

## RESEARCH ARTICLE

### Biodiversity Conservation

# A holistic conservation approach for threatened filmy and grammitid ferns of Sri Lanka

PGSA Kumarasinghe<sup>1</sup>, RHG Ranil<sup>2\*</sup>, RMSR Chamara<sup>3</sup>, UGTN Janaranjana<sup>4</sup>, GMWL Gunawardena<sup>5</sup>, and B Parris<sup>6</sup>

<sup>1</sup> School of Natural Science, University of Chester, CHI 4BJ, United Kingdom.

<sup>2</sup> Department of Crop Science, Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka.

<sup>3</sup> Department of Plantation Management, Faculty of Agriculture and Plantation Management, Wayamba University of Sri Lanka, Makandura, Gonawila, Sri Lanka.

<sup>4</sup> Postgraduate Institute of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka.

<sup>5</sup> Typhoon Science and Technology Research Center, Yokohama National University, 79-1 Tokiwadai, Hodogaya Ward, Yokohama, Kanagawa, Japan.

<sup>6</sup> Fern Research Foundation, 21 James Kemp Place, Kerikeri, Bay of Islands, 0230, New Zealand.

Submitted: 03 January 2025; Revised: 28 September 2025; Accepted: 30 January 2026

**Abstract:** Isolated tropical islands support unique biodiversity and high endemism but face high extinction risks for some plant species due to small, fragmented populations and increasing anthropogenic pressures. Sri Lanka, a continental island in the Western Ghats–Sri Lanka biodiversity hotspot, hosts remarkable pteridophyte flora, including two highly threatened groups: the filmy ferns (Hymenophyllaceae) and grammitid ferns (Grammitidoideae). Owing to their narrow ecological niches and dependence on humid, shaded microhabitats, these taxa are highly sensitive to microclimatic shifts and habitat disturbance. This study proposes a holistic conservation approach to safeguard these fern groups by integrating historical and contemporary data, herbarium records, geospatial analyses, hotspot identification, and expert knowledge. Using 752 herbarium specimens from 22 global herbaria, together with recent field collections, we mapped species distributions, examined temporal collection patterns, and identified priority regions and climatic envelopes essential for their survival. Results reveal that high-elevation and southwestern wet-zone forests are key hotspots. Additionally, the analysis identified three hotspots for grammitid ferns and two for filmy ferns. The study outlines a roadmap incorporating species prioritization, targeted field surveys, microhabitat restoration, *in situ* conservation, *ex situ* propagation via high-tech greenhouses, community engagement, and collaborative research. Emphasis is placed on strengthening national herbarium resources,

integrating citizen science, applying genomic tools, and aligning conservation actions with global frameworks. This holistic, multidisciplinary strategy provides a comprehensive foundation for conserving Sri Lanka's threatened filmy and grammitid ferns and offers a model applicable to other island flora worldwide.

**Keywords:** Conservation, grammitidoideae, hymenophyllaceae, island populations, threatened species.

## INTRODUCTION

Isolated islands are characterized by rich biological diversity and high endemism, but the unique biodiversity of many islands is experiencing higher extinction rates than that of mainland populations (Frankham, 1997; Woinarski, 2010; Ronsted et al., 2022). Hamabata et al. (2019) claimed that endangered island endemic plants have vulnerable genomes and face a higher extinction risk than non-endangered species. Also, global change agents often have a greater impact on the dynamics of island ecosystems (Oro et al., 2022). The small and isolated populations of many island taxa are particularly vulnerable to human activities (Nogué et al., 2017), and

\* Corresponding author (rrajapaksha@agri.pdn.ac.lk; <https://orcid.org/0000-0003-2880-5428>)



This article is published under the Creative Commons CC-BY-ND License (<http://creativecommons.org/licenses/by-nd/4.0/>). This license permits use, distribution and reproduction, commercial and non-commercial, provided that the original work is properly cited and is not changed in anyway.

the rapid increase in natural resource exploitation on tropical islands, often pursued to address rural poverty and stimulate economic growth, has already driven numerous species to extinction or to an endangered status, a trend that is further intensified by the impacts of climate change (Jaisankar et al., 2018). Therefore, island populations demand greater conservation priority compared to mainland populations.

Sri Lanka is a tropical continental island characterized by rich floristic diversity and high endemism, primarily due to its long-term isolation from mainland India and its unique climate, soils, and geography (Gunatilleke et al., 2008; Pethiyagoda & Sudasinghe, 2017). Despite the collective importance of the Western Ghats–Sri Lanka biodiversity hotspot, the island of Sri Lanka has distinct and exceptional biodiversity that differs from the Ghats and southern India (Sarathchandra et al., 2021). Pteridophytes are a vital component of biodiversity and have great potential as ecological indicators due to the correlation between their geographic distribution and abiotic variables (Della, 2022). Sri Lanka is home to 389 pteridophyte taxa with 42 endemic species, which is a considerable number compared to the size of the island (Ranil et al., 2022). According to the National Red List 2020, 25 species of 350 native pteridophyte taxa are classified as critically endangered (possibly extinct), including four endemics. Additionally, 207 taxa (59%) are considered threatened, and 16 are listed as data deficient. Of particular concern is that 28 out of 42 Sri Lankan endemic taxa (67%) have been classified as threatened, highlighting the urgent need for conservation efforts.

From a conservation point of view, Sri Lankan ferns, specifically filmy and grammitid ferns, hold significant importance as they face a considerably higher risk of extinction than other pteridophyte species. In fact, 95% of filmy ferns and 68% of grammitid ferns in Sri Lanka have been classified under the threatened category, according to the National Red List 2020. Filmy and grammitid ferns predominantly thrive in epiphytic or rupestral habitats, with terrestrial occurrences being rare, and their epiphytic and epilithic nature makes them highly sensitive to microclimatic changes due to their close dependence on host trees. Consequently, they are largely restricted to the humid, shaded environments of Sri Lanka's rainforest ecosystems, which provide the stable microhabitats essential for their survival. Among the various factors, the moisture content of their immediate environment plays a critical role in determining their survival. A notable example is the family *Hymenophyllaceae*, which exhibits poikilohydric characteristics (Aros-Mualin & Kessler, 2024).

By the dawn of the nineteenth century, Sri Lanka's forest cover was estimated at around 70% of the total land area, but it has progressively decreased over time. These facts highlight the critical need for the conservation of these particular fern species against the changing climate and unsustainable land use. Furthermore, their vulnerable status emphasizes the urgency of implementing immediate conservation measures to safeguard their natural habitats while enhancing our understanding of their ecological and biological significance. Thus, assessing the impact of threats, identifying and prioritizing vulnerable taxa, and predicting conservation pockets are vital for the conservation and management of threatened species (Mehta et al., 2020).

Given the high extinction risk and significant ecological value of filmy and grammitid ferns in Sri Lanka, the primary research question guiding this study is: What comprehensive conservation measures and strategies can be implemented to effectively protect and sustain the populations of grammitid and filmy ferns in Sri Lanka? Therefore, the main objective of this study is to propose conservation measures and a roadmap for these two highly threatened fern groups in Sri Lanka. To accomplish this goal, we utilized a holistic conservation approach and developed conservation strategies for species within these two groups. Additionally, this study highlights the areas that need to be strengthened and protocols that should be implemented for the successful conservation of filmy and grammitid ferns in Sri Lanka. The proposed conservation measures and roadmap aim to serve as a comprehensive framework for developing conservation strategies to protect island populations of endangered species worldwide.

---

## MATERIALS AND METHODS

The study was primarily based on a combination of existing literature and the firsthand experiences of the researchers. Additionally, the study used various web-based data repositories and employed several scientific tools and techniques (including GIS applications) together with researchers' opinions. This holistic approach enabled a comprehensive analysis of both qualitative and quantitative data, ensuring a thorough assessment of the current status and future prospects of these highly vulnerable groups of species.

### Selection of candidate families and species

Our analysis was specifically directed toward the family Hymenophyllaceae (filmy ferns) and the subfamily Grammitidoideae (grammitid ferns). The grammitid

ferns were earlier treated as a separate family, the Grammitidaceae, and based on the recent molecular work, they were nested within the family Polypodiaceae (PPG I, 2016). The selection of these two groups was based on the level of threat they face, as determined by the proportion of species classified as threatened in the National Red List (2020). We used Rajapaksha et al. (2022) as a base document to extract the 42 species belonging to two candidate families.

### Data collection and categorization

We primarily considered the locality information given in “*A Handbook to the Flora of Ceylon*” (Volume 16A & B) for the family Hymenophyllaceae (Jayasekara, 2006) and the subfamily Grammitidoideae (Parris, 2006). It consists of 752 herbarium records based on the specimens deposited at 22 worldwide herbaria. Additionally, the collections made by this publication’s corresponding author from 2003 to 2021 were also considered while preparing spatial distribution maps. The virtual herbaria (B, BR, BM, E, K, G, P, W) were also consulted for Sri Lankan ferns deposited there. The information on the date of collection, collector name, locality details (province, district, village, and elevation), and habitat characteristics was extracted from the above-mentioned literature, herbarium records and personal collections. Information on historical herbarium records of all candidate species was organized into 50-year intervals to examine changes in collection intensity over time. All available records from 1800 to 2020 were compiled and categorized into the following periods: 1800-1850, 1850-1900, 1900-1950, 1950-2000, and 2000-2020. The number of specimens representing Grammitidoideae and Hymenophyllaceae in each interval was then quantified. These data were used to construct a temporal bar chart illustrating variations in collection effort and the historical progression of pteridophyte documentation in Sri Lanka. The National Red List (2020) was used to identify the conservation status of each species.

