide range of bioindication studies, from air pollution monitoring to soil and water quality assessment.

Indicators of air pollution

The best known and most researched area of mosses' bioindication role is the study of air pollution. Their unique morphological and physiological characteristics – such as the absence of a cuticle, direct water and ion uptake through the cell wall through their weak cuticle, relatively large surface, and the high cation exchange capacity of their storage tissues – make them extremely vulnerable to atmospheric pollution (Wielgolaski 1975; Vanderpoorten and Goffinet 2009). In the post industrial period, the massive increase in sulfur dioxide (SO_2) emissions was the primary factor contributing to air pollution, the effects of which were also evident in the distribution of bryophytes. In the mid-20th century, epiphytic mosses disappeared completely from many European cities (e.g., London, Essen, Krakow) because they were particularly sensitive to acid deposition and sulfur gases (Wielgolaski 1975; Rao 1982). However, with the reduction in air pollution – for example, in British towns and cities – an increase in diversity of brophytes has been observed since the 1970s, which clearly illustrates the practical significance of bioindication (Wielgolaski 1975). The effect of sulphur dioxide (SO_2) and acid deposition on bryophytes communities is one of the best documented examples of bioindication in practice. In the mid-20th century, high SO_2 levels around industrial sites led to a drastic change in bryophyte communities: direct uptake of sulphur dioxide by leaves and protonemas caused cell damage, chlorophyll degradation and increased membrane permeability, leading to the local extinction of many species (Rao 1982). At the same time some acidophylous species increased their distribution. Following the decline of the sensitive epiphyte species, only a few tolerant taxa, such as *Hypnum cupressiforme* and *Ceratodon purpureus*, remained. However, with the improving air quality, the reintroduction of bryophyte species has been observed in many sites, which is a clear bioindicator of the environmental recovery. Bryophytes also play a key role in the biomonitoring of heavy metal accumulation. Several studies have shown that *Pleurozium schreberi*, *Hypnum cupressiforme, Hylocomium splendens* and *Sphagnum* species are highly efficient in monitoring and quantifying heavy metals (e.g., Pb, Cd, Zn, Cu) from the air (Zechmeister *et al.* 2004; Harmens *et al.* 2010). Using the so-called "moss bag" method, pre-grown sterilised bryophytes are set out at several sampling sites, and pollutant accumulation is then measured, providing data that can be compared both in time and space (Markert *et al.* 2003). The nitrogen compounds – primarily NO_2 and ammonium deposits – have a different effect on the bryophyte communities than sulfur or metal pollution. In nitrogen-rich environments, certain nitrogen-rich species, such as *Ceratodon purpureus* and *Bryum argenteum*, have a marked benefit, while other species adapted to oligotrophic environments are suppressed (Giordano *et al.* 2013). Among the physiological responses associated with nitrogen deposition, an increase in chlorophyll content and a temporary increase in photosynthetic activity can be observed, but in the longer term, acidification and the upsetting of nutrient ratios have a negative impact on community diversity (Wielgolaski 1975). Specifically, near the agricultural areas where ammonium emissions are significant, the modification of the bryophyte flora is well-known and provides an important indication. Overall, the responses of bryophytes to air pollution can be evaluated on several levels: species-level disappearance or colonisation, community-level diversity changes, and cellular physiological and biochemical reactions all contribute to this group of plants being a key bioindicator tool in environmental protection and ecological monitoring.

Water and hydrological indicators

Aquatic and rheophytic bryophytes play an important role in assessing the ecological status of watercourses and lakes. Bryophytes respond directly to the chemical composition and ion concentration of water, as well as to streamflow conditions, and are therefore well adapted for use as bioindicators in water quality monitoring (Ceschin *et al.* 2012) or even to the changes of water level. The presence or absence of certain species in large numbers indicates the trophic status and pollutant content of the water (Kovács 1986; Papp and Rajczy 1998). The known aquatic moss is

