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Japanese Climbing Fern, *Lygodium japonicum* (Thunb.) Sw. : A Potential Invasive and Ecological Threat

Aurfeli D. Nietes* and Inocencio E. Buot Jr.

Institute of Biological Sciences, University of the Philippines Los Baños, Laguna, Philippines
*Corresponding Author: adnietes@up.edu.ph

ABSTRACT

The Japanese climbing fern *Lygodium japonicum* (Thunb.) Sw. has manifested its invasive tendencies, not just in countries outside of its native origin, but also in some areas of its original distribution. The proliferation of such species resulted in economic instability and ecological damage which alarms ecologists, environmentalists and area managers. Thus, it is important to understand the mode of introduction and proliferation of such species to be able to prepare and formulate specific and effective guidelines in managing future invasion of such species. This paper discussed the contribution of trading, importation and transport of wildlife in the introduction of and spread of *L. japonicum*. The reproductive biology of the Japanese climbing fern has been reviewed to highlight the role of vegetative reproduction and spores in the immense proliferation of this species, and the challenges it imposes in the control and regulation of its spread. Containment and isolation of the invasive species is still considered as the best preventive method to avoid the invasion of *L. japonicum*, but in the occurrence of infestation, available research-based control methods must be applied. Existing control methods were included in this review with the addition of general considerations regarding the application of each method. Management plans are recommended to be formulated specific for *L. japonicum* (Thunb.) Sw. and applied in a long-term approach to achieve and ensure effective and sustainable practices and strategies in regulating invasion.

Keywords: control strategies, international trade, introduction, invasion.

INTRODUCTION

The "Japanese climbing fern" *Lygodium japonicum* (Thunb.) Sw. is native to Eastern Asian countries (Bangladesh, Bhutan, China, India, Indonesia, Japan, Laos, Myanmar, Nepal, Pakistan, North and South Korea, Sri Lanka, Taiwan, Thailand and Vietnam) including the Philippines, where it is locally called "nitong-pula" and utilized in basketry and weaving industries (Chang *et al*., 2014; Ngatinem-Praptosuwiryo, 2003; EPPO, 2018). Such a perennial fern is easily recognized for its vine-like habit with indeterminate frond that is capable of scrambling and winding through neighboring vegetation (Lott *et al*., 2003; Hutchinson and Langeland, 2010; Bohn *et al*., 2011). It can be morphologically delineated from other species of *Lygodium* through its vein free, pinnate pinnae with fertile pinnae more dissected than the sterile one (Copeland, 1958).

This species has been introduced to and cultivated in several countries like South Africa, America, Singapore, and Oceania (except Papua New Guinea), Mexico, Puerto Rico, and some European countries mainly for ornamental purposes where they are used for its added beautification of botanical gardens and greenhouses (Ferriter, 2001; Minogue *et al*., 2010; EPPO, 2018; CABI, 2021).

The distribution of *L. japonicum* (Thunb.) Sw. expanded widely outside of its native origin; however, it has become noxious, especially in the state of Florida as its uncontrolled spread leads to the collapse of the natural communities and outcompetes rare and threatened species (*Actinostachys pennula* (Sw.) Hook., *Sideroxylon thornei* (Cronquist) T.D. Penn., *Aristolochia tomentosa* Sims and *Polygonum meisnerianum* Cham. & Schltdl.). These caused challenges in the tourism industries by damaging biological resources of parks and other natural ecosystems (Ferriter, 2001; Munger, 2005; GISD, 2021). Pine plantations were endangered not just by the increase of the population of *Lygodium* that interferes during the harvest period but also with the possibility of severe wildfires, as the habit of *L. japonicum* (Thunb.) Sw. may serve as a fuel ladder that could cause the spread of fire to forest canopies creating more devastating impacts (Minogue *et al*., 2019).

The Centre for Agriculture and Bioscience International (CABI, 2021) noted its tendencies of becoming invasive in its natural range, such as in the Philippines, where it is observed to invade upland rice farms (Moody, 1989; Galinato *et al*., 1999). This calls for the need of *L. japonicum* (Thunb.) Sw. to be included in the "watchlist" of possible invasives even in countries of its natural distribution. There is a need to initiate and prepare for possible proliferation of this species. Thus, a review paper is conducted to assess the surprising encroachment of *L. japonicum* (Thunb.) Sw. in forests, plantations and other ecosystems, evaluate its reproductive biology that aids in its posing invasiveness, and design holistic management strategy for *L. japonicum* (Thunb.) Sw. invasion.

