REVIEW

The invasive weed Gorse (*Ulex europaeus* L.) in Sri Lanka: Implications of Naturalization over a Century

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Submitted: 11 December 2021

Accepted for publication: 23 June 2022

Published: 30 June 2022

Abstract

Gorse (*Ulex europaeus* L.) has invaded about 50 countries outside its native range (the Iberian peninsular and Western Europe), extending its range from the high-elevation tropics to the sub-Antarctic islands. Its habit, adaptability, and ability to colonize disturbed ground make it one of the world's most invasive weeds. Gorse has a long history in Sri Lanka, after its initial introduction in 1988 as an ornamental plant at the Royal Botanical Gardens, at Peradeniya. However, it is only about three decades since Sri Lanka first initiated research and assessments on gorse and similar *Invasive Alien Plant Species* (IAPS).

Gorse eradication has been widely attempted in the Central Highlands of Sri Lanka, where gorse populations are localized. These control attempts have had limited success thus far. We reviewed ~60 country-specific and worldwide articles on gorse to gather information on its biology, impacts on biodiversity, and gorse management. We identified some significant gaps in research data and inadequate information, specifically on ecology, invasive behaviour, and management actions in reducing the weed's spread. The IAPS project in Sri Lanka, initiated with the support of the Global Environment Facility (GEF) in 2011, was an eye-opener for more research on the ecology and behaviour of invasive plants, as well as their biodiversity values.

Our studies, conducted exclusively on gorse-infested areas in Sri Lanka are still preliminary and limited. However, it was evident that gorse negatively affected the biodiversity of specially protected sites and natural forest areas, while playing a beneficial ecological role by providing habitat for specific endemic fauna. There is a possibility of gorse expanding its range and distribution into neighbouring zones with climate change occurring in the near future. Management actions taken against gorse in Sri Lanka are primarily mechanical removal, which is only marginally successful. Long-term, more effective and sustainable approaches are required to manage gorse in Sri Lanka. These will have to incorporate competition from fast-growing indigenous vegetation, herbicides, biological control agents, and possibly, controlled grazing and controlled burning. In implementing such integrated management, particular attention needs to be paid to the identified research gaps, especially the impacts on native and endemic fauna and flora in sensitive habitats.

Keywords: Gorse, *Ulex europaeus*, naturalization, invasive alien plant species (IAPS), climate change

Introduction

The struggle of each species for its existence and to become dominant in an ecosystem is influenced by genetic and external biotic and abiotic factors. In this context, weeds of exotic or invasive nature have evolved through a series of barriers enabling them to establish and invade an introduced area (William, 2003). During the invasion process, such plants undergo, tolerate, and overcome several biotic and abiotic stresses, and once established, tend to expand from the place of introduction to the surrounding areas (Richardson and Pysek, 2006).

Gorse (*Ulex europaeus* L.) is one such invasive alien species plant (IAPS), which is now distributed from equatorial to temperate regions of the world. The *International Union of Conservation of Nature* (IUCN) has listed it as one of the top 100 invasive plants on earth (Scott et al., 2005; Atlan et al., 2015). Gorse is a native of the temperate Northern Hemisphere (mainly the Iberian Peninsular and other parts of Western Europe).

Over several centuries, it was introduced to many countries as an attractive garden ornamental, a forage plant, and a hedge plant. Since its introduction, gorse has spread in most countries and has been recorded as a serious weed in countries, including Hawaii, New Zealand, Australia, and Chile. It is also recorded as a common weed in parts of Western Asia (Iran), the Mediterranean region (Italy, and Eastern Europe (Poland).

Gorse had already been declared a noxious weed a hundred years ago in Australia and New Zealand, and in many other countries as posing a threat to native biological diversity (ARMCANZ, 2000). The global distribution of gorse has been reported as increasing through the 19th and 20th centuries, owing to its use as a hedge, an ornamental, and a forage plant. However, in most countries, it is usually limited by being acclimatized to cold and temperate climate conditions, such as those in high altitude, mountainous regions.

Gorse is a woody, spiny, long-lived, tall shrub with a long-lived seed bank, thus rendering its control more difficult. Thickets of this species displace vegetation in grassland habitats and outgrow and supplant tree seedlings in plantation forests (CABI, 2021). Heavy infestations modify the soil and hydrological conditions, and so modify ecosystem processes. Gorse is also known to pose a severe fire risk for indigenous ecosystems and managed habitats and human habitations in some countries and regions (CABI, 2021).

Sri Lanka is an island nation of 65,610 km^2 land area, with natural ecosystems having extremely high levels of species diversity. The island has a higher species richness per unit area than most other tropical Asian countries (Bambaradeniya, 2002). Although Sri Lanka has been recognized as one of the 35 biodiversity hotspots of international significance by conservationists, it is also one of the eight hottest hotspots of habitat loss that would affect biodiversity (MMDE, 2016).

