Research Article

Habitat environment data and potential habitat interpolation of *Cyathea lepifera* at the Tajen Experimental Forest Station in Taiwan

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Abstract

Cyatheaceae (tree ferns) are an ancient plant family widely distributed in tropical and subtropical regions, and are valued as witnesses to the evolution of the earth's species. The factors affecting tree fern growth include temperature, moisture, and light. In recent years, mass mortalities of *Cyathea lepifera* have occurred in Taiwan, threatening the survival of this species. To examine the growth situation of tree ferns in Southern Taiwan, we used the Tajen Experimental Forest Station as a study area and surveyed 214 samples of *C. lepifera* trees to establish spatial information for a database of *C. lepifera* to be used for conservation strategy. The results show that the ecological optima are an elevation of 500–800 m, slope of 20–30°, aspect of 90–135° (Eastern), and whole light sky space of 20%–80%. Most tree ferns grow in open areas and valley areas, and the health of *C. lepifera* is greatest in the valley areas. In addition, a high light environment is not conducive to seedling regeneration, and low light conditions lead to competition for resources. Therefore, *C. lepifera* can grow in a medium-high photometric environment, which promotes plant growth and seedling regeneration. In the future, we will designate conservation areas according to the optimal habitat as well as adopt forest management practices to protect this species.

Keywords: Ecological database, Tree fern, Conservation strategy

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Introduction

Cyatheaceae are a large tree fern family that first appeared in the Middle Jurassic age. Because of changes in ecology and the evolution of the Earth, most of the Cyatheaceae are extinct. Only a few of the species growing in certain local areas with suitable ecological environments escaped extinction. Currently, the Cyatheaceae are distributed in warm and moist tropical and subtropical forests [1-4]. To protect these epibiotic tree ferns from being sold randomly and overexploited, the Convention on International Trade in Endangered Species of Wild Fauna and Flora incorporated all Cyatheaceae species in 1997 [5]. Currently, only seven species of the Cyatheaceae grow in Taiwan. Of these, *Cyathea lepifera* (J. Sm. ex Hook.) Copel. (Cyatheaceae), with the common name ''flying spider-monkey tree fern'', is the most widely distributed, highest in number, and tallest, and also has ornamental and medicinal values [6]. *C. lepifera* are widely distributed in low-altitude areas in Taiwan. Globally*, C. lepifera* are primarily distributed in Taiwan and scattered in the Philippines and the Ryukyu Islands. In addition, *C. lepifera* are important for biodiversity conservation.

Developing the database of its habitat to conserve a species is basically on understanding the distribution, physiological characteristics and habitat preferences of species which is selection of conservation areas to maintain its biodiversity [7-10]. Geographic Information System (GIS) provides the spatial analysis module for applying overlay analysis on the individual tree location map, slope, aspect, sea-level altitude, and whole light sky space (WLS), various habitat environment data of tree positions can be obtained [11, 12]. The habitat environment data estimated by GIS could conserve human resources and enhance data objectivity and accuracy than ground survey [13, 14]. For rare species, the habitat environment data of species integration can be used to select suitable habitats as conservation areas for forest management, prohibiting human disturbances that may result in species death and promoting the growth and health of the species [7, 15].

Since 2007, *C. lepifera* have died in high numbers in Taiwan. The angiospermae of *C. lepifera* were infested and bitten by weevils, allowing ascomycota to enter the *C. lepifera* from the wounded angiospermae and destroy its water and nutrient transportation systems. In afflicted angiospermae, the central tissue of the stem turns brown, and the heart-center and vascular tissue are destroyed. When the vascular bundle loses its function to transport water and nutrition, water cannot be transported to the leaves, thus causing the leaves to wilt and die [16]. In previous studies, numerous cases have indicated that weevils and fungi are the causes of tree fern deaths [17, 18]. Insecticide treatment is the primary prevention method, which against pests with thiabendazole, benomyl, and kasugamycin…etc., inhibiting cell cleavage or protein synthesis respectively, *C. lepifera* growth preferences in wet and warm of valley, insecticide treatment retains residues, toxicity, and biodeposition of characteristics that must be used within carefully; thus, we examined the habitat environment data of *C. lepifera* and used the habitat environment data of species distribution to interpolate the potential habitat of *C. lepifera*. In addition, we investigated management methods and regulations that can reduce the mortality rate of *C. lepifera*.

The purpose of this study was (1) to develop the environment data of slope, aspect, sea-level altitude, and WLS adopted a frequency analysis to determine the optimal habitat environment for *C. lepifera*, (2) to use the habitat environment data and species distribution of *C. lepifera* to estimate the potential habitat of *C. lepifera*, and (3) to establish specific and optimal conservation areas for *C. lepifera*.