### Construction of phylogenetic tree

Phylogenetic analysis was conducted to determine the placement of Sri Lankan pteridophyte families within the global pteridophyte phylogeny, with particular focus on the Grammitidoideae and Hymenophyllaceae. Chloroplast *rbcL* gene sequences were used for this analysis. Representative *rbcL* sequences from selected species of each family were obtained from GenBank and incorporated into the dataset. This phylogenetic tree was used to illustrate the approximate placement of Sri Lankan pteridophyte families within the broader global pteridophyte phylogeny, providing readers with an

overview of where the Sri Lankan families, particularly Grammitidoideae and Hymenophyllaceae, fit within the global context. It also summarized their total, endemic, and threatened taxa in Sri Lanka.

### Mapping of spatial distribution

Locality information for Hymenophyllaceae and Grammitidoideae was obtained from *A Revised Handbook to the Flora of Ceylon* (Jayasekara, 2006; Parris, 2006), which includes 752 herbarium records from 22 international herbaria. Additional records were incorporated from collections made by the corresponding author between 2003 and 2021. All locality descriptions were checked against original herbarium labels and updated, when necessary, using topographic maps and online gazetteers. Records that could not be georeferenced with reasonable accuracy ( $\pm 5$  km), were duplicates, or represented cultivated plants were excluded. When multiple specimens of the same species came from the same locality, only one representative record was retained. After screening, a total of 471 unique and reliably georeferenced localities were selected for mapping.

Spatial analyses were carried out in QGIS (v. 3.28.3) and ArcGIS (v. 10.3), with all coordinates standardized to the WGS 84 coordinate system. Administrative boundary layers for Sri Lanka’s 25 districts and three major climatic zones (wet, intermediate, dry) were obtained from the Survey Department of Sri Lanka and reprojected to the same coordinate system. Each locality was assigned to a district and climatic zone through spatial overlay. Species distribution maps were generated separately for Hymenophyllaceae and Grammitidoideae. Locality points were symbolized by species presence, and district-level species richness was calculated by counting the number of species recorded within each district. Maps were exported using standardized scale, layout, legends, and scale bars to allow easy comparison among figures.

### Identification of hotspots

Species occurrence hotspots were identified using the Hot Spot Analysis (Getis–Ord  $G_i^*$ ) tool in ArcGIS. Each species locality point was assigned a constant weight of one. Spatial relationships were conceptualized using the default fixed-distance band, with the threshold distance selected based on the tool’s recommendations for the dataset. Local  $G_i^*$  statistics were computed, and clusters with  $G_i\_Bin \geq 2$  ( $\geq 95\%$  confidence) were interpreted as significant hotspots. These clusters were compared with known forested regions and major topographic features to confirm their biological significance for conservation planning.

### Climatic preferences and habitat characteristics

Climatic preferences for hotspots and species-rich areas were assessed using gridded climate data from the NASA POWER database (1981–2021). For each hotspot and locality, mean annual temperature, rainfall, and relative humidity were extracted from the NASA rasters. Climate layers were resampled, where necessary, to a common resolution and processed using raster calculations and zonal statistics in ArcGIS. The resulting values were summarized into ecologically meaningful ranges, representing the preferred climatic envelopes for filmy and grammitid ferns. No additional interpolation or species distribution modelling was performed; analyses were based solely on observed localities and hotspot areas.

### A roadmap and proposed conservation measures

Future conservation measures were proposed based on gathered information from past herbarium records, relevant literature, developed distribution maps, and the authors' personal observations. To effectively achieve the conservation goals, we have extensively discussed the importance of accommodating additional supportive services and technological tools. A flowchart was developed to visually represent the diverse fields, elements, and tools to develop these conservation guidelines and the roadmap to achieve future conservation targets. Furthermore, results highlight areas that require further strengthening and attention.

## RESULTS AND DISCUSSION

Here, we provide detailed guidelines for developing a conservation plan for filmy and grammitid ferns of Sri Lanka, aligned with the proposed schematic diagram. In addition, we highlight conservation gaps and provide supportive information for bridging these gaps to facilitate the development of a comprehensive strategic plan for the candidate species.

### Understanding of overall diversity

Understanding the overall diversity of the target taxa or group within a specific geographic unit and their past and current status is the initial step in developing any conservation plan. Figure 1 illustrates the placement of pteridophyte families of Sri Lanka within the global pteridophyte phylogenetic tree, along with their total number of taxa and number of endemics and threatened species. This information serves as a foundational resource for the selection and prioritization of families in developing conservation and management guidelines.

The Hymenophyllaceae is represented by 20 species, including one endemic to Sri Lanka. Jayasekara (2006) has provided a description of each species in the enumeration of the Hymenophyllaceae for “*A revision of the flora of Ceylon*”, Volume 15(A). His enumeration included recent collections of some taxa from a few selected localities across the wet and intermediate zones of Sri Lanka. The subfamily Grammitidoideae is represented by 22 species in eight genera, 36% (8 species) of which are endemic to the country. Parris (2006) has provided detailed descriptions of all species for “*A revision of the flora of Ceylon*, Volume 15(A)”. Such enumeration was based on the specimens available at the 22 worldwide herbaria. However, having comprehensive and detailed botanical descriptions greatly facilitates the process of setting conservation guidelines.

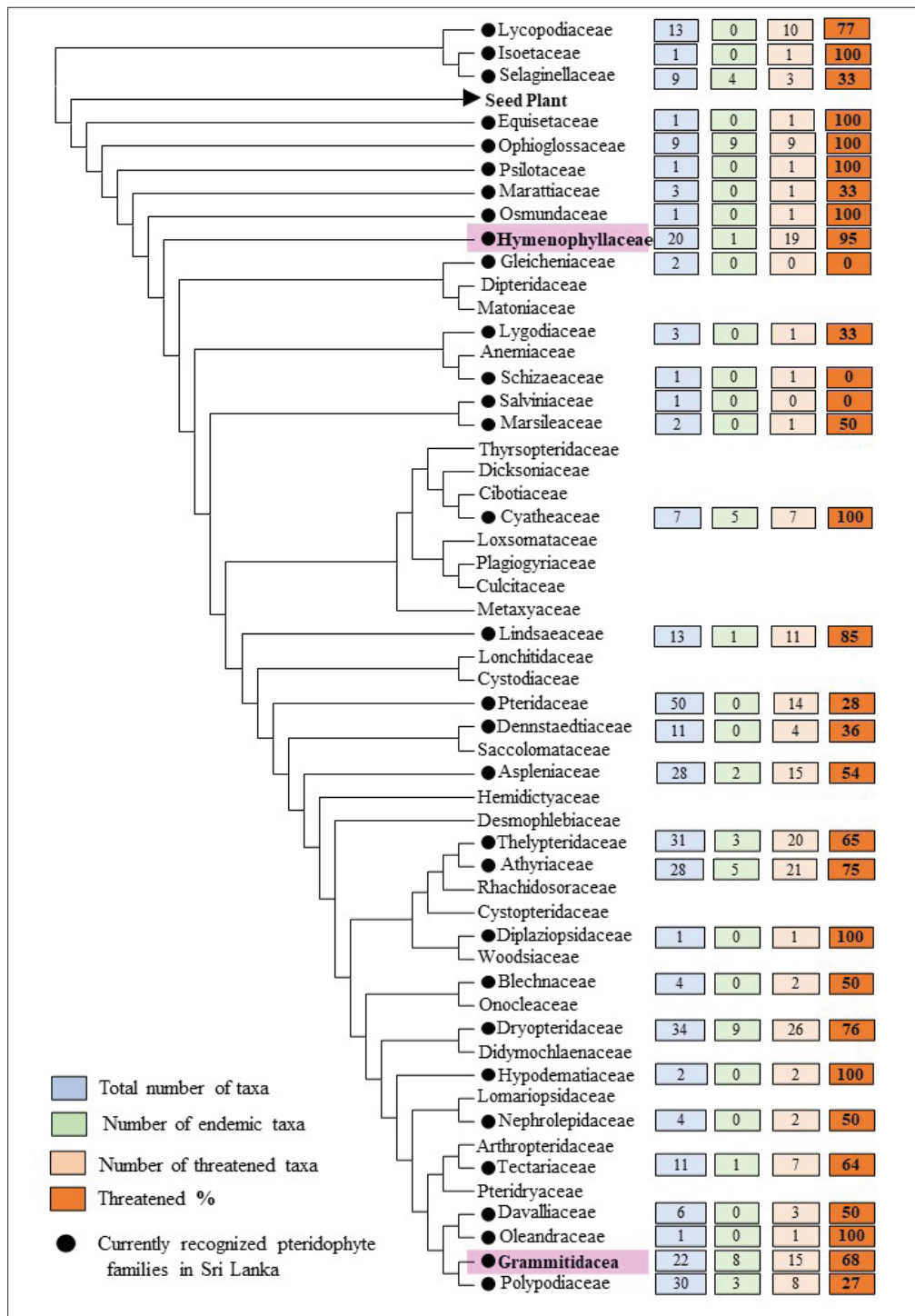
Figure 2 illustrates the number of specimens used in the present study, collected between 1800 and 2020 and currently housed in 22 herbaria. This reveals that the highest number of specimens have been collected between 1950–2000, followed by 1850–1900. W.A. Sledge's specimen collections from his enumeration of Sri Lanka's fern flora (1950–1951 and 1954) significantly contributed to the increase in recorded specimens during this period, followed by additional collections made by Robert B. Faden in 1976. Most Sri Lankan fern specimens were collected in the 19<sup>th</sup> century during the British Colonial period (Rajapaksha *et al.*, 2022). It is the main reason for the deficit in the second-largest collection from 1850 to 1900. The recent explorations reveal that some species are overlooked and demonstrate a wider range of distribution than previously assumed (Figure 3). However, future collections should be expedited to bridge research gaps and set more effective conservation priorities.

