1 ABSTRACT

The paper provides the first comprehensive, region-wide assessment of mosses, evaluated according to IUCN's Guidelines for Application of IUCN Red List Criteria at Regional Level. The IUCN Red List criteria were applied to 961 Italian moss taxa to assess their current extinction risk and to highlight the major threats affecting the Italian moss flora. Overall, 246 moss taxa assessed in this study are assigned to a risk category and, therefore, considered threatened in Italy, with a percentage of 28.6%. One species is considered Regionally Extinct and 15 species Possibly Extinct at regional level. A further 5.8% are categorized as Near Threatened, 10.6% as Data Deficient and 56.0% as Least Concern. Most threats are co-occurring, indicating that many taxa are subjected to a set of correlated adverse processes. The main IUCN major threats identified were Climate Change and Natural System Modifications (mostly dams and water management and use). Considering the overall Italian bryophyte flora, 330 taxa (246 mosses, 83 liverworts, and 1 hornwort) are considered threatened with extinction at Italian level (29.0% mid-point value), five species are classified as RE and 18 as CR(PE); moreover, 84 taxa are NT (6.6%) and 130 are considered as DD (10.3%).

Introduction

Red Lists, drawn up following the IUCN guidelines, are a powerful tool in the field of conservation biology, providing useful information on the species towards which protection measures should be addressed as a priority. They give a picture of the state of biodiversity health of territories, also allowing it to be monitored over time. Red lists categorize species into different levels of risk, from Least Concern to Critically Endangered, giving a standardized and internationally recognized information on the extinction risk of species.

By highlighting species that are at a extinction higher risk, Red Lists can be used by researchers, as well as policymakers (governments and environmental organizations), to guide efforts to protect and conserve biodiversity on a global, as well as regional scale, and to develop policies and egislation related to biodiversity conservation (Rodrigues et al. 2006).

Bryophytes are the second largest group of embryophytes or land plants made up of three ineages, i.e. hornworts, liverworts and mosses. Bryophytes are of great interest due to their role in the floristic composition, vegetation structure and ecosystem functioning of different ecosystems (Hallingbäck and Hodgetts 2000). They play essential roles in nutrient cycling, soil stabilization, and microhabitat creation, underscoring their importance in sustaining ecosystems. Bryophytes are particularly sensitive to habitat changes and are easily affected by pollution and habitat estruction; therefore, they are subject to threats, from habitat degradation to climate change.

Italy, with its great variety of landscapes, hosts one of the richest bryophyte floras in Europe, represented by 1273 taxa (1220 species, 17 subspecies and 36 varieties), with liverworts and hornworts represented by 301 species, 5 subspecies, and 4 varieties, and mosses by 919 species, 12 subspecies, and 32 varieties (Aleffi et al. 2024).

The first and so far, only complete Italian Red List of bryophytes was published in 1992 (Cortini Pedrotti and Aleffi 1992), based on the first IUCN categories drawn up in 1978. The implementation in Italy of the new categories and criteria IUCN (2001) led to a new red listing phase of the Italian bryophytes with the publication of several papers regarding the conservation status assessment only of some species (e.g. Aleffi 2008; Aleffi and Cogoni 2008; Campisi et al. 2008; Privitera and Puglisi 2008; Aleffi and Privitera 2011; Aleffi and Tacchi 2011; Miserere 2011a, 2011b; Puglisi and Privitera 2011a, 2011b; Cogoni 2012; Rossi et al. 2013). Therefore, the working group for Bryology of the Italian Botanical Society decided to organize a working team to draw up the new Red List of the Italian bryophytes according to the most recent IUCN criteria. The first goal has been achieved and the Red

List of the liverworts and hornworts has recently been published (Puglisi et al. 2023). In this paper we present the second phase of the project, with the assessment of all mosses of Italy, thereby completing the Red List of the bryophytes of Italy. Therefore, these two Red Lists represent the first comprehensive, updated, region-wide assessment of bryophytes of Italy, highlighting species that are at the greatest risk of extinction, to promote their protection in Italian conservation policies.

Material and methods

The investigation area, with a total extension of 302,068.26 km2, corresponds to the entire Italian territory and includes the Republic of San Marino and the Vatican City State, the same as that of the recent Italian Red List of liverworts and hornworts (Puglisi et al. 2023).