Fontinalis antipyretica, which lives in streams and rivers that are pure, oxygen-rich and moderately fast-flowing. Its presence is often an indicator of good ecological condition, while its absence or decline indicates pollution, particularly an increase in organic matter and nutrient levels (eutrophication) (Ceschin *et al.* 2012). Another commonly used species is *Hygrohypnum luridum*, a moss that lives on rocks in watercourses and is constantly submerged, and is also sensitive to changes in water quality (Vitt and Glime 1984). Aquatic mosses are also particularly well suited for detecting heavy metal pollution. Several studies have shown that the tissues of *Fontinalis antipyretica*, *Amblystegium riparium* and *Rhynchostegium riparioides* effectively accumulate copper, cadmium, lead and zinc ions in their tissues, so these species can be used as living bioaccumulators to detect spatial and temporal changes in pollutants (Wehr and Whitton 1983a, b). Due to this property of aquatic mosses, they are widely used not only for 'passive biomonitoring' but also for 'active biomonitoring' (artificial placement). In several countries in Central Europe (e.g., Italy, Hungary, Czech Republic), aquatic mosses are among the official indicators used to assess the ecological status of watercourses and have been classified as official indicators for assessing the ecological status of watercourses (Ceschin *et al.* 2012). In the case of Mediterranean rivers, for example, they are particularly useful as they provide constant vegetation elements even during summer water level fluctuations, in contrast to the rapidly changing algae flora. Altogether, aquatic and semi-aquatic mosses are reliable indicators of water conditions because they reflect chemical and physical changes directly and form permanent and highly assessable communities that are well suited for long-term monitoring programmes.

Forest management and habitat change indicators

Bryophytes are important indicators of the natural and structural condition of forest habitats. They are sensitive to forest management activities such as logging, deadwood removal, and microclimate changes. The study of the composition and diversity of bryophytes is therefore an important tool for forest ecology research and nature conservation assessment (Vellak and Paal 1999; Rydin 1997).

Epixylous bryophytes, i.e. bryophytes living on decaying tree trunks, are particularly good indicators of the continuity of forest habitats. Species such as *Nowellia curvifolia, Riccardia palmata* and *Lophocolea heterophylla* often occur only in natural or old-growth forests with a high abundance of dead wood, while they are absent or rare in managed forests (Ódor and van Hees 2004). The quantity and quality of deadwood is hence a key component in maintaining the diversity of mosses, which implicitly indicates the natural state of the forest. A dense canopy and a stable microclimate are also essential for the survival of many shade-preferring bryophytes. Opening up the canopy, for example through excessive slashing or clear-cutting, significantly changes exposure to sunlight and temperature, which can lead to the decline of sensitive species. For example, *Bazzania trilobata* and several *Dicranum* species are absent from disturbed forests, while pioneer, disturbance-tolerant species such as *Ceratodon purpureus* or *Bryum capillare* are widespread (Vellak and Paal 1999). Differences in management practices are also clearly evident in populations of mosses. Studies in Hungary have shown that species richness and the proportion of specialist species are significantly higher in natural, undisturbed forests than in regularly managed stands (Ódor and Standovár 2001). Comparative studies conducted in boreal and Central European forests have also shown that the indicator role of bryophytes is one of the most reliable methods for assessing the conservation value of forest habitats (Rydin 1997).
Overall, bryophytes are sensitive indicators of the effects of forest management, as they directly reflect changes in microclimate, deadwood quantity and forest continuity. Their regular integration into forest monitoring programmes therefore contributes not only to biodiversity conservation but also to the long-term sustainability of forest management.