The threat of IAPS is one of the growing threats to biodiversity in Sri Lanka. Several studies in the past attempted to compile lists of invasive alien plants in Sri Lanka, but the unavailability of generally accepted criteria to identify the invasive nature of specific species was a limitation of those studies (Wijesundara, 1999; Bambaradeniya, Ekanayake and Gunawardena, 2001; Marambe et al., 2003; Wijesundara, 2009).

A post-entry Weed Risk Assessment was conducted in 2015 by the *Ministry of Mahaweli Development and the Environment* (MMDE). It listed gorse among the 20 plant species, which were subsequently included in Sri Lanka's National Invasive Alien Plants List (MMDE, 2016).

The introduction of gorse to Sri Lanka dates back to 1888 (Wijesundara, 1999). Since then, gorse has invaded natural ecosystems in the hill country of Sri Lanka. The biodiversity of Horton Plains National Park (HPNP), a world-renowned nature reserve, has been significantly affected due to the spread of gorse. Community organizations, assisted by sponsoring private industries, have made several attempts to eradicate this weed by uprooting and burning it, with marginal success (Marambe, 2001). There is still a deficiency of scientific literature on gorse in Sri Lanka, and many of the observations are only found in abstracts, web articles, and blog spots.

As a result, in this paper, we reviewed the literature on gorse to compile data and knowledge on its distribution, biology, biodiversity impacts, and management in the past, present and future. We also reviewed the available information on its current trend of further expansion, interactions with its environment, and ecological values.

Information Review

We conducted a review of peer-reviewed literature on gorse in Sri Lanka and interrogated the Google Scholar, Web of Science, and Scopus databases using only one search term, "Gorse *Ulex europaeus* in Sri Lanka." Initially, 350+ articles were identified, and then we refined the search by removing duplicates and irrelevant articles, such as the applications of gorse for pharmaceutical products and chemical applications.

After the removal of irrelevant articles, 34 remained specifically on gorse, specific to Sri Lanka. An additional 26 sources were identified by Google browsing with the same search item, in travelogues, blog spots, newspapers, and web articles by several authors possessing information on gorse in Sri Lanka. We obtained information from technical reports, conference proceedings, thesis reports, and published abstracts because of the lack of peer-reviewed articles. Therefore, our final sample contained 60 published materials, covering the period from 1986 to 2021.

Biology and Ecology of Gorse

The genus *Ulex,* a young genus (four or five million years old), belongs to the Genistae tribe of the Family Fabaceae (Cubas et al., 2005). The centre of diversification of the genus *Ulex* is the Iberian Peninsula (Spain and Portugal), as it hosts a dozen *Ulex* species with various ploidy levels (Feoli-Chiapella and Cristofolini, 1981). Only three of these species have been discovered outside their origin, but *U. europaeus* ssp. *europaeus* is the only species that is well established and naturalized outside Europe. This species is a hexaploid and originated from hybridization between a tetraploid and a diploid ancestor belonging to two different *Ulex* lineages (Ainouche et al., 2003; Ainouche et al., 2009).

Gorse is a highly adaptable legume (Leary et al., 2006) that colonizes and thrives in disturbed habitats. It can thrive in nutrient-poor soil (Lee et al., 1986; Clements et al., 2001; Leary et al., 2006) this could be due to its nitrogen-fixing ability. It is a well-known fact that many nitrogen-fixing, shrubby legumes are weedy (Richardson et al., 2000; Leary et al., 2006). Gorse may benefit other plants by invading nitrogen-deficient habitats (Leary et al., 2006). It is also possible that the N_2-fixing ability gives an advantage to gorse in some habitats and could even be part of its success at those sites.

Gorse (Figure 1) is a perennial plant that can live up to 30 years (Gouldthorpe, 2006), and the adult plant can reach several meters high and wide (Chater, 1931; Lee et al., 1986). It is a spiny, multi-branched, and medium-to-tall perennial shrub (Markin and Yoshioka, 1998; Richardson and Hill, 1998; Bowman et al., 2008; Atlan et al., 2010).

The plant height varies from 1-4 m (Atlan et al., 2010, Altamirano et al., 2016), and the dark green spiny leaves are 1-3 cm long and usually alternate (Parsons and Cuthbertson, 1992). Flowers are yellow and 1.5–2.5 cm long, with racemose or solitary inflorescences (Clements et al., 2001). Insects, such as honeybees (*Apis melifera* L.) and bumblebees (*Bombus* L. spp.) pollinate the hermaphroditic flowers (Bowman et al., 2008).

Gorse reaches reproductive maturity around the age of four (Atlan et al., 2010), and its flowering phenology varies greatly depending on the region. The attractive blossoms of this plant are depicted in Figure 1. Gorse reproduces only through seeds, and the seed production is abundant (Moss, 1959). Seed dispersal occurs primarily by release from the pod within a few meters of the mother plant, but seeds can be further spread by ants, water, humans, mammals, birds, and wind (Ridley, 1930; Moss, 1959; Hill et al. 1996).