METHODOLOGY

A comprehensive review of published literature regarding the morphology, ecology, reproductive biology and economic uses of *L. japonicum* (Thunb.) Sw. (Fig. 1) were evaluated and synthesized to assess its invasion among various ecosystems. Reputable scientific journals and databases such as Centre for Agriculture and Bioscience International (CABI), International Union for Conservation of Nature (IUCN) and Global Invasive Species Database (GISD) served as the main source of information for the invasive tendencies of *L. japonicum* (Thunb.) Sw. and management measures employed to control such invasive species. Online references and materials were accessed using structured keyword

Figure 1. *Lygodium japonicum* (Thunb.) Sw.. a. habit; b. lamina; c. fertile lamina showing the sori.

(*Lygodium japonicum*, *Lygodium*, control, invasive, distribution, reproduction *etc*.) search.

RESULTS AND DISCUSSION

Introduction, Encroachment and Reproductive biology

Lygodium japonicum (Thunb.) Sw. originates in Eastern Asian countries (Fig. 2) and has expanded its distribution after being introduced to regions outside of its native range. In a global perspective, *L. japonicum* (Thunb.) Sw. was able to infiltrate several countries with horticultural trade as the chief pathway of introduction. Humans initially considered this plant for ornamental,

landscaping and architectural purpose, wherein it is utilized as a vertical greenery system not just meant to provide aesthetics, but also natural shade that could thermally regulate the walls of infrastructures. The dense mat formed by the spreading habit of *L. japonicum* (Thunb.) Sw. is considered as a natural tool in reducing internal temperatures of buildings thus facilitates adaptation of urban areas to warming climate without the increase of energy consumption (Hara *et al*., 2016). With these aesthetic and energy-saving benefits, many are interested in purchasing and cultivating such an invasive fern.