Soil and microclimate indication

The use of bryophytes as soil and microclimate indicators has long been known as their species composition is sensitive to the chemical and physical properties of the soil and to the subtle changes in environmental conditions. Due to their weak cuticle and direct water uptake, they are particularly sensitive to moisture, temperature and light conditions, thus can be used to provide information about soil moisture, temperature and light conditions. Soil humidity is one of the most determining factors. In dry habitats, like sand grasslands and karst shrub forests, pioneer xerophilous species are characteristic, including *Tortula ruralis*, *Syntrichia ruraliformis*, and *Grimmia pulvinata*, which can withstand longer periods of drought. In wetter, acidic forests and bogs, on the contrary, more water demanding species predominate, such as *Polytrichum commune* or *Mnium hornum* (Rydin and Jeglum 2013). The soil chemistry also plays a role in determining the composition of moss communities. Calciphilous species such as *Neckera crispa* or *Ctenidium molluscum* occur primarily on basic bedrock and soils with high Ca^{2+} content. On soils with acidic chemical properties, however, acidophilic species such as *Dicranum scoparium* or *Sphagnum* species dominate, which also play a role in reducing soil pH (Ellenberg *et al.* 1991; Gignac and Vitt 1994). The microclimate – especially humidity and light conditions – is also crucial for the presence of mosses. Shady, humid forest habitats with a relatively stable microclimate often harbour high species richness in bryophyte communities, including some species that are sensitive specialists, such as *Bazzania trilobata* or *Lepidozia reptans*. In marked contrast, open, sunny habitats are characterised by disturbance-tolerant, drought-tolerant species such as *Ceratodon purpureus* or *Bryum capillare* (During 1992). In order to systematise indicator values, several authors have attempted to incorporate bryophytes into the Ellenberg ecological indicator values, particularly with regard to moisture and nitrogen requirements (Ellenberg *et al.* 1991; Hill *et al.* 2006). These scales allow for the quantitative ecological assessment of bryophyte communities and are widely used in phytocenological and conservation studies. Overall, it can be said that the sensitivity of mosses to soil and microclimate factors makes them ideal for environmental diagnostic purposes. They are particularly useful in revealing hidden habitat changes that other plant groups are less reliable at indicating. Meantime they useful in the detection of changes in underlying habitats, which are less reliably indicated by other plant groups.

Indicators of urban environment and anthropogenic impacts

Urban environments provide specific ecological conditions for bryophytes. Due to human activity, microclimate, air chemistry and substrate availability change significantly in cities. The study of the distribution and communities of bryophyte species can therefore be an important tool for assessing the environmental status of urban ecosystems (Jiang *et al.* 2020; Zechmeister *et al.* 2004). The diversity of bryophytes is generally poorer in urban areas than in their natural habitats. This is due to ongoing disturbance, pollution and microclimatic extremes. Most of the epiphytic mosses are sensitive to air pollution, especially sulphur dioxide and nitrogen oxides, and are therefore often completely lacking in the inner areas of large cities. At the other extreme, nitrophilic and disturbance-tolerant species such as *Ceratodon purpureus*, *Bryum argenteum, Tortula muralis* and *Syntrichia ruralis* are particularly common along roadsides, in pavement clearings and on the tops of buildings (Wielgolaski 1975). The urban microclimate also has a strong influence on bryophyte communities. Due to the "urban heat island effect", central urban areas are warmer and drier than surrounding regions, which leads to an advantage for xerophilous pioneer bryophytes. In comparison, in parks and green spaces, where humidity is higher and there is a higher amount of natural substrate, a more diverse range of bryophyte communities can establish themselves, including more sensitive epiphyte species (Giordano *et al.* 2013). Indicators of heavy metal pollution in cities are also an important area of research. Numerous studies have shown that bryophytes inhabiting busy roadsides, such as *Grimmia pulvinata* and *Syntrichia ruralis*, accumulate significant amounts of lead, cadmium and zinc, which are good indicators of traffic-related air pollution (Giordano *et al.* 2013; Zechmeister *et al.* 2004). Urban species can thus be used for biomonitoring purposes, similar to species used in forest and rural environments. Overall, even in urban environments, bryophytes are important bioindicators: they reflect air pollution, changes in the microclimate, and anthropogenic changes in habitats. As the range of indicator species in cities is limited, the abundant pioneer bryophytes provide a significant source of data on the extent of pollution and disturbance, thus serving as important tools for urban ecological monitoring.