The highly persistent gorse seeds can remain in the seed bank and may germinate for up to 30 years (Zabkiewicz and Gaskin, 1978; Hill et al., 2001).

Figure 1 Gorse – shrubby habit with spiny leaves and showy, crowded flowers

In Sri Lanka, no comprehensive studies on the biology and ecology of gorse have been published. Kariyavasam and Ratnayake (2019) compared gorse reproductive biology in Sri Lanka with that in South Australia's Mount Lofty Ranges.

The Nuwara Eliya, the Kirigalpotta Nature Trail in HPNP, and a point near the Horton Plains Park entrance were the study locations. Gorse blooms all year in Sri Lanka, according to Kariyawasam and Rathnayake (2019), the fruit-to-flower ratio in terms of average fruit set values at the two Horton Plains locations were significantly variable (58.8 and 11.9).

The distribution of Gorse in Sri Lanka – Current Status

Sri Lanka has a history of several invasions of flora and fauna after the country's European colonization commenced with the Portuguese in 1505. Colonization ended in 1948 after the British gave independence to Sri Lanka. However, some of the plants introduced during the past centuries of colonial rule have spread throughout the island, becoming invasive plants.

The Department of National Botanic Gardens and the Department of Agriculture have played a significant role in early plant introductions. Gorse is also one of the IAPS that have been intentionally imported by the British to Sri Lanka due to its horticultural value through the Royal Botanic Garden at Peradeniya, Sri Lanka.

Records show that gorse was brought to the Gardens in 1888 from Europe (Wijesundera, 1999; Marambe et al., 2003). People may have smuggled plant parts of gorse from the Botanic Garden and planted them in their own gardens at Nuwara Eliya, from where the plant has probably escaped into natural areas in the hill country of Sri Lanka. The prevalence of gorse, especially in the HPNP and Nuwara Eliya township areas, is particularly noteworthy (see Figure 2), although there are no specific records to indicate how it migrated to the Horton Plains.

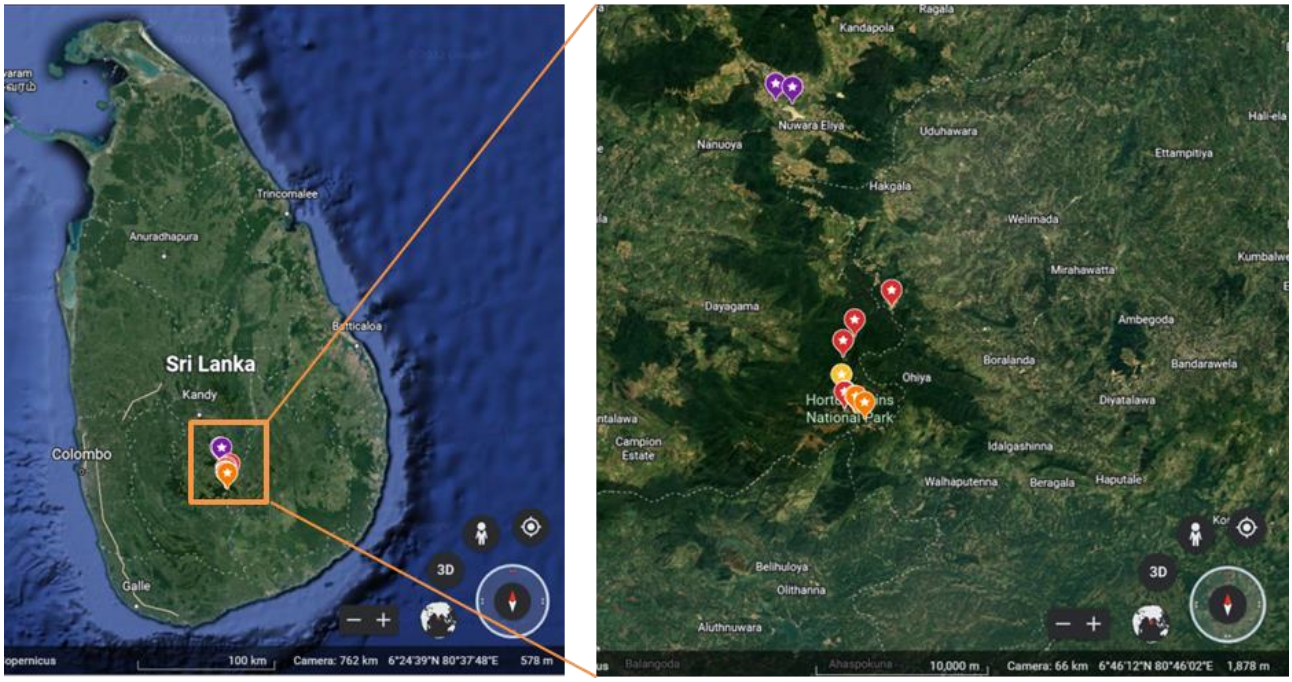

Figure 2. Map showing the Central Highlands in Sri Lanka and locations where gorse infestations were recorded (purple- undisturbed sites, orange- incidental occurrences, yellow - infestations along with the roadsides, red - regenerated populations after some control efforts)