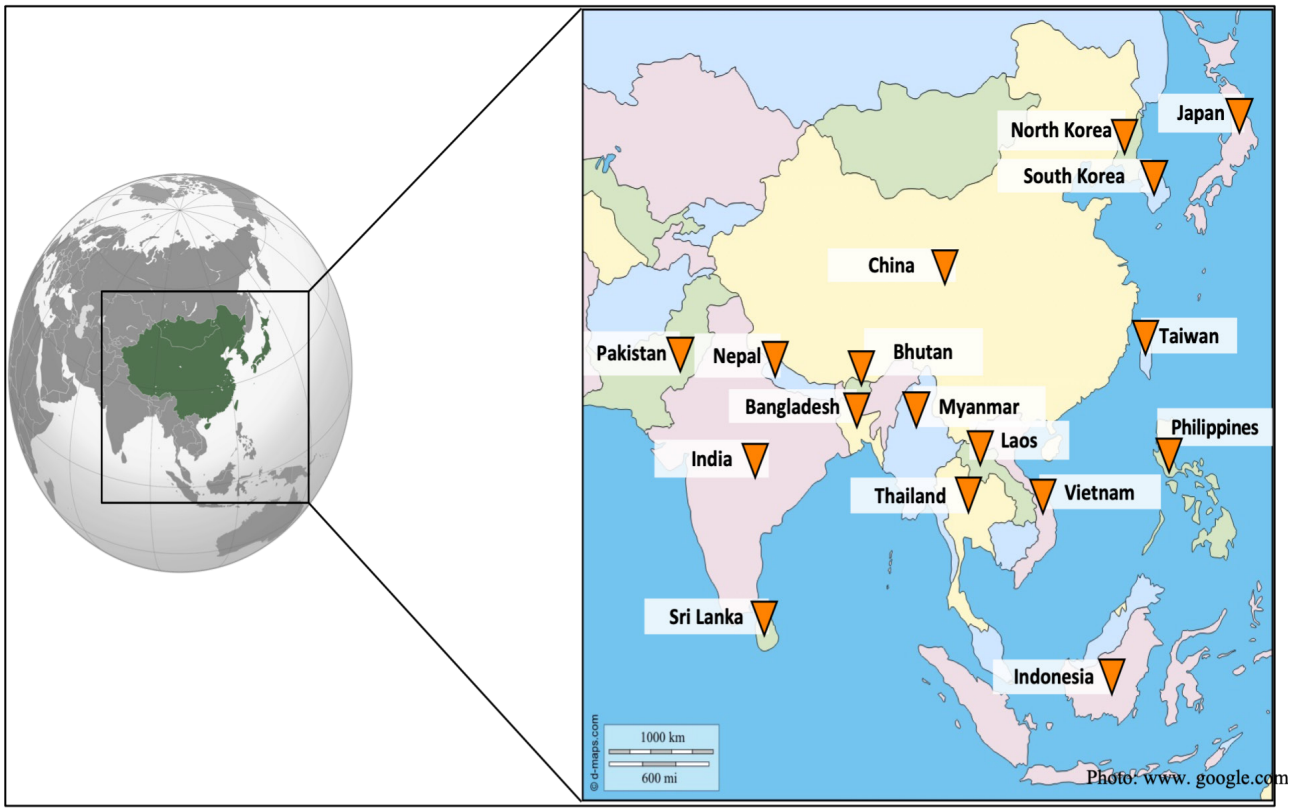

Figure 2. Native distribution of *Lygodium japonicum* (Thunb.) Sw.

Some introductions were even indirectly caused by trading. The EPPO (2018), has reported that *L. japonicum* (Thunb.) Sw. was able to invade the Netherlands by the trading of bonsai from China. Gametophytes were notedly observed in the growing media of bonsai, whereby they indirectly introduced such species in the country. Aside from this, mistakes in identification is also a problem that leads to *L. japonicum* (Thunb.) Sw. invasion. Orchard and McCarthy (1998) noted that *L. japonicum* (Thunb.) Sw. was mistaken as *L. flexuosum* (L.) Sw. which is native in Australia. This mistaken identity paved ways for *L. japonicum* (Thunb.) Sw. to escape from cultivation and become naturalized in the coastal districts of Queensland, northern areas of the Northern Territory and Sydney. It is also considered as invasive in these areas. All of these scenarios show the contribution of wildlife trading to the introduction of invasive species outside of its natural origin.

In the local ecosystem scale, *L. japonicum* (Thunb.) Sw. infiltrates forests, plantations and agricultural fields. These encroachments were mostly brought by *L. japonicum* (Thunb.) Sw. spores contaminating agricultural and logging machinery, timber, wood materials, as well as clothes of control managers, and visiting tourists in recreational areas serving as its dispersal vector. The sporangium of *L. japonicum* (Thunb.) Sw. is capable of housing 256-minute spores that can easily adhere to surfaces causing the unintended spread of this invasive species. The size of its spore ranges from 64-80 µm in diameter (Murtaza *et al*., 2004) which therefore caters to long distance dispersal (Sharpe *et al*., 2010, Barrington *et al*., 2020) that can be easily carried through wind (Wolf *et al*., 2001) and water due to its size. Rainwater run-off and flooding may act as the main pathway towards infiltration of natural ecosystems increasing the potential of spores to move in a wider distribution.

Lygodium japonicum (Thunb.) Sw. spores are characterized as chlorophyllous (Van Loan, 2006) which are more prone to degradation caused by environmental stress and with shorter viability in comparison to non-chorophyllous spores (Van Loan, 2006; Ballesteros and

Walters, 2007; Sharpe *et al*., 2010). However according to Berry (2019), spores of *Lygodium* species remain viable for a number of years; as it was documented to last for a minimum of eight years in the soil bank (Hutchinson and Langeland, 2006; Rowe and Lockhart, 2011). Its spores could start germinating within six days, which is short enough for it to easily establish its population and start colonizing in broader ranges, invading natural ecosystems, as long as conducive ecological requirements for spore germination are met.

Ecological factors are involved in fern establishment. One of these factors is its mating system (Klekowski, 1972; Bystriakova *et al*., 2014). *Lygodium japonicum* (Thunb.) Sw. produces homosporous spores which have a bisexual potential. It is capable of intra-gametophytic fertilization which therefore allows successful reproduction from a single spore, ensuring germination and establishment of a population (Klekowski, 1982; Suter *et al*., 2000; Lott, 2003; Sharpe *et al*., 2010). Spore germination and fertilization are also dependent on two main abiotic factors – light and water. Light is needed for spores to germinate and produce the reproductive stage of fern which is the gametophyte. These gametophytes house the sexual parts (antheridia and archegonia) which are aided by water in uniting the gametes for fertilization resulting to the formation of sporophytes of *L. japonicum* (Thunb.) Sw. (Sharpe and Mehltreter, 2010).