### Mapping of spatial distribution pattern

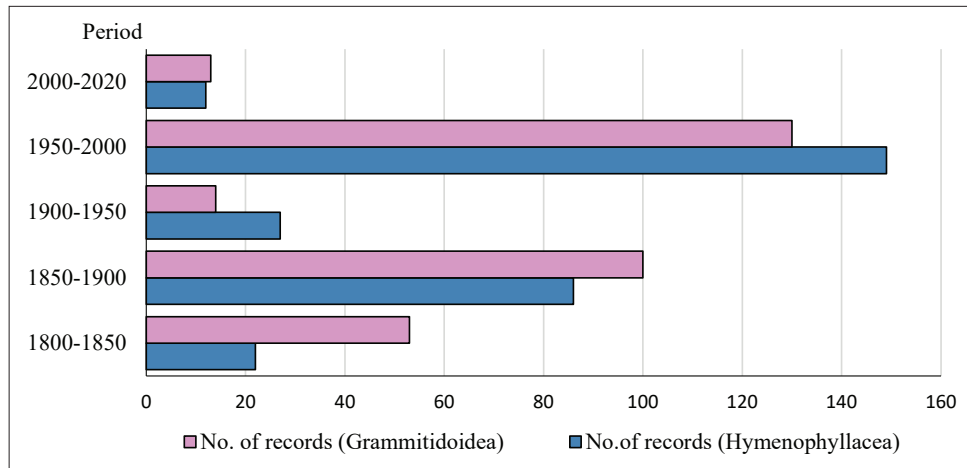
Mapping geographical distribution patterns provides valuable information for understanding the ecological requirements and identifying the most preferable habitats. This knowledge forms the fundamental basis for developing effective conservation plans. Spatial distribution maps depicting the distribution of each group across the administrative districts and the three major climatic zones are provided herein (Figure 4). It is evident from these maps that the vast majority of the recorded locations are positioned within the wet zone of Sri Lanka (Figures 4A and 4B). This aligns with the general distribution pattern of the fern flora of Sri Lanka. As Jayasekera & Wijesundara (1993) reported, approximately 81% of Sri Lankan lycophytes and ferns

are confined to the wet zone ecosystems. Moreover, the wet zone, which accounts for only one-third of the

country's total land area, contains all currently known endemic pteridophytes (Ranil *et al.*, 2008).



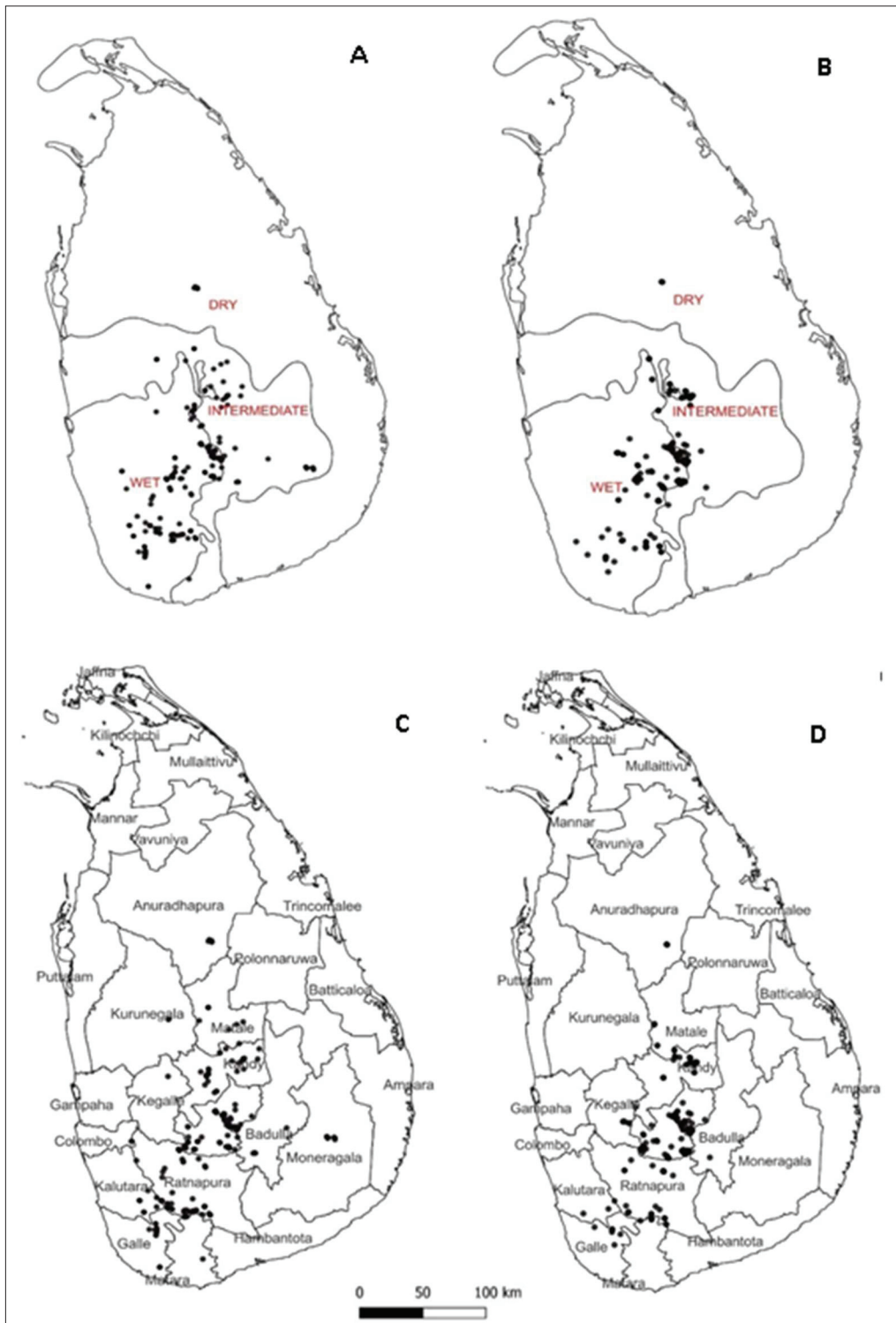
**Figure 1:** Global pteridophyte phylogenetic tree showing the currently recognized pteridophytes families in Sri Lanka, including the number of threatened and endemic species, with emphasis on the Grammitidaceae and Hymenophyllaceae families.



**Figure 2:** Temporal distribution of herbarium records of Grammitidoideae and Hymenophyllaceae in Sri Lanka from 1800 to 2020.