Methods

Research area

The Tajen Experimental Forest Station (TEFS) is situated at the juncture of Pingtung County and Taitung County in Taiwan. Its altitude is between 180 and 900 m asl. Located in the southwest of the TEFS is Mount Chiluzhike, which is 916 m high, the highest altitude in its surroundings. The entire terrain descends from the west to east. Because of its warm and humid environment, the TEFS has abundant species. An automatic weather station located at the nearby Mount Mudanchih showed an annual average temperature of 20 °C, average annual precipitation of 3,354.6 mm, and precipitation from May to October that comprised 85.47% of the annual precipitation. Because of the southwesterly current brought by typhoons in summers and northeast monsoons in winters, the TEFS has precipitation all year round. Figure 1 shows the TEFS location.

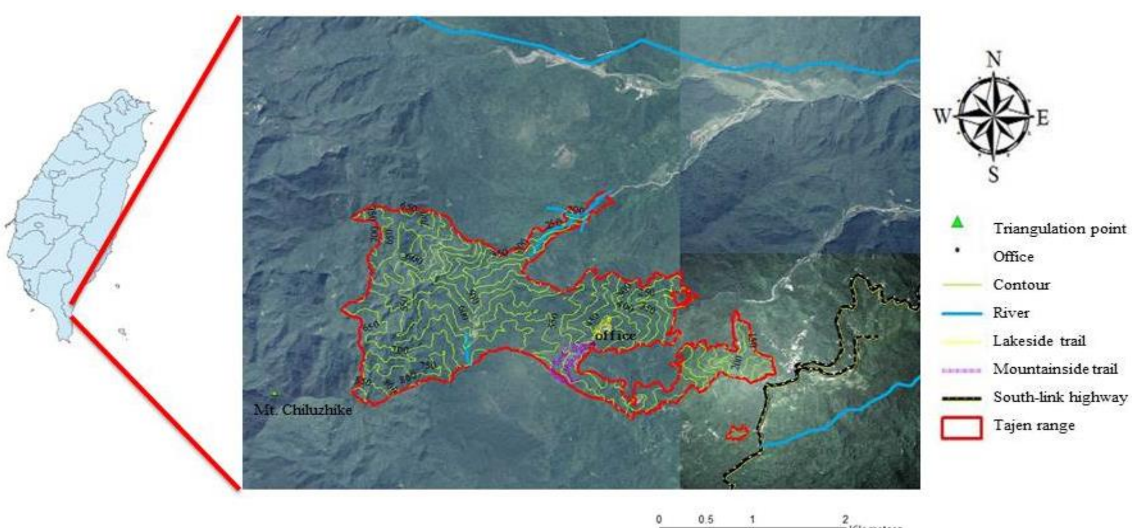

Fig. 1. Location map of the Tajen Experimental Forest Station.

Data collection

For our analysis, we used aerial photographs of the TEFS taken on January 26, 2013 by an unmanned aerial vehicle (Swinglet CAM, produced by the Swiss company senseFly). Each pixel represented an area of 89 × 89 cm. These high-resolution photographs provided detailed information on the tree species and *C. lepifera* distribution at the TEFS (Fig. 2). We used these high-resolution photographs to determine the spatial distribution of *C. lepifera* on a large scale, to determine the habitat preference of *C. lepifera*, and to establish a database for species conservation.