At the sporophytic phase, encroachment is mostly supported by rachis and rhizome elongation which primarily gives this species its creeping habit. The rachis of *L. japonicum* (Thunb.) Sw. are capable of indeterminate growth thus enabling such species to form ladders as it invades and builds its population in an area (Munger, 2005, Van Loan, 2006; Minogue *et al*., 2010). *Lygodium japonicum* (Thunb.) Sw. prefers areas that have warm climates (CABI, 2021) and with pronounced wet and dry seasons. During cold winter season, *L. japonicum* (Thunb.) Sw. leaves may die but the plant can still survive through its underground root and rhizome that undergo dormancy in a freezing environment. After the freezing period, it can then continue to grow reviving the lost foliage (Miller *et al*., 2010).

Lygodium japonicum (Thunb.) Sw. can infiltrate a variety of ecosystems including mesic forests, river edges, ditches, areas adjacent to swamps, marshes, lakes, and creeks (Langeland and Cradock Burks, 1998; Minogue *et al*., 2010). As it continues to grow and creep profusely around the vegetation, it can restrain the growth of other species either through allelopathy (Berry, 2019), resource competition, and mechanical pressure, enhancing its invasive potential. The dense thickets and canopies formed by this fern limits the acquisition of light by other species (Leichty *et al*., 2011) and the rachis of *L. japonicum* (Thunb.) Sw. may wrap profusely around the habit of neighboring vegetation resulting in physical strangulation. Through these ways, it hinders the growth and establishment of other species in the ecosystem, which therefore causes the alteration of community structure and decline of biodiversity (Minogue *et al*., 2019, Bohn *et al*., 2011; Leichty *et al*., 2011).

Control and Management Strategies

Invasive management plans are formulated with the chief goal of maintaining economic and social goals. However, these strategies lack in-depth insights on biological concepts and holistic approaches which result in ineffective common management plans. To attain efficient and sustainable results in weed and invasive management, they have to be linked to biological factors and with holistic knowledge on the interaction of factors such as social, economic and environmental aspects (Swanton and Murphy, 1996).They should be anchored to scientific information and research to acquire efficient and sustainable results. Control and management measures guided by science includes several factors that should be taken into consideration in formulating control and management strategies (ecosystem, cost, community *etc*.) among these is the species and its biology.

In the control of *L. japonicum* (Thunb.) Sw., mode of proliferation and reproduction are the factors to consider in the formulation of management strategies. Once this species establishes its propagule, it can then rapidly grow and reproduce. With the indeterminate growth of its twining frond and wiry rachis, this plant can expand long distances and even to canopies, reaching lengths of 30 m (Langeland and Craddock Burks, 1998). Its numerous long lived spores are also able to be disseminated easily (Lott *et al*., 2003). Thus, these two are the main challenges in the control and management of this species.

a. Prevention

Numerous models have been developed to manage biological invasions mainly focusing on the invasion process after introduction and establishment of population. However, pre-emptive measures promoting the prevention of initial introduction of invasive species to natural habitat are still considered to be cost-effective and a sound precautionary principle to be applied (Skarpaas and Økland, 2009).

Trading and transport have shaped patterns of biological invasion. As industries moved towards globalization, international trade facilitated the introduction of invasive species involving long distance and short distance dispersal through international and local transport and storage (Hulme, 2009; Skarpaas and Økland, 2009). Thus, to prevent further invasion of *L. japonicum* (Thunb.) Sw., containment and regulation of transport should be implemented. Selling, import and growing of this invasive species outside of its origin should be banned to avoid spread of this invasive. Industries and buyers should also be informed through awareness campaigns to help them understand the reasons for banning such trade (EPPO, 2018).