The importance of bryophytes in climate change monitoring

Bryophytes play an important role in studying the effects of climate change, as their species composition and distribution are very sensitive to changes in temperature, precipitation, and microclimate. Changes in populations of bryophytes in high-mountain and lowland habitats can be considered as early indicators of climate change (Gignac 2001; Tuba *et al*. 2011). In high-altitude ranges such as the Alps, Scandinavia and the Carpathians, increasing temperatures are leading to a decline in the distribution and population size of cold-adapted species, while species that prefer warmer conditions (e.g., *Brachythecium rutabulum*, *Hypnum cupressiforme*) are expanding (Bergamini *et al.* 2001). This shift affects not only individual species but also the composition of entire bryophyte communities, providing a valuable indicator of global climate change. In lowland habitats, rainfall distribution changes and longer dry periods have a similar effect on the communities of mosses. Reduced soil moisture and habitat drying result in the decline of water-demanding species, like *Sphagnum* species, while drought-tolerant pioneer species become predominant (Gignac and Vitt 1994). In the case of peat mosses, changes in water balance directly affect peat formation, thus serving as important indicators of the ecological impacts of climate change. The indication role of bryophytes in climate change research can complement traditional meteorological and habitat monitoring methods. In long-term studies, changes in the composition of species and population shifts provide reliable information about the temporal and spatial patterns of biological responses (Gignac 2001; Bergamini *et al.* 2001). In addition, bryophytes are cost-efficient and feasible bioindicators due to their small size and simple methods of sampling and analysis. Overall, bryophytes are not only useful for monitoring local environmental changes, but are also key to track the long-term effects of global climate change (Frahm and Klaus 2001) and anticipate the ecological consequences of climate change in depth (Tuba *et al.* 2011).

CONCLUSION

The study of bioindicator role of bryophytes clearly shows that these ancient plant groups can be sensitive and reliable indicators of numerous environmental changes. The paper reviewed the indications of air pollution, water quality, forest management, soil and microclimate, urban environment, and climate change, showing that changes in moss communities are directly related to changes in environmental factors. In the study of air pollution, the species composition, diversity, and heavy metal accumulation of mosses provide a reliable picture of spatial and temporal changes. In the case of aquatic and semi-aquatic species, the detection of chemical composition, nutrient load, and heavy metal pollution has become an effective tool for monitoring water quality. In forest habitats, the presence or absence of epixyl and shade-loving species serves as an indicator of naturalness, the amount of dead wood, and changes in the microclimate. Through soil and microclimate indication, mosses are suitable for detecting subtle local changes, such as changes in soil moisture, pH, and light conditions. In urban environments, mosses reflect the effects of air pollution, disturbance, and microclimate, while in the case of climate change, changes in species composition and distribution serve as indicators of global trends. In summary, the bioindicator value of bryophytes is valid on several levels and across a range of environmental factors. Their advantages include rapid and sensitive response, ease of sampling, and specific sensitivity to various ecological factors. At the same time, limiting factors include the difficulty of species identification and the complexity of multifactorial effects, which make clear environmental interpretation difficult. A promising direction for future research is the integration of molecular and genetic methods into traditional ecological studies, as well as the development of global monitoring networks. These will provide a more accurate picture of the long-term effects of biodiversity, environmental change, and climate change, confirming the role of bryophytes as bioindicators in nature conservation and ecological research.

REFERENCES

BADACSONYI, A. & TUBA, Z. (2001). A környezet állapotának jelzése mohákkal. *Botanikai Közlemények* **86**–**87**(1–2): 207–219.

BERGAMINI, A. & PEINTINGER, M., SCHMID, B. & URMI, E. (2001). Effects of management and altitude on bryophyte species diversity and composition in montane calcareous fens. *Flora* **196**: 180–193. https://doi.org/10.1016/S0367-2530(17)30040-3

CESCHIN, S., ALEFFI, M., BISCEGLIE, S., SAVO, V. & ZUCCARELLO, V. (2012). Aquatic Bryophytes as Ecological Indicators of the Water Quality Status in the Tiber River Basin (Italy). *Ecological Indicators* **14**: 74–81. https://doi.org/10.1016/j.ecolind.2011.08.020

DURING, H.J. (1992). *Ecological classification of bryophytes and lichens.* In: BATES, J.W. & FARMER, A.M. (eds): *Bryophytes and Lichens in Changing Environment*. Clarendon Press, Oxford, pp. 1–31. https://doi.org/10.1093/oso/9780198542919.003.0001

ELLENBERG, H., WEBER, H.E., DÜLL, R., WIRTH, V., WERNER, W. & PAULIßEN, D. (1991). Zeigerwerte von Pflanzen in Mitteleuropa. *Scripta Geobotanica* **18**: 1–248.