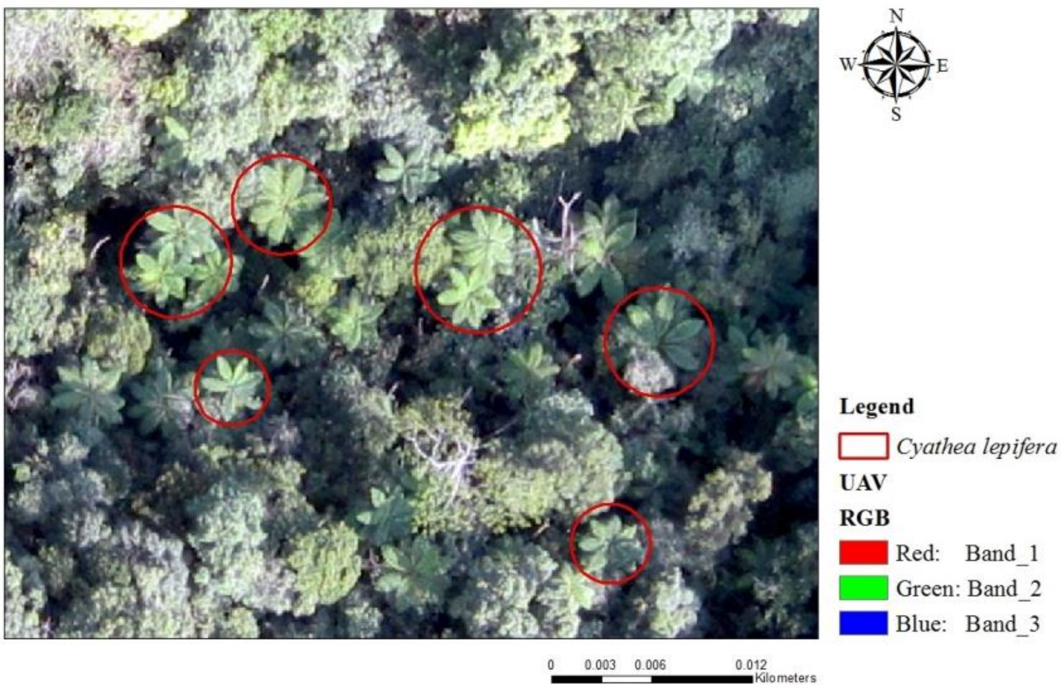

Fig. 2. Top view of *Cyathea lepifera* at the Tajen Experimental Forest Station.

For the *C. lepifera* habitat data, we selected 40 sample plots of 10 × 25 m and a total of 214 plants. In addition to basic information on the tree species, we collected the microhabitat light penetration rate of the crown canopy to examine the influences of light exposure on fern seedling growth. We used the WLS value to determine the influences of long-term available light exposure (intense or moderate) on *C. lepifera* growth. From the 12 azimuths and for four weeks, we measured the WLS in the sample plots and measured the altitude angle of the shadow to obtain the percentage of direct light sky [19]. We used the LAI-2000 plant canopy analyzer (produced by LI-COR) to measure the leaf area index (LAI). A fisheye light sensing lens and control recorder were used for horizontal shooting of the research area, to compare light exposure of the WLS above the canopy to the areas shadowed by plants. The influences of light exposure on the *C. lepifera* adult plants and seedling growths were determined according to the WLS value and LAI, which measured the light exposure of the microhabitat.

Interpolating the potential habitat of Cyathea lepifera

Because physical environmental factors are closely correlated with vegetation distribution and forest tree growth, the ecological niche of species can be determined by investigating correlations among physical environmental factors, vegetation distribution, and forest tree growth. The aerial photographs indicated that the canopy of *C. lepifera* is palmate shaped, making *C. lepifera* unique among other tree species and easy to identify in the photographs. We used the high-resolution aerial photographs to extract the *C. lepifera* positions on a large scale and established 1,359 positions to analyze the *C. lepifera* habitat data. However, the weakness of using aerial photographs for interpretation was that only the upper dominant tree layer, and not the trees of middle and lower levels, can be identified in those photographs. Consequently, all of the extracted data of the habitat preference of *C. lepifera* reflected only the characteristics of the upper dominant tree layer. We used the 1,359 positions data of *C. lepifera*, employed the ArcGIS to extract the environment data of the slope, aspect, sea-level altitude, and WLS (Fig. 3, Table 1), used frequency analysis to examine the optimal habitat for *C. lepifera*, and investigated the habitat preference of *C. lepifera* based on light exposure in the microhabitat and soil information obtained from field investigations.