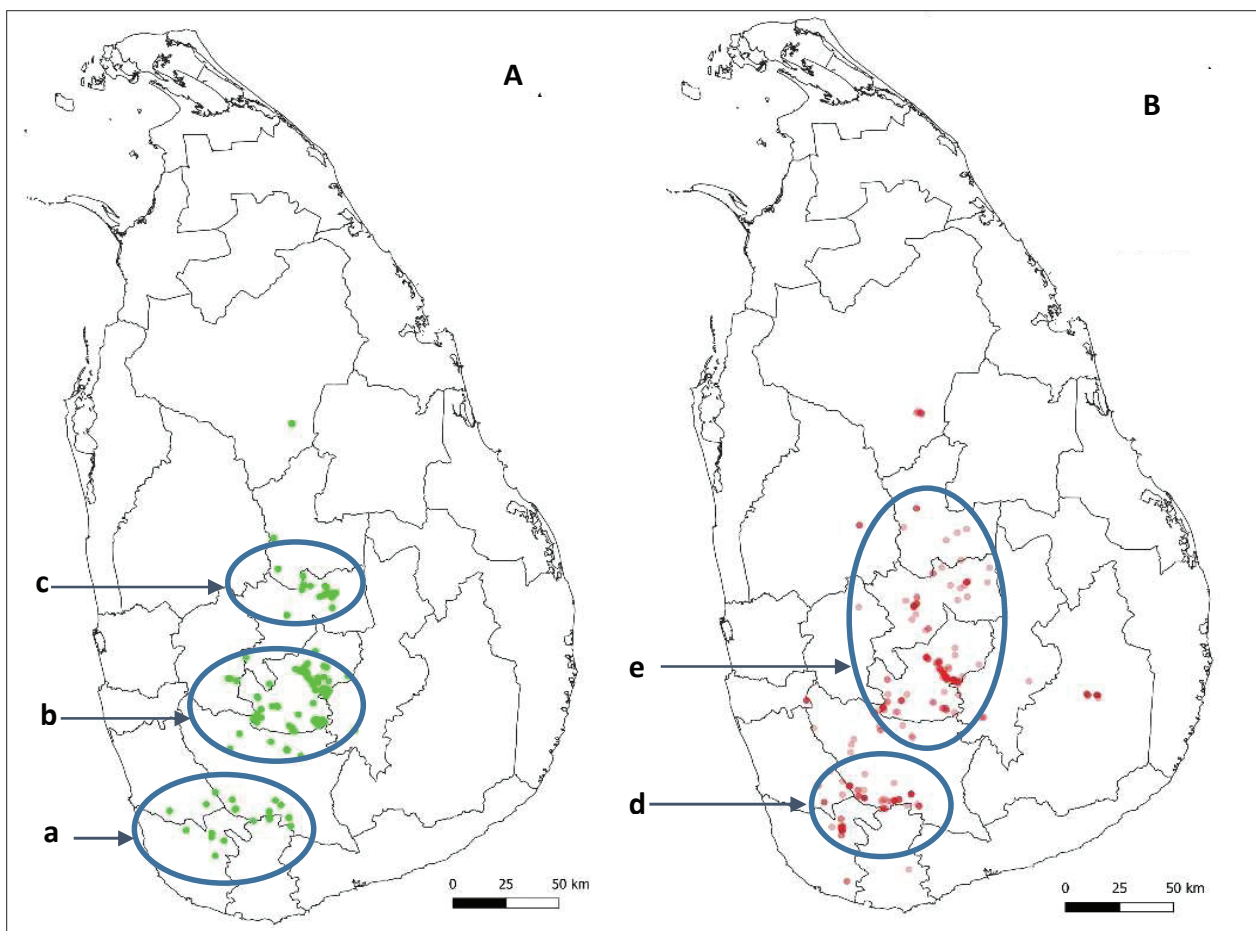
**Figure 3:** A few rare filmly and grammitid ferns recorded from Sri Lanka. **A.** *Crepidomanes minutum* (Blume) K. Iwats, a rare and endangered filmly fern species reported from the Ritigala Strict Nature Reserve. **B.** *Hymenophyllum macrogrossum* Bosch, an endemic and highly microhabitat-specific filmly fern species recorded from the Adam's Peak Forest Reserve. **C.** *Didymoglossum bimarginatum* (Bosch) Ebihara & K. Iwats, a simple-leaved and one of the smallest fern species in Sri Lanka growing on moist rocks in the Kanneliya Forest Reserve. **D.** *Prosaptia obliquata* (Blume) Mett., a locally common epilithic grammitid fern observed in the Dothalugala Forest Reserve. **E.** *Oreogrammitis medialis* (Baker) Parris, a grammitid fern species mostly restricted to moist rocks in the spray zones of fast-flowing streams in the south-western forests. **F.** *Ctenopterella blechnoides* (Grev.) Parris, an endangered grammitid fern species reported from the Kanneliya Forest Reserve.



**Figure 4:** Spatial distribution patterns of filmy and grammitid ferns in Sri Lanka, based on 752 herbarium records housed across 22 herbaria worldwide. Map A. Distribution of filmy ferns in the three major climatic zones of Sri Lanka. Map B. Distribution of grammitid ferns in three major climatic zones of Sri Lanka. Map C. Spatial distribution pattern of filmy ferns in 25 administrative districts of Sri Lanka. Map D. Spatial distribution patterns of grammitid ferns in 25 administrative districts of Sri Lanka.

The distribution of filmy and grammitid ferns reveals some exceptional localities that are situated in the isolated and biologically diverse mountains within the dry zone and intermediate zones of Sri Lanka (Figures 4A and 4B). These distinct areas are unique habitats for these fern groups, showcasing their presence outside the typical wet zone regions. However, except *Abrodictyum obscurum* (Blume) Ebihara & K. Iwats, all other taxa of both groups thrive well in epiphytic and epilithic substrates of humid and shady environments. Moreover, according to the analysis, the Nuwara Eliya district offers habitats for 23 species (55%), with five species exclusively confined to this particular district (Figures

4C and 4D). Among the nine administrative provinces, the Central Province records the presence of 35 species (83%), followed by 21 species (50%) distributed in the Sabaragamuwa Province. The combination of factors such as the highest annual rainfall, elevated relative humidity, and favorable soil and elevational gradients explains the occurrence of the highest number of species in both provinces. This spatial distribution pattern provides insight into the rediscovery of possibly extinct species and find new locations for other endangered species to facilitate future studies on various aspects of filmy and grammitid ferns of Sri Lanka.



**Figure 5:** Map A. Grammitid ferns hotspots (a- lowland forests in southwest Sri Lanka: Sinharaja World Heritage Site, Kanneliya-Dediyagala-Nakiyadeniya forest complex, Gilimale forest reserve, Morapitiya-Roonakanda forest reserve, Beraliya forest reserve and Hiniduma forest reserve. b- forests of Kandy and Nuwara Eliya districts: Horton Plains National Park, Piduruthalagala mountain, Ambagamuwa forest reserve, Hakgala strict nature reserve, Hantana mountain range; Adam's Peak mountain range. c- Knuckles Mountain Range in Sri Lanka). Map B. Filmy ferns hotspots (e-lowland forests in southwest of Sri Lanka: Sinharaja world heritage site, Kanneliya forest reserve, Gilimale forest reserve, Morapitiya- Roonakanda forest reserve, Beraliya forest reserve and Hiniduma forest reserve). d- high altitude forests in central highlands: Knuckles Mountain Range, Adam's Peak mountain range, Horton Plains National Park, Piduruthalagala mountain, Ambagamuwa forest reserve, Hakgala strict nature reserve in Sri Lanka).

Over time, due to changes in regional landscaping for agricultural and industrial development and rapid urbanization, some previously known localities of certain species no longer exist. For example, the possibly extinct species *Chrysogrammitis glandulosa* (J.Sm.) Parris and *Calligrammitis beddomeana* (Alderw.) Parris, Sundue, Li Bing Zhang, X.M. Zhou & Ralf Knapp have been collected only from the Nuwara Eliya district, and such previous localities have undergone cultivation and various human activities. Furthermore, the endemic *Prosaptia ceylanica* Parris has only been reported from its type locality, which is now significantly disturbed. Utilizing the generated maps, revisiting previously documented localities, and exploring adjacent areas can provide valuable information and help expand these species' known areas of occurrence.

### Identification of hotspots

Species distribution maps are widely used to identify priority areas based on occurrence data and environmental factors (Lannuzel *et al.*, 2021). Identifying hotspots holds significant value for conservationists, policymakers, and researchers engaged in biodiversity conservation. These hotspots serve as repositories of valuable information. In this study, we utilized the available occurrence data to identify specific areas of high importance for the conservation of filmy and grammitid ferns. Based on the available data, we identified three hotspots for grammitid ferns (Figure 5A) and two hotspots for filmy ferns (Figure 5B). The extent of hotspots can be further expanded by incorporating new data on species occurrences.

### Identification of preferable climatic requirements and habitats

Identifying appropriate climatic requirements is essential for determining suitable habitats and predicting future population size and distribution changes. It is also necessary to understand appropriate ecological requirements for *ex situ* conservation. Identifying suitable climates ensures successful reintroduction into their natural range or similar areas. Moreover, understanding the specific conditions a plant requires (e.g., temperature, rainfall, soil type) helps prioritize the protection and restoration of suitable habitats. In this study, we have identified the preferred climatic requirements by analyzing their natural distribution patterns. Our results are primarily based on three major climatic factors: temperature, relative humidity, and annual rainfall (Figure 6). To validate these findings,