All specific and infraspecific taxa reported for Italy (Aleffi et al. 2024) were assessed. The conservation status of the selected taxa was assessed according to the Criteria and Categories of IUCN (2012a, 2012b, 2022a), and considering the guidelines for bryophytes (Hallingbäck et al. 1998; Hodgetts et al. 2019). According to the IUCN (2022a), nine categories were used: RE (Regional Extinct), CR (PE) (Critically Endangered Possibly Extinct), CR (Critically Endangered), EN (Endangered), VU (Vulnerable), NT (Near Threatened), DD (Data Deficient), LC (Least Concern), and NA (Not Applicable). In particular, when information about the status of a species is so uncertain that both Critically Endangered (CR) and Least Concern (LC) can represent plausible categories Data Deficient (DD) was assigned (IUCN (2022). Moreover, we follow the Guidelines for Reporting on Proportion Threatened (IUCN 2022b), concerning the uncertainty that Data Deficient species introduce to estimates of proportions of species threatened, since that for these species (DD) insufficient information is currently available to assess their risk of extinction. Therefore, for the proportion of threatened species in Italy we report the mid-point [(CR + EN + VU)/(Assessed-Ex-DD)], corresponding to the best estimate of extinction risk. The assessments were mostly based on criterion B, since in Italy, as well as in other European countries, data on the bryophyte population trend, useful for the application of criteria A and C, are very scarce.

For all assessments, the following information was collected: updated taxonomic status of taxa; distribution data in Italy, from published and unpublished data, herbarium specimens, and recent field surveys of the authors; habitat and ecological requirements of taxa from Dierßen (2001) and Hodgetts et al. (2019); threat category in neighbouring countries and in Europe from Hodgetts and Lockhart (2020) and personal data of the authors; actual and potential threats from Hodgetts et al. (2019) and personal data of the authors; incidence of old reports not recently confirmed; conservation measures. Distribution data were used for calculating EOO and AOO, obtained through the software “GeoCAT” (Geospatial Conservation Assessment Tool), (Bachman et al. 2011) with the grid for the calculation of AOO of 4 km2 (2 × 2 km). Like for the recently published Red List of liverworts and hornworts (Puglisi et al. 2023), the present work was coordinated by the directive council of the Working Group for Bryology of the Italian Botanical Society that promoted several workshops for a preliminary approach to the methodology applied to the bryophytes, and for gathering of distribution data. The resulting finalised IUCN Red List assessments are a product of scientific consensus concerning species status and are supported by relevant literature and data sources. The main threats at local level were identified by means of expert-based observations and available literature and were reported according to the IUCN threats classification scheme (IUCN 2012c).

In applying the IUCN criteria, 1968 has been chosen as the cut-off date to represent the threshold between old and recent records for the purpose of assessing decline (Puglisi et al. 2023). A taxon was considered Regionally Extinct (RE) when it was not recorded in the last 50 years, and whenrecent field surveys focused on finding the taxon in its historical area of occurrence were

unsuccessful. A taxon was categorized as Critically Endangered – Possibly Extinct [CR(PE)] when it was not recorded during the previous 50 years, indicating species that are highly likely to be extinct but for which uncertainty regarding extinction remained. The nomenclature and taxonomy follow Aleffi et al. (2024).

Results and discussion

Overall, 961 specific and infraspecific taxa were evaluated, corresponding to all mosses up to now known in Italy (Table 1). The distribution of these species across IUCN categories is shown in Figure 1. Three species were placed in NA (Not Applicable), considered to be neophytes and introduced in Italy; they are: Campylopus introflexus (Hedw.) Brid., Hypopterygium tamarisci (Sw.) Brid. ex Müll.Hal., and Sematophyllum adnatum (Michx.) E.Britton. One species was indicated as RE, i.e. Helicodontium capillare (Hedw.) A.Jaeger; it was reported from a single recordfor the Apuan Alps in Italy in the late 1860s and it was not found in Europe since. This species is assessed as RE since extensivesearches have been conducted in the area recently and the species could not be found. Moreover, 15 species (1.7%) were classified as CR(PE). 36 species, (3.7%) are CR, 106 species (11.0%) are EN, and 104 species (10.8%) are VU. A further 56 species (5.8%) are classified as NT. A relatively large group (102 species, 10.6%) is represented by species of the DD category. For the last ones, available data reflect their insufficiently known distribution and endangerment and do not allow a reliable assessment. Finally, 538 species (56.0%) are assessed as (LC). At the Italian level, considering the mid-point value, that provides the best estimation of the proportion of threatened species (IUCN 2022b), 28.6% of moss species are considered threatened (i.e. assessed as having an elevated risk of extinction). However, the proportion of threatened species is uncertain given the number of DD species and could lie between 25.6% (lower bound), if all DD species are not threatened, and 36.2% (upper bound), if all DD species are threatened for Italy.
In Europe, there are currently 1327 moss species, with best estimate of threatened taxa of 22.5% (Hodgetts et al. 2019). Of the 246 taxa considered threatened in Italy, 69 are threatened and 26 near threatened also at the European level (Hodgetts et al. 2019); in particular, seven taxa are assessed as CR, 22 as EN, and 40 as VU. Moreover, 10 taxa are considered as DD in Europe. The remaining 137 taxa are considered LC or NE (13 taxa) at the European level. Conversely, only four taxa considered threatened in Europe are assessed as LC in the Italian territory (Table 1).