FRAHM, J.-P. & KLAUS, D. (2001). Bryophytes as Indicators of Recent Climate Fluctuations in Central Europe. *Lindbergia* **26**: 97–104. https://doi.org/10.2307/20150069

GIGNAC, D. (2001). Bryophytes as indicators of climate change. *The Bryologist* **104**(3): 410–420. https://doi.org/10.1639/0007-2745(2001)104[0410:BAIOCC]2.0.CO;2

GIGNAC, D. & VITT, D. (1994). Responses of Northern Peatlands to climate change: effects of bryophytes. *Journal Hattori Botanical Laboratory* **75**: 119–132. https://doi.org/10.18968/jhbl.75.0_119

GIORDANO, S., ADAMO, P., SPAGNUOLO, V., TRETIACH, M. & BARGAGLI, R. (2013). Accumulation of airborne trace elements in mosses, lichens and synthetic materials exposed at urban monitoring stations: Towards a harmonisation of the moss-bag technique. *Chemosphere* **90**(2): 292–299. https://doi.org/10.1016/j.chemosphere.2012.07.006

GLIME, J.M. (2017). *Bryophyte Ecology.* Vols. 1–5. Ebook, Michigan Technological University.

HARMENS, H., NORRIS, D.A., STEINNES, E., KUBIN, E., PIISPANEN, J., ALBER, R., ALEKSIAYENAK, Y., BLUM, O., COŞKUN, M., DAM, M., DE TEMMERMAN, L., FERNÁNDEZ, J.A., FROLOVA, M., FRONTASYEVA, M., GONZÁLEZ-MIQUEO, L., GRODZIŃSKA, K., JERAN, Z., KORZEKWA, S., KRMAR, M., KVIETKUS K, LEBLOND, S., LIIV, S., MAGNÚSSON, S.H., MANKOVSKÁ, B., PESCH, R., RÜHLING, A., SANTAMARIA, J.M., SCHRÖDER, W., SPIRIC, Z., SUCHARA, I., THÖNI, L., URUMOV, V., YURUKOVA, L. & ZECHMEISTER, H.G. (2010). Mosses as biomonitors of atmospheric heavy metal deposition: spatial patterns and temporal trends in Europe. *Environmental Pollution* **158**(10): 3144–3156. https://doi.org/10.1016/j.envpol.2010.06.039

HILL, M., BELL, N., BRUGGEMAN-NANNENGA, M., BRUGUES, M., CANO, M., ENROTH, J., FLATBERG, K., FRAHM, J.-P, GALLEGO, M., GARILLETI, R., MONTES, J., HEDENÄS, L., HOLYOAK, D., HYVÖNEN, J., IGNATOV, M., LARA, F., MAZIMPAKA, V., MUÑOZ, J. & SÖDERSTRÖM, L. (2006). An annotated checklist of the mosses of Europe and Macaronesia. *Journal of Bryology* **198**: 198–267. https://doi.org/10.1179/174328206X119998

JIANG, Y., ZHANG, X., HU, R., ZHAO, J., FAN, M., SHAABAN, M. & WU, Y. (2020). Urban Atmospheric Environment Quality Assessment by Naturally Growing Bryophytes in Central China. *International Journal of Environmental Research and Public Health* **17**(12): 4537. https://doi.org/10.3390/ijerph17124537

KOVÁCS, M. (1986). *A vizek terhelésének biológiai indikátorai.* In: KOVÁCS, M., PODANI, J., TUBA, Z. & TURCSÁNYI, G. (eds): *A környezetszennyezést jelző és mérő élőlények.* Mezőgazdasági Kiadó, Budapest, pp. 99–111.