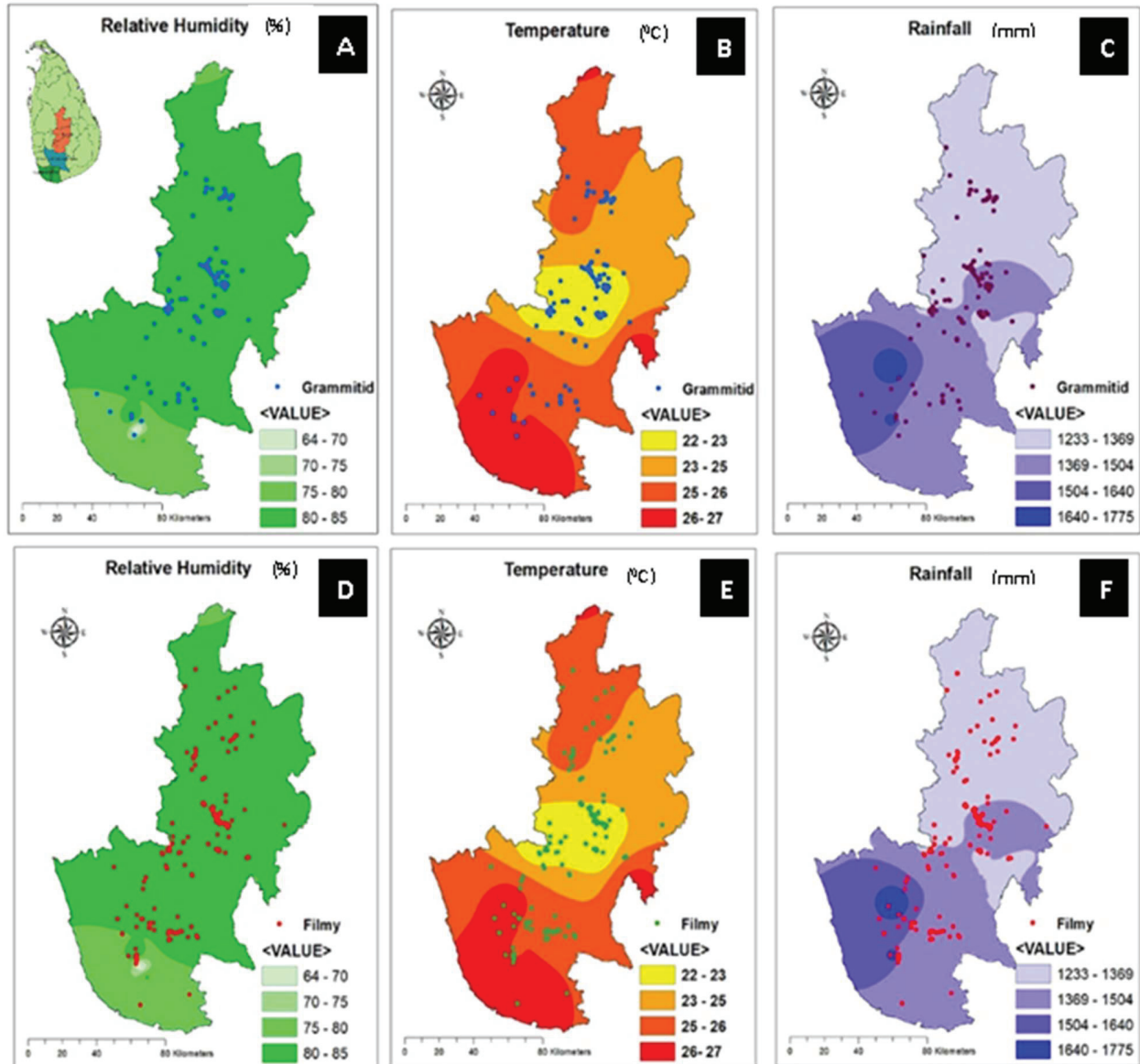
screening the natural population of both plant groups across the country is essential. In the meantime, it is essential to develop probability area maps based on past and future observations because probability area maps offer a wealth of information that can help to expand the occurrences of species or groups by revealing areas with similar habitats and specific ecological niches. They offer further support to find if previously undiscovered populations or suitable habitats for target species or groups may exist. Thus, developing such probability area maps for future investigation of both plant groups is a major requirement.

### Assessment of conservation status

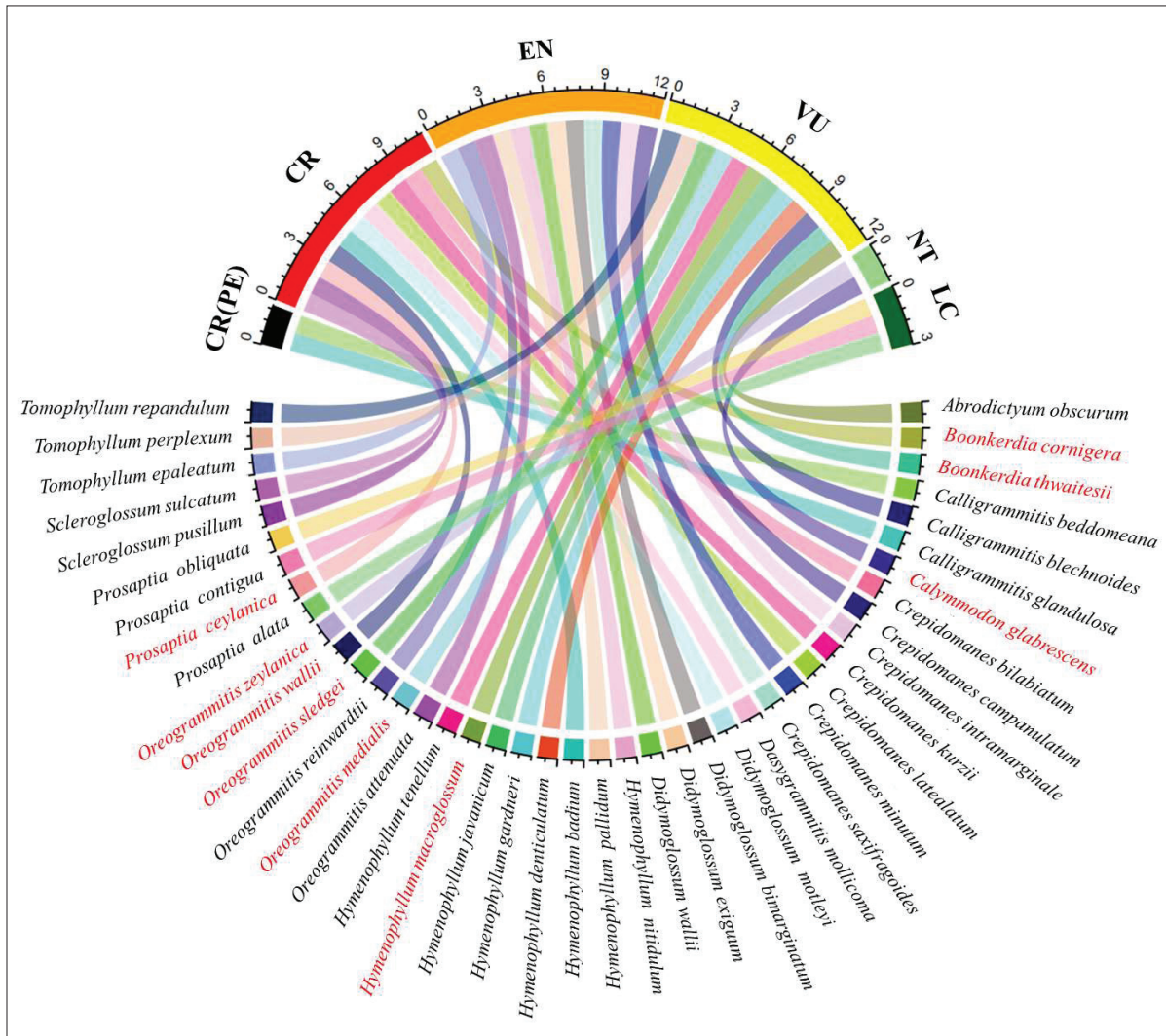
Assessing species for their conservation needs is a vital first step in identifying and prioritizing species for *ex situ* and *in situ* conservation actions (Johnson *et al.*, 2020). The first list of conservation status for the pteridophyte flora of Sri Lanka was published in 2012, followed by the second list in 2020.

The conservation status of each taxon remained relatively the same due to the lack of collections during the period between the two assessments, although conducting an island-wide survey was a key recommendation of the 2012 assessment. Moreover, both assessments were largely based on herbarium specimens of 34 worldwide herbaria (Ranil *et al.*, 2022). Therefore, here we considered the 2020 list the most updated document concerning species conservation status (Figure 7).

Accordingly, 19 species of filmy ferns (95%) are treated under the threatened category. Out of 22 grammitid species, 17 (68%) are also in the same category, indicating that both groups are at a high risk of extinction. However, it is essential to emphasize the importance of conducting comprehensive field surveys across the priority areas for these species prior to compiling the next Red List. Without updated occurrence data, any conservation status assessment is worthless and likely to produce similar results as before. Comprehensive analysis and a systematic island-wide field survey are essential for policymakers and conservationists in decision-making. Such updated assessments also provide researchers with guidance for setting future research goals, specifically in prioritizing species for conservation within these two highly threatened plant groups of Sri Lanka. This prioritization is necessary because resources for nature conservation are limited (Arponen, 2012). However, the conservation status given in the 2020 list provides adequate support to prioritize the species for future conservation efforts.



**Figure 6:** Maps A–C show the most preferred relative humidity, temperature, and rainfall ranges for the occurrence of grammitid ferns. Maps D–F show the corresponding preferred ranges for filmy ferns. These patterns are illustrated for the districts of Galle, Matara, Ratnapura, Kandy, and Matale in Sri Lanka.



**Figure 7:** Conservation status of 42 species in the subfamily Grammitidoideae and the family Hymenophyllaceae (based on the 2020 National Red List). The botanical names highlighted in red indicate that they are endemic to Sri Lanka.