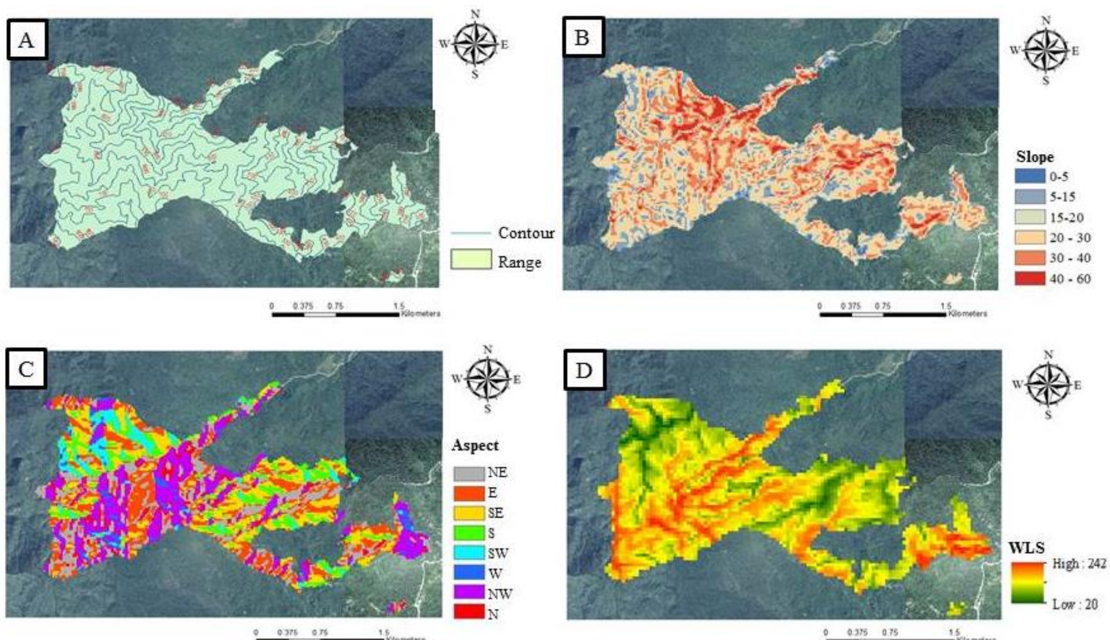

Fig. 3. Environmental factor maps of the TEFS: (A) altitude, (B) slope, (C) aspect, (D) whole light sky space.

Conservation methods for Cyathea lepifera

Since 2007, *C. lepifera* in the northern region of Taiwan have died in high numbers. The angiospermae of *C. lepifera* were bitten by weevils, allowing Ascomycota (sac fungi) to enter the *C. lepifera* from the wounded angiospermae, destroying its water and nutrient transportation systems and causing the death of the angiospermae. Our research area used the southern-most areas of Taiwan to discern whether the same symptoms and cause of *C. lepifera* death occurred. According to the wilted angiospermae observed during the field investigations, *C. lepifera* exhibit two wilt conditions. In the first condition, when the angiospermae wilts naturally, the leaves fall slowly to maintain the life of *C. lepifera,* or the dead leaves turn brown and persist on the stems (Fig. 4). The second condition is the same as that reported in Fu et al. [16] for *C. lepifera* death caused by pests. The *C. lepifera* within the research area must therefore be protected and cared for by using external measures.

Fig. 4. Growth conditions of *Cyathea lepifera* at the TEFS: (A) healthy condition, (B) naturally wilted condition, (C) abnormal wilted condition.

The conservation approaches for protecting *C. lepifera* can be primarily divided into *in situ* conservation and *ex situ* conservation, which both consider the habitat environment of *C. lepifera*. An effective method of *in situ* conservation is to provide legal protection for endangered species, establish specific conservation areas, and protect endemic species and their genetic diversity, by executing conservation measures at the original habitats of the endangered species. Based on the potential distribution of *C. lepifera*, we marked the conservation areas for *C. lepifera* and investigated the forest management methods (*e.g.*, branch pruning and vine removing) and forest operations (*e.g.*, operation methods for improvement felling) at various intensities. The influences on the growth and health conditions of *C. lepifera* can be used for *C. lepifera* management in the future as well as for species protection.

Table 1. *Cyathea lepifera* distributions of habitat fundamental characteristics.

	Slope (◦)			Aspect			Altitude(m)			WLS (%)		
	Grade	Amount	Ratio (%)	Grade	Amount	Ratio (%)	Grade	Amount	Ratio (%)	Grade	Amount	Ratio (%)
1	0-5	14	1	N	219	16	500<	5	1	0-10	0	0
2	5-15	136	10	NE	339	25	500-600	235	17	10-20	23	2
3	15-20	378	28	E	485	36	600-700	1045	77	20-30	139	10
4	20-30	505	37	SE	224	16	700-800	74	5	30-40	264	19
5	30-40	316	23	S	15	1				40-50	199	15
6	>40	10	1	SW	1	0				50-60	228	17
7				W	8	1				60-70	215	16
8				NW	68	5				70-80	270	20
9										80-90	21	2
10										90-100	0	0
	Total	1359	100	Total	1359	100	Total	1359	100	Total	1359	100

Results

Slope

Slopes have certain influences on soil. Because the solar angle-of-incidence and wind action differ on various slopes, the soil water, soil moisture, and soil temperature of slopes are indirectly influenced [20]. The number of *C. lepifera* distributed on the various slopes can be used to indirectly investigate the soil water requirement for *C. lepifera* growth. *C. lepifera* is widely distributed at a slope of 15°–40°, and particularly at a slope of 20°–30°. We used the chi-square test to examine the significance of various slopes, and obtained a chi-square value of 921.605 and *P* value of < 0.001.The *C. lepifera* growth on slopes exhibited extremely significant differences. The slope of 20°–30° had the highest frequency of *C. lepifera* occurrence, whereas the extremely steep slopes and smooth slopes had the lowest frequency of *C. lepifera* occurrence.