Table 1. Red List status and assessment criteria of the Italian mosses. (Annexed)

Most species categorized in Italy as CR(PE) are considered threatened or near threatened also in Europe, with the exception of *Dicranum fragilifolium* Lindb., *D. groenlandicum* Brid., *Ptychomitrium nigrescens* (Kunze) Wijk & Margad. and *Timmia megapolitana* Hedw., that are still present in other European countries and are considered LC at European level; one species is considered DD (*Acaulon piligerum* (De Not.) Limpr.).
As regards the distribution of the threatened taxa in Italy, it is possible to observe the highest incidence of taxa in the alpine regions (Val d'Aosta, Piemonte, Lombardia, Trentino Alto Adige, Veneto and Friuli Venezia Giulia) with values ranging from 11.7% to 20.7%. These data confirm the impact of climate change on the montane flora, and pressure from land use change and tourist developments in the mountain areas. Moreover, many montane species are naturally rare and therefore more susceptible to disappearance. Significant percentages of threatened taxa are also found for Sicily (13.1%) and Sardinia (11.2%) where threatened species occur not only on the mountains but also along the coastal areas (Puglisi et al. 2015), the latter impacted by climate change and human settlements.

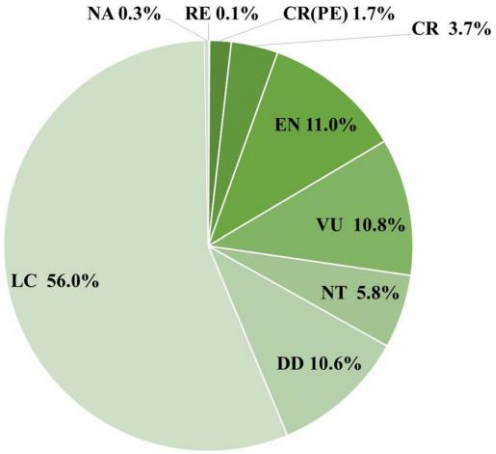

Figure 1. Incidence of Red List categories in the Italian moss flora.