A recent study conducted by Kariyavasam et al. (2019a) identified dense patches of gorse at the HPNP and some areas around the Nuwara Eliya township areas. In Sri Lanka, the heaviest infestations of gorse occur in areas experiencing a sub-tropical monsoon climate with a 150°C mean annual temperature and 2150 mm of mean annual rainfall (Premathilake et al., 2003).

The vegetation in natural habitats in this Central Highlands area is composed of Wet Montane Evergreen Forests (MoFE, 1999) (sometimes comprising "*cloud forests*") and wet *patana* grasslands, with a narrow ecotone of shrubs and herbs between them (Gunatilleke and Gunatilleke, 1986). Around half of the total tree species in these forests are endemic (Gunatilleke, 2007).

The montane forests are restricted to the uppermost elevations of the country (> 1500 m), which is home to about half of the country's endemic birds (Pethiyagoda and Gunatilleke, 2006). The wet patana grasslands above 1800 m altitude are best seen in Horton Plains and around Nuwara Eliya.

The annual rainfall in this area ranges between 2500 and 5000 mm, but the temperature is significantly low and cool (MoFE, 1999). The Central Highlands of Sri Lanka are of significant hydrological importance as they contribute to the water catchment of all Sri Lanka's major rivers.

The soil type in these areas is red-yellow podsolic (MoFE, 1999), with acidic topsoil rich in organic matter due to the slow rate of decomposition (Ranasinghe et al., 2007).

Gorse infestations are scattered and quite widespread in the upper-montane grasslands (MMDE, 2016), threatening the native plant biodiversity in those areas. The plant species that share the same environment as gorse in the Central Highlands are listed in Table 1. The occurrence of these grasses and herbaceous species was identified from the quoted scientific literature. However, there is no information available, as yet, in Sri Lanka on the ecological effects of gorse on the listed species.

Table 1 Typical native flora in the HPNP Grasslands and known to be affected by gorse infestations

Common name	Botanical name	Conservation status *
Tussock grasses	[1] *Chrysopogon nodulibarbis* Hochst. ex Steud.	Native, VU
	[2] *Andropogon polyptychs* Steud.	Native, VU
	[1] *Garnotia exaristata* Gould	Native, VU
	[1] *Arundinella villosa* Arn. ex Steud	Native, VU
Carpet Grass	[1] *Axonopus fissifolius* (Raddi) Kuhlm.	Native
Dwarf bamboo	[1] *Sinarundinaria densifolia* (Munro) C.S.Chao & Renvoize	Endemic, EN
Herbaceous species	[1] *Pedicularis zeylanica* Benth.	EN
	[1] *Satyrium nepalense* D.Don	NT
	[1] *Exacum walkeri* Arn. ex Griseb.	EN
	[1] *Calophyllum walkeri* Wight.	Endemic, VU
	[1] *Osbeckia* L. spp.	Some are Endemic
	[1] *Ranunculus* L. spp.	VU
Ferns	[1] *Pteridium revolutum* (Blume) Nakai	LC
Trees	[1] *Rhododendron arboretum* ssp. *zeylanica* (T.J. Booth) Tagg	Native, Endemic and VU
	[1] *Gaultheria leschenaultii* DC.	Native, Endemic

National Conservation Status: VU- Vulnerable; LC-Least Concerned; EN-Endangered; NT-Near Threatened
References: [1] Gunatilleke et al. (2007) [2] Jayasekara et al. (2021)

Although the presence of gorse has a long history in Sri Lanka, no systematic studies of its abundance and distribution have been conducted to date. According to Devendra et al. (1998), the HPNP's gorse infestation in 1997-1998 was approximately 6 hectares. No updates were done in the subsequent decades; hence, an accurate picture of gorse spread within the HPNP is hard to obtain.

According to a report issued in 2012 on the management of gorse in Sri Lanka (DWC, 2012), the proliferation of gorse has a substantial influence on the HPNP's biodiversity and must be addressed before the problem worsens. The publication, however, failed to mention the local indigenous species that were threatened by the environment and how they were harmed by the gorse infestation.

Another study by Shirantha et al. (2010) revealed the presence of large gorse infestations surrounding the recreational water body - Gregory Lake - at Nuwara Eliya, forming dense thickets along with the peripheral areas of the lake (Figure 3). The study noted that gorse displaced the grassland vegetation incrementally while modifying the structure and dynamics of the riparian vegetation associated with the lake.