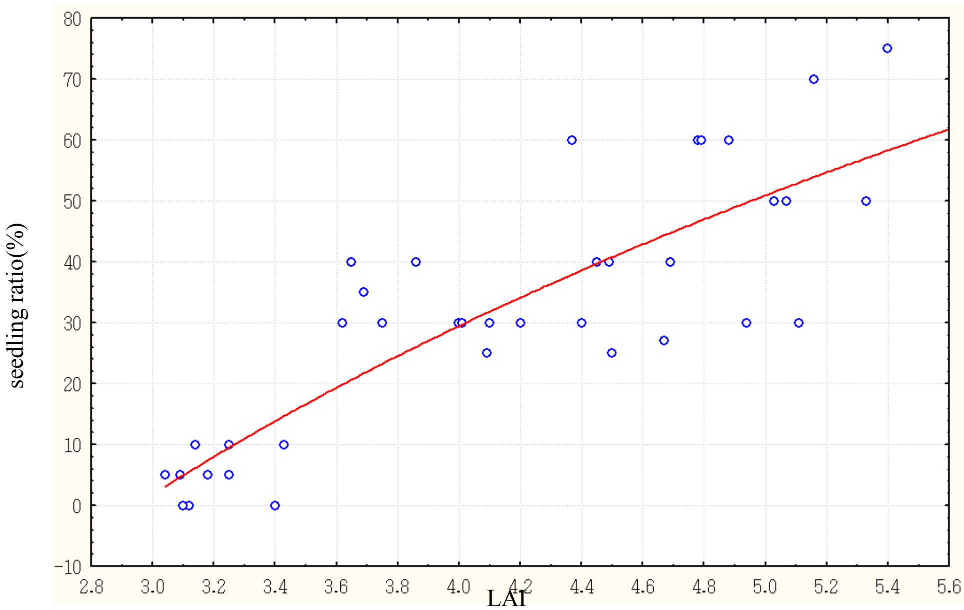

Fig. 5. Logistic regression model on the relationship between the seedling ratio of *Cyathea lepifera* and LAI.

Aspect

The TEFS primarily has eastern, northeastern, southeastern, and northern aspects. We used the chi-square test to examine the aspects and obtained a chi-square value of 1308.8 and a *P* value of < 0.001, indicating that *C. lepifera* growth has extremely significant differences among aspects. The growth morphology of *C. lepifera* on the eastern aspect was extremely evident superior, and the frequency of *C. lepifera* occurrence on the northeastern and southeastern aspects were higher and differed significantly from the other aspects.

Sea-level altitude

The TEFS is located at low altitude, where *C. lepifera* are widely distributed. Statistical analysis of the aerial photographs indicated that the frequency of *C. lepifera* occurrence was the lowest below 500 m and that the frequency of occurrence increased as the altitude increased. For example, the frequency of occurrence at 600–700 m was 77%, indicating that the *C. lepifera* within the research area were primarily distributed in areas with high altitude and exhibited a significant difference on growth condition at a high altitude. The chi-square test revealed a chi-square value of 2033.9 and *P* value of < 0.001, suggesting that the *C. lepifera* growth at altitude was statistically significant.