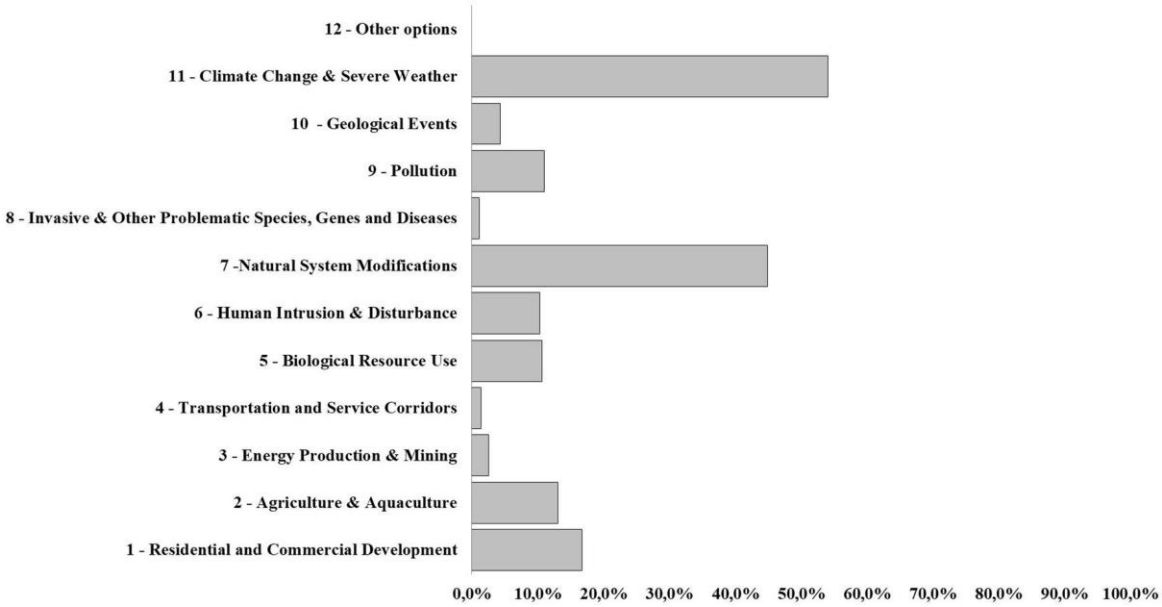

Figure 2. Incidence on the Italian moss flora of the major threat category according to the IUCN threats classification scheme (version 3.2).

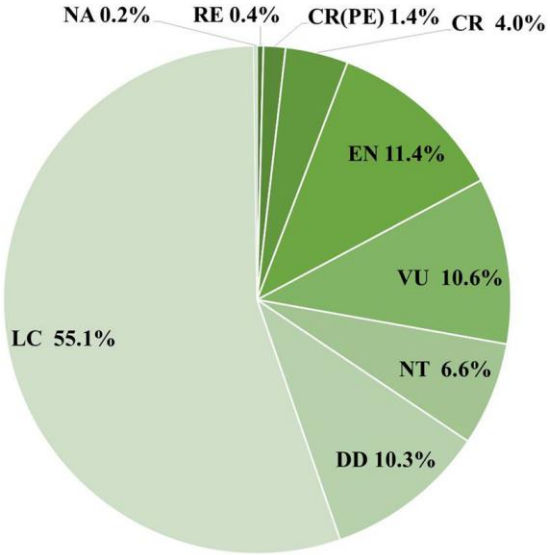

Figure 3. Incidence of Red List categories in the Italian bryophyte flora.

IUCN major threats

In total, it was possible to identify threats for 283 species, in most cases with multiple threats listed for a species. The main threat to the Italian moss flora is represented by "Climate Change and Severe Weather" with 153 taxa (corresponding to 54.1%) affected by this driver of decline (Figure 2). Ninety-eight taxa are impacted by "Habitat Shifting and Alteration", 49 taxa by "Droughts", and 43 taxa by "Temperature extremes". Many species threatened by climate change live in wetlands. These areas, already reduced due to land-use changes (e.g. intensive agricultural practices), drainage, pollution, are further under extra pressure from desiccation caused by climate change. Species that are found at high elevations are probably significantly more susceptible to the impacts of climate change than other species, as they have nowhere else to go if temperatures increase significantly. Mosses of southern Italy and Sicily, territories already affected by increasing aridity with desertification risk (Salvia et al. 2019), are subjected to higher risk of extinction if the climate becomes warmer and drier; they are, for example, *Acaulon fontiquerianum*, *A. triquetrum*, *Crossidium aberrans*, *C. geheebii*, *C. laxefilamentosum*, *Gigaspermum mouretii*, *Pterygoneurum subsessile*. Although many species show strategies for avoiding or tolerating drought (xero-pottioid life syndrome), they will not be able to survive in conditions of more extreme desertification.

"Natural system modifications" ranked second in the list of threats to Italian mosses, with 127 taxa (44.9%) impacted by this driver of decline. Most species (58) are affected by dams and water management and use. This threat, including changing water flow patterns from their natural range of variation, focuses on human activities that lead to either not enough water or too much water in the ecosystem. Water-dependent species growing in wetlands (bogs, marshes, swamps, fens, springs, peatlands) are subjected to the greatest impact from these threats, e.g. *Meesia triquetra* (L. ex Jolycl.) Ångstr., *Hygrohypnum styriacum* (Limpr.) Broth., *Hydrogonium bolleanum* (Müll.Hal.) A. Jaeger, *Sphagnum* sp. pl. Bogs and fens are among the most threatened habitats in Europe (Janssen et al. 2016), and so are the bryophytes living in these habitats.

A total of 47 taxa (16.7%) are affected by the threat "Residential and Commercial Development", and in particular by Tourism and Recreation Areas (37 taxa). Taxa occurring in coastal habitats, e.g. *Acaulon mediterraneum* Limpr., *Aschisma carniolicum* (F.Weber & D.Mohr) Lindb, *Calymperes erosum* Müll.Hal., *Crossidium geheebii* (Broth.) Broth., *Crossidium laxefilamentosum* W.Frey & Kürschner, *Pseudocrossidium replicatum* (Taylor) R.H.Zander resulted more subject to tourism development and disturbance.