Invasion Potential of Gorse with climate change

Climate change and IAPS are posing extraordinary ecological challenges to the globe today. The impact of climate change can profoundly influence geographical ranges of species that are often set primarily by climate and, consequently, the host environment (Tausch, 2008).

It is essential to anticipate which species will spread to new habitats and understand how the characteristics of specific invaders may disrupt or have the potential to disrupt invaded ecosystems to manage IAPS under a changing climate. Vegetation managers must be able to (1) predict which species will likely expand under climate change, (2) predict and detect sites likely to be invaded, and (3) deter incipient invasions before they are out of control to contain the spread of the IAPs (Finch et al., 2021).

Sri Lanka now expects dramatic changes in its climate due to global warming. The future consequences of climate change on the spread and distribution of gorse in Sri Lanka are yet to be studied in detail by researchers.

Premalal and Punyawardena (2013), Nissanka et al. (2011), Panabokke and Punyawardena (2009), Premalal (2009), De Costa (2008), and Malmgren et al. (2003) reported a significant increase in ambient temperature as well as an increase in rainfall variability.

Figure 3. Undisturbed and dense *Ulex europaeus* populations mixed with another major weedy species *Austroeupatorium inulifolium* (H.B.K.) R. M. King & H. Rob. (white flowers) [1] at highly disturbed sites on the Racecourse, Nuwara Eliya, Sri Lanka

[1] *Austroeupatorium inulifolium* (syn. *Eupatorium inulifolium* Kunth.) is another South American species that was introduced to Sri Lanka and Australasia during the British Colonial period (source: Kew Science - **https://powo.science.kew.org/taxon/urn:lsid:ipni.org:names:27149-2**.

In particular, Southwest and Northeast monsoon rains and showers of convectional origin have become much more variable in recent decades, resulting in extreme weather events such as droughts and floods, which frequently destroy crops (Marambe et al., 2015). Climate downscaling of the ECHAM4 general circulation model revealed that Sri Lanka's average annual temperature could rise anywhere between 2.5–4.5 °C by 2080, while rainfall projections revealed that the dry zone would become drier and the wet and intermediate zones may become wetter than they are now (Marambe et al., 2015; Punyawardena et al., 2013).

Kariyavasam et al. (2019b) investigated the future invasions of gorse in Sri Lanka using the *MaxEnt* model, trained with environmental variables. The model predictions encompassed the same localities, i.e., Nuwara Eliya and surroundings, and the HPNP, where infestations currently occur. However, *MaxEnt* modelling did indicate habitat suitability for more extensive spread and distribution of gorse in Sri Lanka's Central Highlands, and other parts of the Wet Zone. These findings are significant in predicting and managing gorse in Sri Lanka.

The outcomes of the above research highlighted the potential of gorse to spread further in Sri Lanka. Hence, relevant precautionary actions are required to control the spread of gorse in the central highlands of Sri Lanka. Invasion model predictions are essential for government organizations, environmentalists, and policymakers in laying out effective management strategies to prevent the spread of gorse in Sri Lanka.

According to Marambe and Wijesundara (2021), prioritizing actions against species such as gorse and similar IAPS in a changing and variable climate, particularly using the provisions granted by the National Weed Strategy (NWS), National Adaption Plan for Climate Change in Sri Lanka (NAP-CC) 2016-2022, and National Policy on Invasive Alien Species, Strategies and Action Plan of 2016, is an urgent need to protect the country's fragile agro-ecosystem

Possible ecological roles of Gorse in invaded areas

In many cases, the spread of invasive plants has had an adverse effect on the composition, structure, and function of biotic communities over the last several decades. Some native animals, however, can adapt to using even introduced, potentially invasive plants as habitats and living spaces. Somaweera et al. (2012) discovered such a relationship between gorse and a threatened

highland agamid lizard (*Calotes nigrilabris* Peters) in Sri Lanka's Central Highlands. The research discovered that *C. nigrilabris* occupied habitats non-randomly and selected gorse-infested areas over the native and other introduced vegetation in disturbed habitats.

Figure 4. Black-Cheek Lizard (*Calotes nigrilabris*)

More recently, Jayasekara et al. (2019) also studied the microhabitat utilization of C. nigrilabris in the grasslands of HPNP. They found that the gorse is one of the most critical plants for the survival of this lizard species in its grassland habitat. The selection of these bushes as living spaces by the endemic lizard may be driven by reduced predator risk and increased foraging benefits.

Marambe et al. (2001) also indicated that eliminating gorse in montane grasslands could threaten the endemic herpetofauna that inhabits these bushes to protect them from predators. Several bird species, such as the endemic dull-blue flycatcher (*Eumyias sordidus* Walden) and pied bush chat (*Saxicola caprata* L.), have also been observed to frequent gorse shrubs to prey upon various insect pollinators (Dharmarathne and Mahaulpatha, 2018). Nanayakkara et al. (2018) also reported that the pied bushchat has been observed feeding on juveniles of the *C. nigrilabris* lizard, which is associated with gorse infestations.