### Species selection and prioritization for developing a conservation plan

The criteria used for species-level conservation prioritization are multidimensional and range from aesthetic to evolutionary considerations (Arponen, 2012; Mee *et al.*, 2015). Given that both filmy and grammitid ferns in Sri Lanka have yet to be extensively studied regarding their ecology, reproductive biology, phylogeny, and population dynamics, the IUCN conservation status is the sole criterion for prioritizing species for future conservation efforts. We highly recommend implementing urgent conservation measures for all

critically endangered and potentially extinct species, considering them as top priorities for intervention. Table 1 provides a list of high-priority species for setting future conservation guidelines.

Hereafter, we discuss the areas that need to be integrated into conservation planning after selecting specific species. Although Sri Lanka lags behind in adopting the fields mentioned below due to a lack of general interest, financial limitations, inadequate technical expertise, and dedicated personnel, it is crucial to include these areas in the country’s future research mandate to safeguard these highly endangered species.

**Table 1:** The species required immediate attention for conservation.

Species	Conservation status	Last record	Herbaria
<i>*Boonkerdia cornigera</i>	CR	1950	K, L, PDA,
<i>Calligrammitis beddomeana</i>	CR (PE)	1849-1888	BO, BM, K, PDA
<i>Chrysogrammitis glandulosa</i>	CR (PE)	1849	B, BM, CGE, K, PDA
<i>Crepidomanes bilabiatum</i>	CR	1996	BM, K, L, PDA
<i>Crepidomanes kurzii</i>	CR	1954	BM, K, L
<i>Crepidomanes latealatum</i>	CR	-	K
<i>Dasygrammitis mollicoma</i>	CR	1843-1849	K, GH, UC, US
<i>Didymoglossum motleyi</i>	CR	1996	PDA, BM, K
<i>Hymenophyllum badium</i>	CR	-	K
<i>*Oreogrammitis wallii</i>	CR	1954	B, BM, GH, K, L, PDA, US
<i>*Prosaptia ceylanica</i>	CR	1954	K
<i>Scleroglossum pusillum</i>	CR	1870-1872	E
<i>Scleroglossum sulcatum</i>	CR	1889	B, BM, CGE, E, GH, K, GH, P, PDA, US

Note: \*species endemic to Sri Lanka

### Detailed and systematic studies of selected and prioritized species

After selecting a species or species group, conducting in-depth, systematic study of various aspects will guide the accurate application of effective conservation measures. Conducting comprehensive studies in these areas is essential to implement an effective and efficient conservation approach. Accommodating recent knowledge such as biotechnology, GIS applications, and mathematical models is also important when necessary. Apart from having a taxonomically well-focused list and old herbarium specimens, particularly in European herbaria, Sri Lanka has not demonstrated significant interest in studying species within these two groups thus far. Therefore, the highest priority should be given to surveying the country's natural ecosystems to discover new localities and expand the areas of occurrence, followed by strengthening the national herbarium collections.

The family Hymenophyllaceae and subfamily Grammitidoideae have been extensively studied for global phylogenies. Some Sri Lankan non-endemic grammitid species have been included in these studies: *Calligrammitis beddomeana*, *Chrysogrammitis glandulosa*, *Ctenopterella blechnoides*, *Dasygrammitis mollicoma*, *Prosaptia alata*, *P. contigua*, *P. obliquata*, *Scleroglossum pusillum*, and *S. sulcatum* (Zhou et al., 2023), although Sri Lankan material has not

been sampled. However, Sri Lankan collections of the endemic grammitids *Oreogrammitis medialis* and *Tomophyllum perplexum* have been sampled, together with *T. repandum*, a species described from Sri Lanka (Zhou et al., 2023). As an isolated gene pool in the Indian Ocean, it is important to elucidate the position of all Sri Lankan Hymenophyllaceae and Grammitidoideae species in the global phylogeny, utilizing Sri Lankan material to ascertain the relationships of the endemics and to confirm the identification of non-endemic species typified from elsewhere. Therefore, future studies should also focus on genomic analysis and biogeographic aspects as well. Given the current scenario, the only feasible ways to advance the study and conservation approach of fern species in Sri Lanka are through networking with experts in pteridology and establishing effective collaborations with international institutions.

In addition to the areas discussed above, we emphasize the significance of ethnobotanical knowledge associated with these species. According to Ranil and Bussmann (2021), traditional uses of filmy and grammitid ferns have not been reported in Sri Lanka. However, the communities residing in the vicinity of the wet zone forests possess a deep understanding and knowledge of the habitats, particularly the ecological niches of wild species. Their expertise in ethnobotany and ethnoecology can therefore be integrated to explore new localities for these species. Today, the use of citizen science in biodiversity conservation projects is growing

in number, size, and scope, and it is gaining recognition as a valuable data source that builds public engagement (Burgess et al., 2017). In Sri Lanka, there is a growing interest among the younger generation, particularly those involved in local environmental organizations and societies, in exploring plant diversity, discovering rare or new species, and engaging in activities such as nature photography. Moreover, they extensively utilize social media platforms to share their knowledge and experiences while networking with professionals and the international community. Since community engagement is a key component of effective species conservation, policymakers and conservationists also need to pay special attention to integrating community knowledge, participation, and citizen science initiatives into future conservation strategies.

### Mass propagation of selected species for conservation

Mass propagation of endangered fern species has been practiced for several decades using both conventional and micro-propagation techniques (Fay, 1992; Amoroso & Amoroso, 2003; Manickam et al., 2003; Chiou et al., 2006; Magrini et al., 2020; Suneetha & Hegde, 2022). Although micro-propagated plants may exhibit reduced genetic variability within their homogeneous populations, this approach can still be considered a viable solution for species with limited population sizes. However, the importance of *in vitro* tools to complement other *ex situ* methods for saving plants from extinction is more relevant than ever before (Barnicoat et al., 2011). *In vitro* propagation of the endangered filmy fern, *Trichomanes punctatum* subsp. *floridanum* revealed that *in vitro* propagation methods could be used to provide plants for restoration (Pence, 2014). Considering the widespread popularity of Polypodiaceae species among plant growers and commercial nurseries, grammitid ferns, being part of the same family clade, emerge as promising candidates for various horticultural and commercial endeavors.

However, both *in situ* and *ex situ* conservation pose a significant challenge for this specific group of ferns. Both fern groups studied here have chlorophyllous spores, making their cultivation particularly complex (Lloyd & Klekowski, 1970). These spores are typically adapted to specific ecological niches where they can access light and moisture immediately after dispersal, conditions that are essential for their survival and germination. Chlorophyllous spores are short-lived (Mellado-Mansilla et al., 2022), a characteristic that has puzzled many pteridologists. Their short lifecycle ensures rapid germination in suitable conditions, providing a competitive advantage in dynamic environments like forest canopies.

However, this trait also limits their viability under less favorable circumstances. Further research in this area is essential, as it could significantly contribute to developing localized culture protocols for propagating filmy and grammitid ferns. Such advancements would play a vital role in their conservation and sustainable management.

### *In situ* conservation

The *in situ* conservation approach can be implemented through the reintroduction or translocation of species to suitable habitats and the conservation of existing populations, along with the safeguarding of the entire habitat, as explained below. However, these methods have yet to be applied in Sri Lanka for any fern species.

#### (a) Reintroduction

There is substantial evidence supporting the successful reintroduction of endangered ferns into suitable habitats (McHaffie, 2006; Agurajuja, 2011; Baker et al., 2014). For example, Baker et al. (2014) provide valuable insights into the rescue, ecology, and conservation of the rediscovered island endemic *Anogramma ascensionis* through *ex situ* approaches, and propose a roadmap for species reintroduction and habitat restoration. However, evidence for the successful reintroduction of filmy and grammitid ferns in particular is limited and remains poorly documented. Their epiphytic and epilithic growth forms, narrow habitat preferences, and strong sensitivity to microclimatic variation make reintroduction particularly difficult and technically demanding. Consequently, any reintroduction programme involving these groups must emphasize careful site selection, microhabitat restoration, and long-term monitoring of population dynamics, habitat conditions, and adaptive responses. Despite these limitations, well-designed reintroduction efforts still have the potential to make meaningful contributions to the conservation of rare and threatened filmy and grammitid ferns, particularly those with restricted distributions and small population sizes.

#### (b) Conservation of existing populations

The outcome of hotspot analysis provides valuable insights in identifying population hotspots for individual species or groups. To achieve this objective, innovative approaches like mathematical modeling can also be employed. These methods hold significant potential for enhancing our understanding and identification of hotspots for candidate species. If these areas are not currently part of the country's protected area network, declaring them as conservation areas should align

with the policy and legislation of the country, with the involvement of responsible government institutions.

However, some of the sensitive areas and hotspots identified in this study directly overlap with the existing protected area network; unless influenced by the impacts of climate change, they are not highly subject to other external pressures. This indicates that they benefit from sufficient legal protection. However, future attention and conservation priorities should focus on hotspots outside the country's protected area network. Successful conservation plans are not solely achieved by acquiring optimally designed reserves, and ongoing monitoring and managing the biodiversity in those reserves are an equally important, but often neglected or poorly executed, part of the conservation process (Regan *et al.*, 2008). Therefore, conducting scientific investigations, accompanied by continuous and long-term monitoring of these identified

hotspots, will help minimize the risk of extinction for these particular groups of plants in Sri Lanka.