LONGTON, R.E. (1992). *The role of bryophytes and lichens in terrestrial ecosystems.* In: BATES, J.W. & FARMER, A.M. (eds): *Bryophytes and Lichens in a Changing Environment.* Clarendon Press, Oxford, pp. 32–76. https://doi.org/10.1093/oso/9780198542919.003.0002

MARSCHALL, M. & MÉSZÁROS, I. (1994). Some data to the applicability of bryphytes as bioindicators. *Acta Biologica Debrecina-Supplementum Oecologica Hungarica* **5**: 245–254.

MARKERT, B., BREURE, A. & ZECHMEISTER, H. (2003). Bioindicators and Biomonitors: Principles, Concepts and Applications. *Trace Metals and Other Contaminants in the Environment* **6**: 15–25.

ÓDOR, P. & STANDOVÁR, T. (2001). Richness of bryophyte vegetation in near natural and managed beech stands: the effects of management-induced differences in dead wood. *Ecological Bulletins* **49**: 219–229.

ÓDOR, P. & VAN HEES, A.F.M. (2004). Preferences of dead wood inhabiting bryophytes for decay stage, log size and habitat types in Hungarian beech forests. *Journal of Bryology* **26**: 79–95. https://doi.org/10.1179/037366804225021038

PAPP, B. & RAJCZY, M. (1998). The role of bryophytesas bioindicators of water quality in the Danube. *Verhandlungen des Internationalen Verein Limnologie* **26**: 1254–1256.

PROCTOR, M.C.F. (2000). *Physiological ecology*. In: GOFFINET, B. & SHAW, A.J. (eds): *Bryophyte Biology*. Cambridge: Cambridge University Press, pp. 225–247.

RAO, D.N. (1982). *Responses of bryophytes to air pollution.* In: SMITH, A.J.E. (ed.): *Bryophyte Ecology.* Chapman & Hall, London, pp. 445–471.

RYDIN, H. (1997). Competition among Bryophytes. *Advances in Bryology* **6**: 135–168.

RYDIN, H. & JEGLUM, J.K. (2013). *The Biology of Peatlands* (2nd edn), Biology Of Habitats Series; Oxford Academic (online edition). https://doi.org/10.1093/acprof:osobl/9780199602995.001.0001

SCHOFIELD, W.B. (1985). *Introduction to Bryology.* Macmillan Publishing Co, New York, 431 pp.

TUBA, Z., SLACK, N.G. & STARK, L.R. (eds) (2011). *Bryophyte Ecology and Climate Change.* Cambridge University Press, Cambridge, 506 pp. https://doi.org/10.1017/CBO9780511779701

VANDERPOORTEN, A. & GOFFINET, B. (2009). *Introduction to Bryophytes*. Cambridge University Press, 303 pp. https://doi.org/10.1017/CBO9780511626838

VELLAK, K. & PAAL, J. (1999). Diversity of bryophyte vegetation in some forest types in Estonia: a comparison of old unmanaged and managed forests. *Biodiversity & Conservation* **8**: 1595–1620. https://doi.org/10.1023/A:1008927501623

VITT, D.H. & GLIME, J.M. (1984). The structural adaptations of aquatic Musci. *Lindbergia* **10**: 95–110.

ZECHMEISTER, H.G., RISS, A. & HANUS-ILLNAR, A. (2004). Biomonitoring of Atmospheric Heavy Metal Deposition by Mosses in the Vicinity of Industrial Sites. *Journal of Atmospheric Chemistry* **49**: 461–477. https://doi.org/10.1007/s10874-004-1260-5

WEHR, J. & WHITTON, B. (1983a). Accumulation of heavy metals by aquatic mosses. 2: *Rhynchostegium riparioides*. *Hydrobiologia* **100**: 261–284. https://doi.org/10.1007/BF00027433

WEHR, J. & WHITTON, B. (1983b). Accumulation of heavy metals by aquatic mosses. 3: Seasonal changes. *Hydrobiologia* **100**: 285–291. https://doi.org/10.1007/BF00027434.

WIELGOLASKI, F.E. (1975). Biological indicators on pollution. *Urban Ecology* **1**(1): 63–79. https://doi.org/10.1016/0304-4009(75)90005-4

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