The year-round flowering (Jayasekara et al., 2021) and the bright yellow flowers of gorse attract many pollinators, mostly bees. At the HPNP, gorse is a crucial feeding plant for the Western honey bee (*Apis mellifera* L.; Gunatilleke, 2007) and the larvae of the pea blue butterfly (*Lampides boeticus* L.) (Somaweera et al., 2012, Jayasinghe et al., 2014).

Jayasekara et al. (2021) evaluated the influence of gorse eradication initiatives on the balance of floral and faunal communities, with a focus on the effects on fauna that benefit from gorse's ecological benefits. The elimination of gorse has resulted in a dramatic drop in the population of the black-cheek lizard in some locations, according to studies. The drop was attributable to the lizard's reduced availability of prey in non-infested areas, according to the authors. This study also found a dramatic decrease in prey populations, including many different types of bees and butterflies. It's also possible that the lizard and its juveniles are less preyed upon by jungle crows (*Corvus levaillantii* Lesson) and other predators due to the sheltered environment offered by gorse.

The Sambar (*Cervus unicolor* Kerr), the primary ungulate at HPNP (Somaweera et al., 2012), consumes young branches of gorse, where Kikuyu grass (*Pennisetum clandestinum* Hochst. ex Chiov.), an exotic grass, was discovered to be a major food source for Sambar (Padmalal et al., 2003; Jayasekara et al., 2021).

The evidence from gorse-related ecological studies (see Figure 5) confirms a significant ecological and biodiversity role of gorse in the invaded habitats. This role is likely to have evolved over the long period of more than a century during which gorse and other organisms have formed mutually beneficial inter-relationships. The management implications for gorse in those habitats are therefore quite challenging. Future eradication programmes will need to consider benign interventions, including the gradual replacement of gorse with other native species, which may perform a similar function.

Eradication of Gorse in Sri Lanka

The HPNP is a world-renowned hotspot of biological endemism in Sri Lanka. The Central Highlands, including HPNP, have been declared UNESCO World Heritage Sites, owing to the vast diversity of endemic flora and fauna inhabiting them. Therefore, it is crucial to undertake gorse management in an ecologically-friendly way and incrementally.

Several other nations have utilized biological control agents to manage gorse (e.g., Hill et al., 2008; Ireson et al., 2008). However, gorse biocontrol has never been attempted in Sri Lanka. Gorse is difficult to control with foliar herbicides due to its spiky foliage and significant deposits of epicuticular wax. Specialized formulations are required to maximize herbicide retention, foliar uptake and translocation (Zabkiewicz and Gaskin, 1978).

Figure 5. Gorse populations – (A) Regenerated after eradication in Horton Plains National Park (HPNP); (B) Gorse flowers visited by butterflies and other pollinating species and pest scale insects; (c) Undisturbed infestation in Nuwara Eliya, Sri Lanka

When employed in wildlife conservation zones, herbicide applications may have detrimental implications. Due to this possibility, in Sri Lanka, control attempts have only been made through mechanical removal (DWC, 2008).

Several local NGOs have enthusiastically launched volunteer control programs in recent years to remove gorse from affected ecosystems. Somaweera et al. (2012) stated that an area of around 5 km^2 was cleared annually at the HPNP by community groups to restore the natural grassland habitat. Most such removals in the past were haphazardly done, without much co-ordination or oversight (Marambe et al*.,* 2001) and may have negatively impacted the sensitive ecosystems and native wildlife.

More dedicated eradication programs were conducted from 2016 to 2017 in the HPNP successfully (De Alwis et al., 2019), and due to these continuous removals, the gorse populations have significantly decreased. It has led to a level of control where the labourers could not collect at least 100 plants from the park by the year 2019. Unfortunately, the eradications were discontinued in 2020 due to the COVID-19 Pandemic and other administrative issues (Park Warden, HPNP, pers. comm., 2021). As a consequence, gorse has started to regenerate.

Concerns about endemic species, such as the endemic lizards, have also made conservationists think twice when attempting to combat gorse, which was also a valid reason for slowing down the eradication efforts after 2019. The fauna that lives in association with gorse must be provided with alternative habitats (native species) similar to the weed to slowly shift their niches. In addition to gorse, Jayasekara et al. (2019) revealed that *Rhododendron* spp., tussock grasses, and ferns (*Pteridium* sp.) are also utilized by the endemic lizards at different life stages.

Areas, where gorse is cleared, could be prone to further invasion by more aggressive alien species

such as *Austroeupatorium inulifolium* (Kunth) R. M. King & H. Rob**.** The restoration process results in disturbance and increases resource availability (D'Antonio and Meyerson, 2002; DeMeester and Richter, 2009), but could also expose their inhabitants to predation. Thus, under certain circumstances, retaining exotics under controlled conditions may benefit natives in degraded natural habitats such as the gorse-infested areas around Nuwara Eliya (the Racecourse and Gregory Lake surroundings).