Apart from accommodating academic disciplines, coordinating government authorities aligned with the country's biodiversity conservation effort is a major requirement. Since the country's protected area network belongs to the central government, direct government involvement is a determining factor for the effectiveness of any conservation plan. Even though public involvement is a major element of the integrative conservation approach, both filmy and grammitid ferns do not show community engagement due to their low economic potential and use value. However, it is mandatory to be aware of the communities around the hotspots and sensitive habitats for these two plant groups to ensure the conservation of the entire ecosystem.

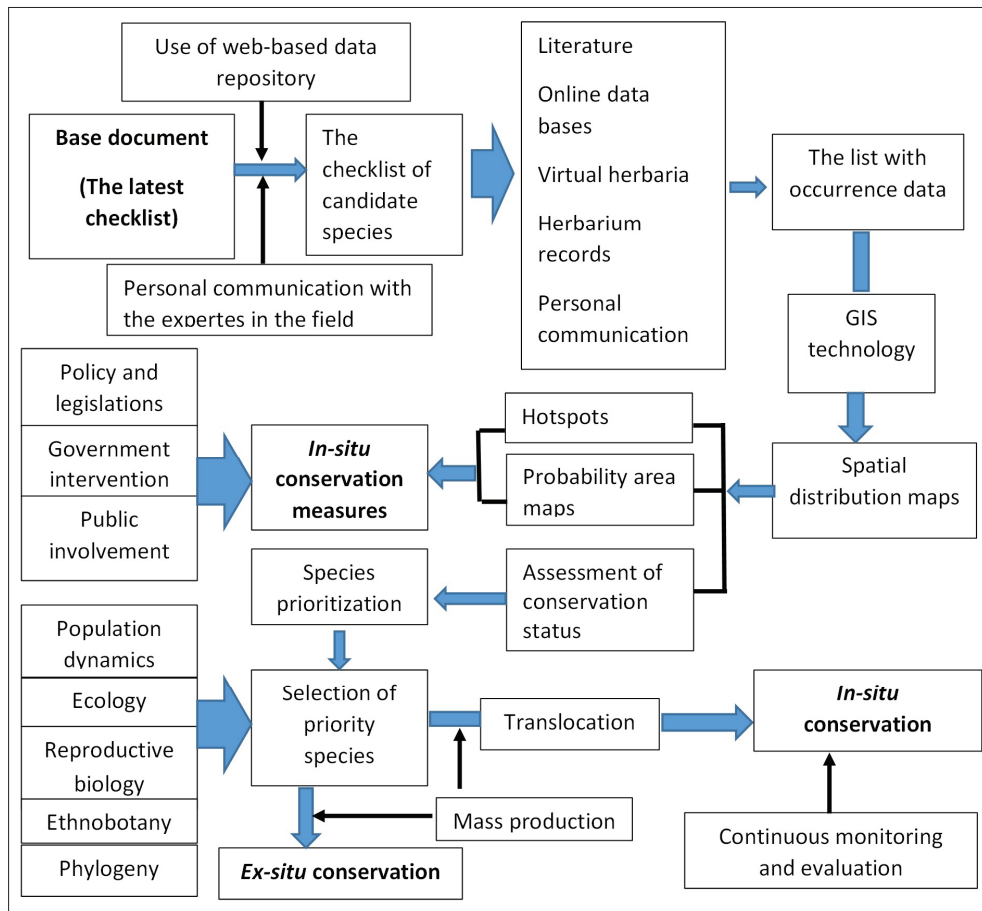


Figure 8: A schematic representation of the diverse fields, elements, and tools employed in a conservation plan.

### Ex situ conservation

Although *ex situ* conservation is challenging for both plant families, it may still be possible to cultivate them in high-tech greenhouses where their preferred microclimatic conditions can be externally provided and maintained. Apart from its conservation significance, *ex situ* conservation is a key element for raising public awareness about such rare and endangered taxa, though it is costly. Since both filmy and grammitid ferns naturally grow in more humid and shaded conditions, it is a challenge for countries like Sri Lanka to conserve such species in an *ex situ* environments for a long time, particularly due to the high establishment and maintenance costs. Therefore, rather than prioritizing *ex situ* conservation of filmy and grammitid ferns, *in situ* conservation is generally more practical and effective.

### CONCLUSION

A holistic conservation approach is essential to conserve both filmy and grammitid ferns, particularly given their climatic sensitivity, habitat specificity, and narrow distribution. However, Sri Lanka has made limited application of holistic conservation methods for these two plant groups due to the lack of recent studies on their distribution patterns, ecological aspects, population dynamics, and phylogeny. This analysis relied heavily on historical literature and herbarium records from the colonial era. This study presents detailed information on filmy and grammitid ferns and proposes conservation options, serving as a valuable resource for conservationists and policymakers to develop new conservation plans or implement conservation actions. The schematic diagram (Figure 8) illustrates the pathway for conserving these two fern families. The developed distribution maps and highlighted areas requiring further research provide valuable insights for effective conservation strategies. This conservation protocol could also be applied to other threatened plant groups. Strengthening institutional capacities and garnering support from government authorities will establish a strong foundation for conserving Sri Lanka's unique biodiversity. Engaging and educating local communities about hotspots and sensitive habitats are crucial for conserving the entire ecosystem. Aligning conservation research and projects with global strategic plans and fostering long-term collaborations with international organizations and research institutes are essential for successful conservation efforts.

### REFERENCES

- Agurauja, R. (2011). Reintroduction of the endangered fern species *Woodsia ilvensis* to Estonia: a long-term pilot study. *Biodiversity Conservation*, 20, 391-400. <https://doi.org/10.1007/s10531-010-9970-2>
- Amoroso, C.B., & Amoroso, V.B. (2003). Plantlet production of the Philippine giant staghorn fern [*Platyserium Grande* (Fee) C. Presl] through spore culture. In: *Pteridology in the New Millennium* (eds. S. Chandra, M. Srivastava), pp. 491-495. Springer, Dordrecht, Netherlands. [https://doi.org/10.1007/978-94-017-2811-9\\_33](https://doi.org/10.1007/978-94-017-2811-9_33)
- Aros-Mualin, D. & Kessler, M. (2024). Untangling poikilohydry and desiccation tolerance: evolutionary and macroecological drivers in ferns, *Annals of Botany*, 134 (7), 1139–1150. <https://doi.org/10.1093/aob/mcae167>
- Arponen, A. (2012). Prioritizing species for conservation planning. *Biodiversity Conservation*, 21, 875–893. <https://doi.org/10.1007/s10531-012-0242-1>
- Baker, K., Lambdon, P., Jones, E., Pellicer, J., Stroud, S., Renshaw, O., Niissalo, M., Corcoran, M., Clubbe, C. & Sarasan, V. (2014). Rescue, ecology, and conservation of a rediscovered island endemic fern (*Anogramma ascensionis*): *ex situ* methodologies and a roadmap for species reintroduction and habitat restoration. *Botanical Journal of the Linnean Society*, 174, 461-477. <https://doi.org/10.1111/boj.12131>
- Barnicoat, H., Cripps, R., Kendon, J. & Sarasan, V. (2011). Conservation *in vitro* of rare and threatened ferns—case studies of biodiversity hotspot and island species. *In Vitro Cellular Developmental Biology-Plant*, 47, 37–45. <https://doi.org/10.1007/s11627-010-9303-x>
- Burgess, H., DeBey, L., Froehlich, H., Schmidt, N., Theobald, E., Ettinger, A., HilleRisLambers, J., Tewksbury, J. & Parrish, J. (2017). The science of citizen science: Exploring barriers to use as a primary research tool. *Biological Conservation*, 208, 113-120. <https://doi.org/10.1016/j.biocon.2016.05.014>
- Chiou, W.L., Huang, Y. M. & Chen, C.M. (2006). Conservation of two endangered ferns, *Archangiopteris somae* and *A. itoi* (Marattiaceae: Pteridophyta), by propagation from stipules. *Fern Gazette*, 17(5), 271-278.
- Della, A.P. (2022). Ferns as ecological indicators. In: *Ferns* (eds. J. Marimuthu, H. Fernández, A. Kumar, S. Thangaiah), pp. 587–601. Springer, Singapore. [https://doi.org/10.1007/978-981-16-6170-9\\_25](https://doi.org/10.1007/978-981-16-6170-9_25)
- Fay, M.F. (1992). Conservation of rare and endangered plants using *in vitro* methods. *In Vitro Cellular Developmental Biology-Plant*, 28, 1-4. <https://doi.org/10.1007/BF02632183>
- Frankham, R. (1997). Do island populations have less genetic variation than mainland populations? *Heredity*, 78, 311–327. <https://doi.org/10.1038/hdy.1997.46>