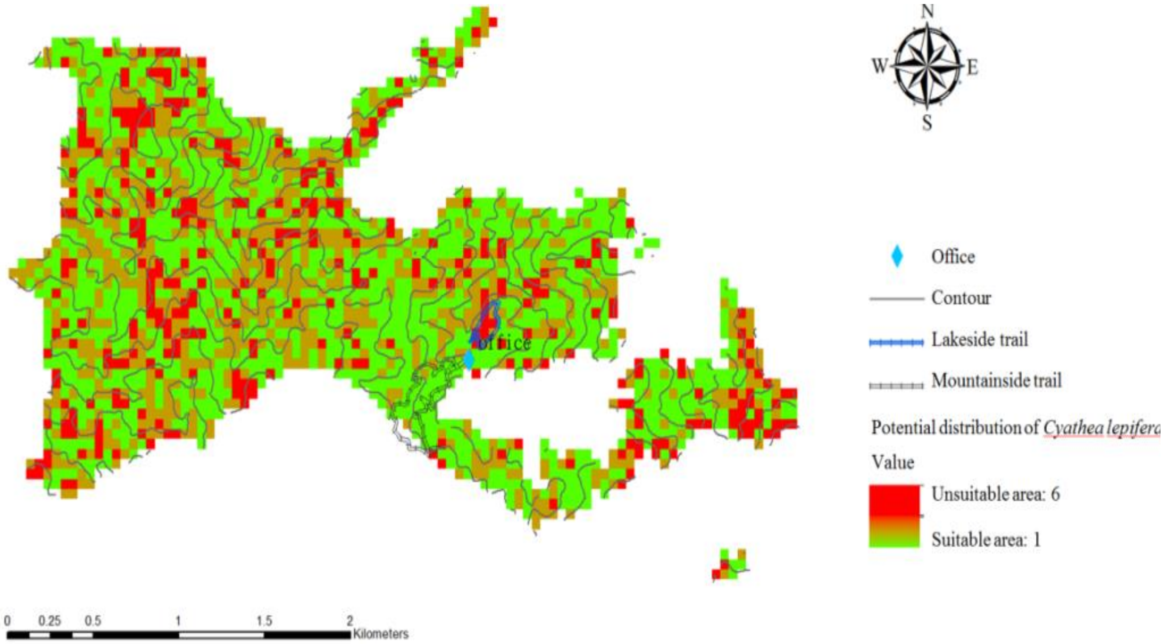

Fig. 6. The potential distribution of *Cyathea lepifera* at the TEFS.

Influences of light exposure on Cyathea lepifera *growth*

Regarding the large scale observation of WLS*, C. lepifera* can grow at a wide level of light exposure and are distributed in areas with low light exposure (20%) to medium-high light exposure (80%). The chi-square test revealed a chi-square value of 411.1 and P value of < 0.001, suggesting that WLS significantly influenced the growth of *C. lepifera*. If the areas were divided according to the ecological amplitude of *C. lepifera*, the habitat preference for *C. lepifera* would be areas with suitable light exposure, whereas *C. lepifera* growth would be suppressed in areas where the light exposure is overly intense or no light penetrates, resulting in poor growth, no growth, or no *C. lepifera* reproduction.

To investigate the microhabitat influences of light exposure in forests on the seedling regeneration of *C. lepifera*, we compared the light exposure of TEFS forests measured by LAI to the corresponding seedling ratio of *C. lepifera* seedling regeneration from relative positions. Figure 5 presents the research results. We excluded Sample Plot 1, which was contaminated by human activity, and used the LAI values from the remaining 39 sample plots as the independent variables, the seedling regeneration ratio of *C. lepifera* in the sample plots as the dependent variables, and the logistic regression model to conduct a regression analysis. The obtained seedling ratio = -103.6995 + 221.2295 × $\log_{10}$(LAI), R^2 value was 0.714, and P value was < 0.001. The results suggested that light exposure significantly influenced the seedling regeneration of *C. lepifera*. Figure 5 indicates that a high LAI value suggests an effective seedling ratio, but when light exposure in the forests falls below a certain level, the growth and germination rates of *C. lepifera* are limited and *C. lepifera* growth is suppressed.