Thirty-seven taxa (13.1%) %) are affected by "Agriculture and Aquaculture", with most of them by "Wood and Pulp Plantations" (14) and by "Livestock Farming & Ranching" (19). These are threats deriving from farming and ranching as a result of agricultural expansion and intensification. Most plantations are on areas previously occupied by natural or semi-natural forests, so the main species threatened by the conversion of natural forest to plantation woodland are those dependent on the long ecological continuity provided by a stable, humid, natural forest. Specialists of dead wood, such as *Buxbaumia viridis* (Moug. ex Lam. & DC.) Brid. ex Moug. & Nestl., have been particularly impacted, as amounts of deadwood are often very low in managed forests.

Thirty-one taxa (11.0%) are impacted by "Pollution" essentially due to agricultural and silvicultural systems, and air-borne pollutants, 30 taxa (10.7%) by "Biological Resource Use" %), mostly logging & wood harvesting, 29 taxa (10.3%) by "Human Intrusion and Disturbance", essentially due to recreational activities, e.g. mountain bikes, hikers, off-road vehicles, etc.

The threat "Geological Events", and in particular Volcanoes, deserves a special mention: 12 species (4.3%) are threatened by volcanic activities. Most of the species affected by this threat are found on the volcano Etna (eastern Sicily), the highest active volcano of Europe and one of the

world's most active volcanoes (Puglisi and Sciandrello 2023). The continuous eruptions and emissions of ash and lapilli have increased significantly in recent years, putting at serious risk the species living in the highest sites, including some of the rarest Italian bryophytes, e.g. *Grimmia alpestris* (F.Weber & D.Mohr) Schleich., *G. fuscolutea* Hook., *Mielichhoferia elongata* (Hoppe & Hornsch. ex Hook.) Hornsch., *M. mielichhoferiana* (Funck) Loeske. Moreover, other species, such as *Calymperes erosum*, *Isopterygium tenerum*, *Rhynchostegium strongylense* and *Trematodon longicollis* at present grow in Italy exclusively around the inner mouth of the fumaroles of the islands of Ischia and Pantelleria; these islands have active volcanoes, and a volcanic eruption could destroy the fumaroles with a remarkable impact on the survival of these species.
Finally, Energy Production & Mining (2.5%), Transportation & Service Corridors (1.4%), and Invasive species (1.1%) currently represent minor threats.

Conclusion

Bryophytes perform many ecological functions, such as water-retention capacity, particularly in forests, soil-building, being efficient colonisers and stabilisers of bare substrates (e.g. cooling lava flows); they provide habitats for other organisms, seed-beds for vascular plants, shelter and food for invertebrates (small animals). Moreover, they are excellent indicators of air pollution. Nevertheless, bryophytes are vulnerable plants, and many species are threatened at global and continental scales (Vanderpoorten and Hallingbäck 2009; Hodgetts et al. 2019). In the last decades, interest in evaluating the extinction risk and conservation status of bryophytes has led to the elaboration of Red Lists, which are resource of information essential to guide conservation efforts focused on species.
After recently publishing the red list of liverworts and hornworts of Italy, in this paper we have assessed the moss flora of Italy with the aim of highlighting the most endangered species and identifying priorities for conservation. Considering the mid-point value, that provides the best estimation of the proportion of threatened species (IUCN 2022b), 27.2% of moss species are considered threatened. Further 5.8% and 10.5% of the moss taxa are assigned to NT and DD categories, respectively. The last category includes taxa with an insufficiently known distribution, and taxa with many historical localities and have not been sufficiently searched. Although the species under NT and DD are not strictly considered threatened, as the term is applied by the IUCN, these categories indicate that these species deserve special attention.
A comparison with the liverworts and hornworts shows that the latter include a slightly higher percentage of threatened species (mid-point value: 30.8%), as well as a higher incidence of NT species (9.8%) and the same amount of DD species (10.8%).
The Italian bryophyte flora, consisting of 1267 taxa (961 mosses, 300 liverworts and 6 hornworts), was assessed according to IUCN Criteria and Categories. Overall, 330 taxa (246 mosses, 83 liverworts, and 1 hornwort) are considered threatened with extinction at Italian level, categorized as CR (51 taxa, 4.0%), EN (144 taxa, 11.4%), and VU (135 taxa 10.6%); five species are classified as RE and 18 as CR (PE) (Figure 3). Moreover, 84 taxa are NT (6.6%) and 130 are considered as DD (10.3%). The high amount of DD species is due to lack of appropriate data and information required to justify the criteria used for categorizing. Taking into account the mid-point value, 29.0% of the Italian bryophytes are considered threatened, i.e. assessed as having an elevated risk of extinction, with a lower bound corresponding to 26.0% and upper bound of 36.3%; the NT taxa are 86 (6.9%) and the DD are 136 (10.9%). The incidence of the threatened Italian species is higher if compared to Europe (22.5%, Hodgetts et al. 2019), or other European countries, e.g. Britain (19.0%), Spain (24%), or Portugal (27.2%), (Sérgio et al. 2012; Brugués and González Mancebo 2014; Callaghan 2023). Also, the incidence of the bryophytes considered DD in Italy is higher than