- Jaisankar, I., Velmurugan, A. & Sivaperuman, C. (2018). Biodiversity conservation: issues and strategies for the tropical islands. In: *Biodiversity and climate change adaptation in tropical islands* (eds. C. Sivaperuman, A. Velmurugan, I. Jaisankar), pp. 525-552. Academic Press. <https://doi.org/10.1016/B978-0-12-813064-3.00019-3>
- Gunatilleke, S., Gunatilleke, N. & Pethiyagoda, R. (2008). Biodiversity of Sri Lanka. *Journal of the National Science Foundation of Sri Lanka*, 36, 25-62.
- Hamabata, T., Kinoshita, G., Kurita, K., Cao, P.L., Ito, M., Murata, J., Komaki, Y., Isagi, Y. & Makino, T. (2019). Endangered island endemic plants have vulnerable genomes. *Communication Biology*, 2, 1-10. <https://doi.org/10.1038/s42003-019-0490-7>.
- Jayasekara, P. (2006). Hymenophyllaceae. In: *A revised handbook to the Flora of Ceylon: Pteridophyta (Ferns and Fern allies)* (ed. M. Shaffer-Fehre), pp. 214-235. Science Publishers, New Hampshire, USA.
- Jayasekera, P.W.B. & Wijesundara, D.S.A. (1993). A herbarium survey of Pteridophytes of Sri Lanka. *Proceedings of the 49<sup>th</sup> Annual Session of the Sri Lanka Association for the Advancement of Science*, Vidya Mandiraya, Vidya Mawatha, Colombo, Sri Lanka, p. 66.
- Johnson, K., Baker, A., Buley, K., Carrillo, L., Gibson, R., Gillespie, G.R., Lacy, R.C. & Zippel, K. (2020). A process for assessing and prioritizing species conservation needs: going beyond the Red List. *Oryx*, 54, 125-132. <https://doi.org/10.1017/S0030605317001715>
- Lannuzel, G., Balmot, J., Dubos, N., Thibault, M. & Fogliani, B. (2021). High-resolution topographic variables accurately predict the distribution of rare plant species for conservation area selection in a narrow-endemism hotspot in New Caledonia. *Biodiversity Conservation*, 30, 963-990. <https://doi.org/10.1007/s10531-021-02126-6>
- Lloyd, R.M. & Klekowski, E.J. (1970). Spore germination and viability in Pteridophyta: evolutionary significance of chlorophyllous spores. *Biotropica*, 129-137. <https://doi.org/10.2307/2989770>
- Manickam, V.S., Vallinayagam, S. & Johnson, M. (2003). Micropropagation and conservation of rare and endangered ferns of the Southern Western Ghats through *in vitro* culture. In: *Pteridology in the new millennium* (eds. S. Chandra, M. Srivastava), pp. 497-504. Springer, Dordrecht, Netherlands. [https://doi.org/10.1007/978-94-017-2811-9\\_34](https://doi.org/10.1007/978-94-017-2811-9_34)
- Magrini, S., Azzella, M.M., Bolpagni, R. & Zucconi, L. (2020). *In vitro* propagation of *Isoetes sabatina* (Isoetaceae): A key conservation challenge for a critically endangered quillwort. *Plants*, 9(7), 887. <https://doi.org/10.3390/plants9070887>
- McHaffie, H. (2006). A reintroduction programme for *Woodsia ilvensis* (L.) R. Br. in Britain. *Botanical Journal of Scotland*, 58(1), 75-80. <https://doi.org/10.1080/03746600608685109>
- Mee, J.A., Bernatchez, L., Reist, J.D., Rogers, S.M. & Taylor, E.B. (2015). Identifying designable units for intraspecific conservation prioritization: a hierarchical approach applied to the lake whitefish species complex (*Coregonus* spp.). *Evolutionary Applications*, 8(5), 423-441. <https://doi.org/10.1111/eva.12247>
- Mehta, P., Sekar, K.C., Bhatt, D., Tewari, A., Bisht, K., Upadhyay, S., Negi, V.S. & Soragi, B. (2020). Conservation and prioritization of threatened plants in Indian Himalayan Region. *Biodiversity Conservation*, 29, 1723-1745. <https://doi.org/10.1007/s10531-020-01959-x>
- Mellado-Mansilla, D., Testo, W., Sundue, M.A., Zotz, G., Kreft, H., Coiro, M. & Kessler, M., (2022). The relationship between chlorophyllous spores and mycorrhizal associations in ferns: evidence from an evolutionary approach. *American Journal of Botany*, 109(12), 2068-2081.
- Nogué, S., de Nascimento, L., Froyd, C.A., Wilmshurst, J.M., de Boer, E.J., Coffey, E.E., Whittaker, R.J., Fernández-Palacios, J.M. & Willis, K.J. (2017). Island biodiversity conservation needs palaeoecology. *Nature ecology & evolution*, 1(7), 0181. <https://doi.org/10.1038/s41559-017-0181>
- Oro, D., Pueyo, Y., Bauzá, J., Errea, M.P. & Arroyo, A.I. (2022). Long transient response of vegetation dynamics after four millennia of anthropogenic impacts in an island ecosystem. *Global Change Biology*, 28(21), 6318-6332. <https://doi.org/10.1111/gcb.16363>
- Parris, B. (2006). Grammitidaceae. In: *A revised handbook to the Flora of Ceylon: Pteridophyta (Ferns and Fern allies)* (ed. M. Shaffer-Fehre), pp. 214-235. Science Publishers, New Hampshire, USA.
- Pence, V.C. (2014). *In vitro* propagation and cryopreservation of the endangered filmy fern, *Trichomanes punctatum* subsp. *floridanum* (Hymenophyllaceae). *Fern Gazette*, 19, 307-317.
- Pethiyagoda, R. & Sudasinghe, H. (2017). The development of Sri Lankan biogeography in the colonial period. *Ceylon Journal of Science*, 46(5), 5-18. <http://doi.org/10.4038/cjs.v46i5.7451>
- PPG I. (2016). A community-derived classification for extant lycophytes and ferns. *Journal of systematics and evolution*, 54(6), 563-603.
- Ranil, R.H.G., Pushpakumara, D.K.N.G. & Wijesunda, D.S.A. (2008). Present status of taxonomic research and conservation of endemic pteridophytes in Sri Lanka. *Proceedings of the 4<sup>th</sup> Symposium on Asian Pteridology and Garden Show* (ed. V.B Amoroso), Central Mindanao University, Musuan, Bukidnon, Philippines, pp. 84-93.
- Ranil, R.H.G. & Bussmann, R.W. (2021). Potential uses of lycophytes and ferns in Sri Lanka: an ethnobotanical perspective. *Ethnobotany Research and Applications*, 21(36), 1-11. <https://ethnobotanyjournal.org/index.php/era/article/view/2761>
- Ranil, R.H.G., Fraser-Jenkins, C.R., Ebihara, E, et al. (2022). An updated checklist of the pteridophyte flora of Sri Lanka. Gampaha, Sri Lanka: ECERO Publishers and Distributors.
- Rajapaksha, R., Zhang, L.B., Pushpakumara, G. & Wijesundara, S. (2022). An analysis of the current status and future prospects of Sri Lankan pteridophytes towards a new dimension. *Biologia*, 77(12), 3333-3351. <https://doi.org/10.1007/s11756-022-01139-y>
- Regan, H.M., Hierl, L.A., Franklin, J., Deutschman, D. H., Schmalbach, H.L., Winchell, C.S. & Johnson, B.S. (2008).

- Species prioritization for monitoring and management in regional multiple species conservation plans. *Diversity and Distributions*, 14(3), 462-471. <https://doi.org/10.1111/j.1472-4642.2007.00447.x>
- Rønsted, N., Walsh, S.K., Clark, M., Edmonds, M., Flynn, T., Heintzman, S., Loomis, A., Lorence, D., Nagendra, U., Nyberg, B. & Opgenorth, M. (2022). Extinction risk of the endemic vascular flora of Kauai, Hawaii, based on IUCN assessments. *Conservation Biology*, 36(4), 13896. <https://doi.org/10.1111/cobi.13896>
- Sarathchandra, C., Abebe, Y.A., Wijerathne, I.L., Aluthwattha, S.T., Wickramasinghe, S. & Ouyang, Z. (2021). An Overview of Ecosystem Service Studies in a Tropical Biodiversity Hotspot, Sri Lanka: Key Perspectives for Future Research. *Forests*. 12(5), 540. <https://doi.org/10.3390/f12050540>
- Suneetha, C. & Hegde, S. (2022). Micropropagation of Pteridophytes. In: *Ferns: Biotechnology, Propagation, Medicinal Uses and Environmental Regulation* (eds. J. Marimuthu, H. Fernández, A. Kumar, S. Thangaiah), pp. 201-242, Springer, Singapore. [https://doi.org/10.1007/978-981-16-6170-9\\_9](https://doi.org/10.1007/978-981-16-6170-9_9)
- Woinarski, J.C.Z. (2010). Biodiversity conservation in tropical forest landscapes of Oceania. *Biological Conservation*, 143(10), 2385-2394. <https://doi.org/10.1016/j.biocon.2009.12.009>
- Zhou, X.M., Yang, J.J., Liang, Z.L., Pollawatn, R., Knapp, R., Parris, B., Sundue, M., Ranker, T. A., Zhou, L., Lu, N.T. & Luong, T.T. (2023). A global phylogeny of grammitid ferns (Polypodiaceae) and its systematic implications. *Taxon*. 72(5), 974-1018. <https://doi.org/10.1002/tax.12992>