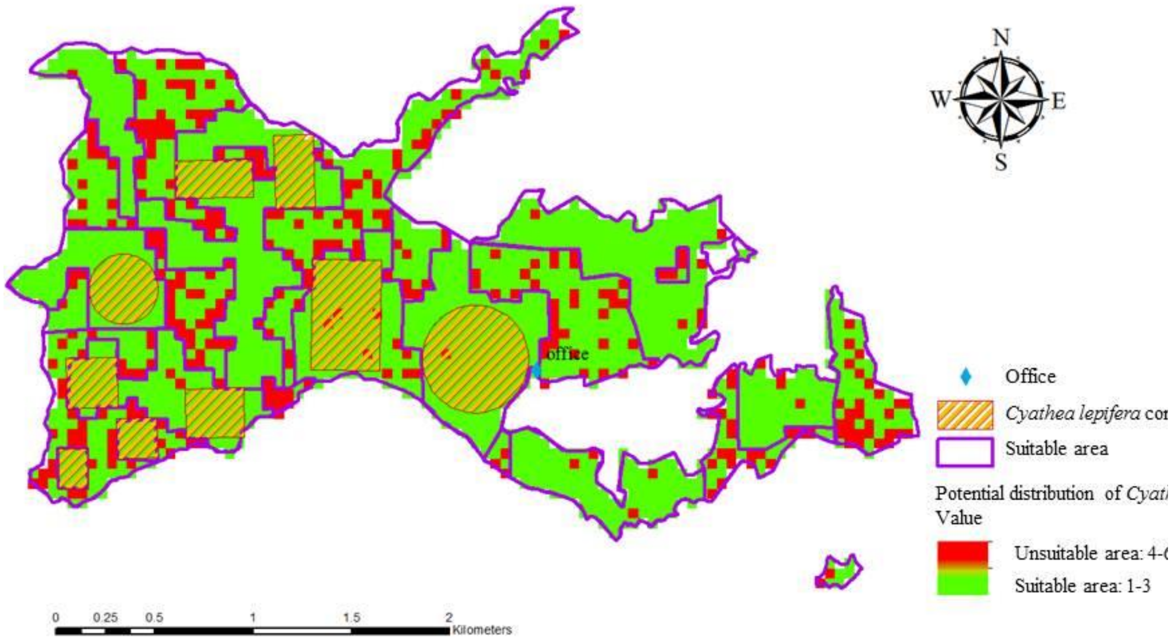

Fig. 7. Establishment of the conservation areas for *Cyathea lepifera*

Designating the conservation areas for Cyathea lepifera

The ecological database was developed by a multiscale evaluation method. Potential habitats for rare plants can be determined by analyzing the spatial distribution preference of the species from forest characteristics, slope, and aspect [7, 8, 11]. Therefore, we used the multiscale evaluation method to designate conservation areas for *C. lepifera* by synthesizing the habitat environment information of the slope, aspect, and WLS associated with *C. lepifera.* Using factor analysis, the weighted values of the habitat preference of *C. lepifera* for slope, aspect, and WLS were 0.3325, 0.3614, and 0.3147, respectively. By standardizing the habitat weighted values, we obtained the suitable index for *C. lepifera* and used the ArcGIS to draw a map indicating its potential distribution. Figure 6 shows the suitable areas for *C. lepifera* growth in the TEFS. Levels 1 to 6 indicate the most suitable to least suitable habitat for *C. lepifera*.

We used the maps showing the most suitable habitat for *C. lepifera* to divide the suitable areas for *C. lepifera* growth into levels. Levels 1 to 3 and Levels 4 to 6 indicate the suitable and unsuitable areas for *C. lepifera* growth, respectively (Fig. 7). After this division, the suitable areas can be further used to establish the conservation areas for *C. lepifera*. The principle for establishing the conservation area was that the area must be large; moreover, because the edge effects of the conservation area shape need to be considered, the primary design for the conservation area has circular and irregular shapes [21, 22]. Therefore, in our study, the designation of the conservation areas for *C. lepifera* focused on maintaining the entirety of the ecological system. In short, the conservation areas for *C. lepifera* were designated according to the suitable areas for *C. lepifera* growth.

Discussion

Habitats for Cyathea lepifera

Topographic factors were used to investigate the growth conditions of *C. lepifera*, which most frequently occurred at slopes of 20°–30°. Short steep slopes and moderate steep slopes are suitable areas for vegetation growth because water can be retained in these areas. Neris et al. [24] reported that in rainforests, a steep slope indicates a high moisture content. Damp habitats are the preferred areas for *C. lepifera* growth. However, because of the rainfall patterns in Taiwan, water cannot be easily retained at steep slopes, and the distribution of *C. lepifera* is predominantly at moderate and slight slopes. The growth environments for Cyatheaceae are influenced by temperature, light, and moisture, and damp environments are beneficial for spore germination and growth [4, 25, 26]. In Taiwan, the water vapor brought by typhoons in summer is retained in the eastern slopes, which are relatively damper than the western slopes. Therefore, for tree ferns such as *C. lepifera*, the preferred areas for growth are the eastern slopes. Studies on *C. lepifera* growth have indicated that *C. lepifera* primarily grow at intermediate-low altitudes. Among the vegetation, the *C. lepifera* located at an altitude of 400–700 m are frequently the dominant species of the area [27].

Influences of light exposure on Cyathea lepifera growth

Most tree ferns must be exposed to light for the spores to germinate. Where light is weak, a long period is required to achieve the maximum rate of spore germination. Contrarily, in an environment where light is intense, gametophytes are prone to albinism and subsequently die. In addition, darkness suppresses the development and growth of rhizoids in gametophytes. Adequate light exposure enables the sporophyte and gametophyte to fully develop [28, 29]. In sum, for seedling regeneration, intense light exposure or a dark environment will suppress sporophyte and gametophyte growth. Consequently, light is a critical factor influencing seedling growth.

According to data obtained from field investigations, lower seedling regeneration of *C. lepifera* was observed in open areas where light exposure was intense, whereas higher seedling regeneration was observed in damp areas where the stand structure was stable and light exposure was moderately low. *C. lepifera* are regenerated by spore spreading. Under intense, long-period light exposure, spore development and growth are suppressed. In addition, the gametophytes grow in areas associated with suitable soil moisture, low light exposure, and a temperature of 20–30 °C [30–32]. Our results determined that light exposure was a critical environmental factor for both adult plants and seedlings. In an environment with intense light exposure, growth environments that are exceedingly dry and with inadequate shelters are unfavorable for seedling regeneration. In addition, intense wind is unfavorable for the health of adult plants.