Aside from direct trade of *L. japonicum* (Thunb.) Sw. (EPPO, 2018), instances of contamination of traded forest products by spores and gametophyte has facilitated invasion (CABI, 2021). According to Piel *et al*. (2008), raw logs are the most important forestry products and a major source of alien species. Thus, managing the contaminants of these products is an essential step towards prevention of the spread of invasive. Hulme (2009) cited the measures formulated by Skarpaas and Økland (2009) in reducing the likelihood of pest spread through timber. Among the seven generic measures established in their work, the ones applicable to prevent the introduction and spread of *L. japonicum* were: (1) lessen the imporation of timber to reduce introduction; (2) processing (cleaning and treatment) of timber to halt the development of contaminants; and lastly, (3) isolation of the forest products from forests to avoid colonization of suitable habitat. With the minute size of the spores and gametophytes of *L. japonicum* (Thunb.) Sw., it is more likely that the contamination of these products are unnoticeable, thus it is important to apply these precautionary and regulatory measures.

Equipment and machinery also caused the infiltration of *L. japonicum* (Thunb.) Sw. into agricultural areas, forests and recreational areas (CABI, 2021). Thus, it is important to regularly clean equipment and machinery to avoid unintentional spread of this species (Halloran *et al.*, 2013). The governing body of International Plant Protection Convention (IPPC) known as Commission on Phytosanitary Measures (CPM) has drafted and adopted the International Standards for Phytosanitary Measures (IPSM), which aimed to reduce the risk of transporting contaminants caused via international movement of vehicles, machinery, and equipment. They have formulated guidelines to avoid the secondhand spread of invasive plants which includes sanitary inspections, decontamination of contaminated vehicles, machines, and equipment through cleaning (pressure washing, abrasive blasting, compressed air cleaning, emptying water reservoirs *etc*.) and treatment (temperature and chemical). Non-compliance of such measures results in phytosanitary action and penalties such as detention, cleaning, treatment or reshipment of the used paraphernalia.

b.Eradication and Biological, Physical and Chemical Control

In instances where initial introduction and populations have been established, it is necessary to identify the right protocol to eradicate or at least curb the spread of invasive species. These protocols should be designed specifically for the species of concern, as there is no standard control strategies for biological invasion. For the case of *L. japonicum* (Thunb.) Sw., its proliferation is greatly aided by its seemingly indefinitely growing rhizome and long-lived spores, thus this should be the guide in formulating measures for its control. Biological, mechanical, and chemical controls were the known methods of management for invasive species, however specific considerations should be done in eradicating and regulating the spread of *L. japonicum* (Thunb.) Sw. to acquire effective and sustainable results.

There have been records of natural enemies of *L. japonicum* (Thunb.) Sw. and these are fungus and species of moth. *Puccinia lygodii* a fungus that has been recorded to cause necrotic eruptive pustules in the pinnules of *Lygodium* species in which severe infection would lead to wilting and death (Rayachhetry *et al*., 2001). However, further research is still needed for the introduction of this biological control as native species of *Lygodium* may also be affected and harmed by such fungus (GISD, 2021).

Moths, namely *Austromusotima camptozonale*, *Neomusotima conspurcatalis* and *N. fuscolinealis*, were recorded to feed on *Lygodium* species (Bennett and Pemberton, 2008; Boughton *et al.*, 2009; Langeland and Hutchinson, 2013). Among these three moth species, only *A. camptozonale* and *N. conspurcatalis* have been approved for release in Florida, as biological control for *L. microphyllum*, but they were also suggested to be effective in controlling *L. japonicum* as these moth species were known to feed on all species of *Lygodium* (Boughton *et al*., 2009; CABI, 2021). At present, no biological control agent has been released specifically for *L. japonicum* (EPPO, 2018) as testing and further evaluation is still necessary. The use of natural predators in the control of invasive species has to be guided and monitored by research to determine the effects of such biological control to the species of concern and also to the other organisms. This is to ensure that such method

will not have an adverse effect in the ecosystem.

Physical/ mechanical means of eradicating *L. japonicum* (Thunb.) Sw. have been done by eliminating the aboveground parts through cutting and pulling (Lockhart and Inventory, 2005) or through heavy equipment. However, the species is still able to regrow through the underground rhizome. Thus, uprooting the rhizome is a necessity to avoid the reestablishment of population. Aside from this consideration, the use of physical control of *L. japonicum* (Thunb.) Sw. may also cause the spread of the species as the clothes and equipment used by the control managers may be contaminated by the spores thereby becoming a vector for dispersal. It is then suggested to conduct physical methods of control during the infertile seasons where no spores developed in the frond of *L. japonicum* (Thunb.) Sw. When controlling fertile *Lygodium* population, proper disposal of the removed vines should be applied. Fertile parts should be securely placed inside plastic bags and avoid disposal in un-infested area, and equipment used should be decontaminated on-site (FLEPPC, 2007). These strategies should be seriously considered to avoid unintentional introduction of species to areas of no infestation.