Mechanical removal is highly successful in controlling gorse in the Sri Lankan scenario, but it may induce soil erosion and land degradation. Jayasekara et al. (2021) recommended continuous removal programs in HPNP. The consequences of continuous eradications of gorse and the impacts on soil and other native plant species have to be studied in parallel. While uprooting the extensive lateral and adventitious roots may disturb the topsoil, it may become vulnerable to erosion, leading to poor soil nutrition. Therefore, mechanical removal should be planned wisely to be implemented in larger-scale eradication programmes. It further requires follow-up management, which is essential for lasting control.

Regeneration following eradication

IAPS constitute a significant threat to biodiversity, including incidents of species extinction. Exotic species interact with native species, creating complex direct and indirect impacts involving competition, predation, and facilitation that can be difficult to explain, let alone predict. In other words, removing one exotic species can favour the expansion of others previously suppressed by the species removed (Courchamp et al., 2011).

However, while IAPS affect ecosystems and their native biota, there is a deficiency of studies demonstrating their long-term impacts and regeneration after eradication attempts. The IAPs have rapidly spread in HPNP during the last few decades, with gorse, *Aristea ecklonii* Baker, and *Ageratina riparia* (Regel) King & H. Rob being the dominant species.

A recent study on quantifying the nature of habitat regeneration after removing gorse from the HPNP, covering an area of 53.7 km^2 in 2016 (De Alwis et al., 2019) reported that known invasive plants, such as *A. ecklonii* and *Pteridium revolutum,* were heavily abundant in the gorse-eradicated areas. Among other species, *Garnotia exaristata*, Kikuyu grass [*Pennisetum clandestinum* (Hochst. ex Chiov)], *Taraxacum javanicum* Soest and *Emilia sonchifolia* (L.) DC were the most abundant non-invasive native species found.

Gorse regeneration was notably high in regeneration plots. There was a significant difference in gorse abundance with dissimilar associations of regenerating species between two types of plots with different times since the last removal. De Alwis et al. (2019) confirmed the need for continued removal programs to control gorse in HPNP successfully. The regenerated plants with early flowers are shown in Figures 6 and Figure 7.

Figure 6. Regenerating gorse among the tussock grasses after eradication at locations in the HPNP

Ranathunga and Wijesundara (2018) recently conducted a study at the Horton Plains to assess the relative coverage of three major IAPS – *Ageratina riparia*, *Aristea ecklonii* and gorse. They concluded that the distribution of gorse was insignificant in the HPNP. On the other hand, the other two species were dominant and widely spread, with an estimated 127 ha of coverage.

An interesting observation by the park warden of HPNP regarding the early onset of flowers (when they reach 15-30 cm height) on regenerated gorse plants requires further investigations into the reproductive biology of the regenerated population. Similar observations were made by Jayasekara et al. (2021) on regenerated gorse infestations, but the reasons for the early onset of flowering are not yet clear. Jayasekara et al. (2021) have indicated the high regeneration capacity of gorse in their research, based on the increase of gorse density in the post-removal periods. The long-term success of mechanical removal operations may be hampered by the high regeneration capacity and early blossoming nature of gorse in Sri Lanka.

Figure 7. (A) Populations of gorse in 2012 before eradication attempts (HPNP, Sri Lanka); (B) Same site, after eradication in 2016; (C) Regenerating gorse populations in 2021

Scope for Management options

Biological control

Biological weed control involves the use of natural enemies or biotic agents to suppress the germination and growth of weed populations to an economically viable level (Hasan et al., 2021). There have been 94 bug and mite species found on gorse in Europe, with 16 of them being sufficiently host-specific to be regarded as biological control agents (Schröder and Zwölfer, 1970; Hill, 1983).

Seed and leaf feeders have both been successfully introduced into gorse's non-native habitat (Broadfield and McHenry, 2019). In 1931, the gorse seed weevil *Exapion ulicis* (Forster) was Introduced to New Zealand as the first biocontrol agent against gorse, it was widely established by 1935 (Miller, 1970) In tropical countries, the introduction of biocontrol agents from temperate zones may not always be successful.

Finally, there may be natural enemies native to Sri Lanka that can be used to control gorse biologically. Research into the distribution and identification of these species could lead to mass production and application in field releases. Table 2 presents some information on gorse biocontrol efforts around the world. Very few of these attempts were long-term successes, but they will be highly efficacious when combined with other control measures.