Field investigation

After an integrated application of the GIS and field investigation, we determined that *C. lepifera* grow in damp habitats with a wide range of light exposure, in dense groups along forest streams. Jones et al. [33] analyzed tree fern habitats and found that light and drainage are two critical factors influencing tree fern growth. Although each tree fern has its own ecological niche, the habitat preferences of most tree fern species are valleys. Volkova et al. [4] reported that light influences the speeds of photosynthesis and leaf growth of tree ferns and that intensive irradiation stimulates the photosynthetic capacity and nitrogen distribution of the thallus. However, light exhibited few influences on the stomata and photosystem II of tree ferns.

In the past, tree felling and forestation occurred at the TEFS. After 30 years of ecological succession, the forest structure of TEFS is currently hierarchical and the forest gaps are extensive in valleys; thus, the valleys with moderate light exposure are the most suitable areas for seedling regeneration. Both the open areas and valleys were the preferred habitat for *C. lepifera* growth; however, the pests demaged *C. lepifera* in TEFS was occurrence in 2011, especially seriously endanger the health of *C. lepifera* in an open area where we found the leaves fall slowly or turn brown and persist on the stems (fig. 4). If restorations are to occur in open areas, protection for *C. lepifera* must be strengthened to prevent conditions that damage the health of the trees. Consequently, valleys would be the most favorable restoration areas for *C. lepifera* in the future.

Implications for conservation

C. lepifera generally grow in areas at an intermediate-low sea level in Taiwan. In recent years, *C. lepifera* has been affected by *Ophiodiaporthe cyatheae* gen. et sp. nov., an ascomycetous pathogen that causes the infected angiospermae to die in high numbers, qualifying C. *lepifera* for protection by The International Union for Conservation of Nature. Currently, the distribution of *C. lepifera* is densest in Taiwan [16]. In addition to providing remedies to manage pests and disease, we used the *C. lepifera* protection database, based on the ecological amplitude of *C. lepifera*, to designate potential restoration areas offering suitable habitats and protection for this species. Although establishing the restoration areas cannot increase the diversity of the stand composition, these areas can improve the health and, most importantly, genetic diversity of *C. lepifera*. To strengthen physical environment protection, conservation policies for *C. lepifera* restoration areas must be established.

Regarding the restoration and management methods for *C. lepifera*, we used the map showing the potential distribution of *C. lepifera* using the GIS. *In situ* conservation was conducted in areas with a high distribution of *C. lepifera* for two factors. First, the *C. lepifera* of all sample plots were fertile, and the forests were covered with *C. lepifera* seedlings. Thus, the fertile adult plants can enable the species to breed at the *in situ* conservation areas. Second, maintaining a healthy native habitat can increase the genetic diversity of a species. In addition, Ranil et al. [3] indicated that the genetic diversity of Cyatheaceae in a natural forest is superior to that in an *ex situ* conservation area. Thus, human disturbance of the habitats must be reduced, and the development of biodiversity should be emphasized. Conservation methods can be divided into germplasm conservation and forest management. *C. lepifera* primarily breed by the sporophyte on the back of a leaf, and June to August are the months for spores to mature. Therefore, for germplasm conservation, the spores that are fertile during this period must be collected and stored at a low temperature either in dry liquid nitrogen or through moisture-storing methods [34]. In the future, the spores can be planted in the *C. lepifera* conservation areas mapped by the GIS. Providing that the ecological amplitude exhibits no changes, areas similar to the natural habitats in which *C. lepifera* grow are more favorable areas for *C. lepifera* growth than *ex situ* conservation areas.

Forest management methods can effectively promote *C. lepifera* growth and regeneration. Tree felling and branch pruning increase the light exposure of a forest and promote *C. lepifera* seedling growth. Ough and Murphy [35] suggested that only a certain number of tree ferns should be kept as mother trees, whereas the other tree species should be felled. In addition, because the health condition of tree ferns has declined annually and the seedlings have received excessive light exposure and are thus unable to breed, the seedlings of other pioneer tree species have become the dominant tree species. According to the history of forestation at the TEFS, a landscape area for *C.*

lepifera was once established. In this area, only *C. lepifera* was retained and other tree species were felled, and forest understorey management was conducted to establish an area purely for *C. lepifera*. However, within two years, the *C. lepifera* continued to be affected by diseases and nearly all the angiospermae died. As noted by scholars in the previous studies, *C. lepifera* are tree ferns that are symbiotic. Thus, for the forest management of *C. lepifera*, mild understorey management must be employed to protect *C. lepifera* growth, to enable spores to receive an intermediate-low light exposure, and to retain adequate space for seedling growth. If thinning operations are required, selective cutting can develop the forest stand into a multilayered forest structure that can increase the light exposure received by the forest and prevent pests from spreading to the entire forest stand.

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