For the chemical or herbicidal approach of control, this is the option made to address great levels of infestation where mechanical/ physical control methods can no longer be accommodated alone. Thus, this method should be used singly or as a supplemental approach to physical strategies of control. These methods have been considered in hopes of maintaining or restoring the native plant community (Minogue *et al*., 2010). Herbicides targets only the foliage thus tendencies of resprouting and reestablishment of population through vegetative means via rhizome is still a possibility. The common herbicides recommended are glyphosate, imazapyr, and triclopyr herbicides that can be applied alone or in combinations (Van Loan, 2006; Miller, 2006; Minogue *et al*., 2010). In the study conducted by Minogue *et al*. (2010), glyphosate alone or in combination with imazapyr or metsulfuron-methyl rendered the highest efficacy (84 to 97%) in controlling *L. japonicum* (Thunb.) Sw. though this does not fully eradicate the species, but the use of such herbicide sprays minimally impacts nontarget vegetation which is a good indicator of its safe use during reapplication in cases of resprouting.

CONCLUSION AND RECOMMENDATION

Lygodium japonicum (Thunb.) Sw. has become a noxious weed in areas outside of its native distribution. However, reports of its invasive tendencies in its native origin have been made which calls the attention of ecologists and area managers of such areas to prepare for the possibility of its infestation. Its introduction is primarily caused by trading and transport in which the globalization of trade resulted to its wider geographical coverage of invation. It resulted in its wider geographical coverage of invasion. The reproductive biology of this species greatly contributes to its invasive abilities. The ability to vegetatively reproduce through its rhizome and the long viability of its minute spores, allows it to establish and continually re-establish its population, promoting it to be dispersed and introduced in longer distances, infiltrating many ecosystems.

The excessive proliferation of this species leads to economic and ecological damage. Prevention of its introduction must be the primary initial action against this invasive species. Regulating the trade and import of this species should be strongly implemented together with the practice of decontaminating forest products, equipment, machinery, and vehicles, which are also viable dispersal vectors. These protocols are made to contain and isolate the invasive species as this pre-emptive measure is considered cost efficient and the best strategy to avoid infiltration of un-infested areas. In instances where initial introduction and population have already been established, control and management strategies specifically made for *L. japonicum* (Thunb.) Sw. have to be formulated. The use of biological, mechanical and chemical controls needs to be applied with precaution, taking into consideration the after effect of applying such methods of control. The application of these measures should be guided by research to monitor its effect on the controlled species and to ensure that there is no threat to the native vegetation. Unintentional spread of the vegetative parts and spores of the species is to be avoided.

Physical/ mechanical control together with herbicidal approach are the strategies that are doable and accessible for local ecosystem managers. Removal of the frond of *L. japonicum* (Thunb.) Sw. can be applied in areas of manageable levels of infestation. However, at excessive proliferation, the use chemical herbicides are a good supplemental option. These two methods of control do not result to absolute elimination of the population as the underground rhizome may cause re-sprouting. Thus, area managers must ensure the total elimination of the whole frond including the rhizome to avoid re-establishment of populations. Controlled populations and areas should be monitored to assess the results of the control methods applied and to detect initial resprouting of the invasive species. Re-application of chemicals and

physical methods can be used in managing the initial formation of re-sprouted individuals.

There is no standard protocol in handling biological invasions and the management of such an environmental dilemma is in a "case to case basis" depending on many factors such as the biology of the invasive species, levels of infestation, existing native species in the area, type of infested ecosystem and the availability of funding for the control; but the formulated strategies have to follow a long-term approach of observation and management to ensure the feasibility of the control methods employed and sustainability of such methods with reference to the health of the native vegetation, ecosystems, and the communities affected. Awareness campaigns focusing on the invasive potential of *L. japonicum* (Thunb.) Sw. must also be initiated to inform the local communities of the possible threats it imposes in the ecosystem. This may encourage the members of the community to take part in the prevention of the encroachment and proliferation of this invasive species.

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