Europe (5.3%) and other countries, e.g. Britain (4.1%), Spain (7.9%). This suggests a lack of distribution data, limited information on threats, and/or significant gaps in taxonomic knowledge for many taxa. Moreover, the occurrence of 18 taxa was not observed in recent times (15 mosses and 3 liverworts), so that they were assessed as CR(PE). Consequently, further field investigations, as well as taxonomic revision of herbarium specimens of the Italian bryophyte flora should be undertaken to fill these gaps, with special regard to least known areas and critical groups of species.

The analysis of threats affecting bryophytes reveals that climate change (56.7%) and natural system modifications (50.9%), due to direct and/or indirect human disturbances, are the main drivers of extinction risk for the bryophyte flora of Italy. Bryophytes are extremely sensitive to changes in environmental temperature and, principally, precipitation rates; for this reason, they are regarded as signallers of climate change showing changes in distribution areas (Frahm and Klaus 2001; Sérgio et al. 2014; Zanatta et al. 2020). Most liverworts are restricted to moist and sheltered habitats, e.g. bogs, fens, and flushes. These wetlands, strongly reduced by land-use changes, are also impacted by droughts due to climate change; consequently, many of the taxa most likely to be threatened by climate change are those confined to wetlands. Moreover, many mosses, living in the highest parts of the mountains especially in the Alpine regions, are also particularly susceptible to the impacts of climate change regarding the increase in temperature; this confirms the important and strategic role of the mountains for the conservation of bryophyte diversity (e.g. Puglisi 2009; Puglisi et al. 2011, 2012, 2013, 2014).

By making a comparison with the previous bryophyte Red List (Cortini Pedrotti and Aleffi 1992), based on the first IUCN categories drawn up in 1978, some considerations can be drawn. That paper listed 473 bryophytes (128 liverworts and 345 mosses) considered at risk in Italy, out of a total of 1,091 bryophytes, representing 43.4% of the Italian bryophyte flora. Their degree of threat was reported according to four categories codified by IUCN: “Ex” (extinct), “E” (endangered), “V” (vulnerable), “R” (rare). Overall, 194 bryophytes were considered as Ex (60 liverworts, 134 mosses), 210 as E (37 liverworts, 173 mosses), 20 as V (6 liverworts, 14 mosses), and 49 as R (25 liverworts, 24 mosses). Even if it is not possible to make an appropriate comparison, due to changes in IUCN approach, we can outline some considerations. Over the last thirty years, that separate the two Red Lists, the species considered to be extinct in Italy (i.e. no longer collected from 1950 onwards) have drastically decreased, reflecting a significant increase in bryological knowledge. In particular, the intensification of field works allowed the rediscovery of several rare species, which led to a new assessment of the risk category, as has just occurred for *Asterella africana* (Mont.) Underw. ex A. Evans (Puglisi et al. 2024). Much has been done but much still needs to be done.

In conclusion, it is known that Red Lists represent powerful tools to inform and catalyse action for biodiversity conservation, providing information about range, population size, habitat and ecology, and threats, from local to global scales. In this context, the results of this study represent a scientific basis to promote bryophyte conservation in Italy, that need to be integrated into regular planning and land management procedures and practices. Furthermore, this Red List can serve in the future as a reference for monitoring over time the conservation status of the Italian bryophyte flora and directing research in order to improve knowledge on species distribution and population consistency.

Acknowledgments

The Authors thank Fiaschi Tiberio and Pandeli Giulio for have given their contribution to the assessment of some taxa.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was financially supported by the research programme (PIA. CE.RI. 2020-2022 Line 2, cod. 22722132149) funded by the University of Catania.

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