Table 2. Biological control efforts against gorse in the world

Biocontrol Agent	Nature of Attack	Location
Tetranychus lintearius Dufour, gorse spider mite	Foliage	New Zealand, Australia, USA
Sericothrips staphylinus Haliday, gorse thrips	Young foliage, seedlings	New Zealand, Australia
Agonopterix ulicetella (Stainton)	Young foliage	New Zealand, Australia
Scythris grandipennis (Haworth)	Mature foliage	New Zealand
Pempelia genistella (Duponchel)	Mature foliage	New Zealand
Cydia succedana (Denis and Schiffermüller), gorse pod moth	Seeds in pods	France, New Zealand, Chile
Exapion ulicis (Forster) Gorse seed weevil	Seeds in pods	France, Great Britain, Hawaii, New Zealand, Australia, USA
Fusarium tumidum- Mycoherbicide	Seedlings, stems and shoot	New Zealand
Chrondrostereum purpureum- Mycoherbicide	Cut sprouts	Canada, New Zealand

Synthetic and bio-herbicides

Despite the unintended side effects, synthetic herbicides are essential for the effective weed management of many colonizing species, such as gorse. The application of herbicide to juvenile leaves aids in efficient uptake. Unless additional surfactants can penetrate the thick, waxy cuticles of mature leaves, foliar herbicides rarely affect mature plants (Zabkiewicz and Gaskin, 1978).

Chemical treatment of cut stumps offers an alternative to foliar sprays in mature plants, but it involves the removal of above-ground vegetation first. Herbicides that have been successfully used to control gorse in various parts of the world include

triclopyr, glyphosate, metsulfuron, clopyralid and picloram and all treatments are effective with young plants and plant parts (Rolston and Devantier, 1983; Motooka et al., 1999).

Among bio-herbicides, *Fusarium tumidum* and *Chondrostereum purpureum*, two myco-herbicides, have been studied and suggested as non-synthetic chemical controls for gorse regeneration. Trichothecenes are bio-herbicidal chemicals made from *Fusarium tumidum* that kill scotch broom, *Cytisus scoparius* (L.) Link. and gorse.

Herbicides are unlikely to be used as part of a multifaceted management approach in fragile environments like Horton Plains in Sri Lanka. Spot sprays could be used to control the infested regions outside Horton Plains. To construct such an effective gorse control program, considerable scientific work and time are required.

Implications of the naturalization of Gorse in Sri Lanka

Based on the literature survey and data review, carried out in this preliminary investigative study, we summarize the following:

1. Gorse infestations in Sri Lanka's Central Highlands have become a topic of considerable public and national interest during the past two decades.
2. The species poses a severe threat to the biodiversity of HPNP, one of Sri Lanka's World Heritage sites. Sri Lanka has listed gorse under the IAPS list as one of the dangerous IAPS that requires priority attention to minimize its negative impacts on ecosystems.
3. Gorse's invasion potential is high, and there is a high probability of gorse spreading towards the mid-country Wet Zone and upcountry intermediate zone of Sri Lanka with climate change.
4. Eradication programs implemented haphazardly at HPNP may create more risks of regenerating gorse and other IAPS with higher invasion potential at this World Heritage site.
5. The existing gorse populations in the Central Highlands of Sri Lanka at HPNP and Nuwara Eliya have to be managed scientifically with regular monitoring while giving special attention to the endemic fauna that thrives within gorse bushes.

Future Outlook

The invasive potential of gorse is possibly due to its successful bio-ecology, and its adaptive features. These and the habitats it invades, make management strategies challenging. The biodiversity values gorse provides also require a careful approach to managing it while maintaining the natural balance of the ecosystems it inhabits.

Weed species prioritization is vital on a national basis because not all weeds can be removed from all conservation sites, and we want to focus our efforts on weeds that have the greatest negative impact on conservation values. Furthermore, weed control utilizes resources that may be better spent on other threat management and conservation efforts, such as wildfire and feral animal control; therefore, it's critical to focus resources on the most urgent issues.

The existing seed bank and the soil characteristics are important factors that may give some unpredicted results after applications of control measures. Spatially explicit simulation modelling showed that seedling survival (in particular the poor ability of gorse seedlings to compete against grasses) and disturbance were key determinants in the population dynamics of Gorse (Rees and Hill, 2001).

Simultaneously, special attention must be given to the frequency of disturbance regimes, and their intensities. These are crucial in selecting suitable management strategies- from spot removal to intermittent herbicide use, occasional grazing, or the use of controlled fire. The integrated use of such techniques depends on the population density of the gorse and other IAPS and the nature of the landscape, as well. The more pristine and valuable the associated vegetation is (such as in the HPNP and other montane forests of Sri Lanka), the more challenging the task is.

At present in HPNP in Sri Lanka, regenerated gorse populations occur as small patches with mother plants of 1-1.5 m in height and numerous juvenile plants and seedlings around each mother plant. These small populations are at a manageable level to plan and implement appropriate long-term plans, including maintaining the ground cover while suppressing the emerging seedlings with suitable and timely follow-up treatments. Generally, herbicide usage is not recommended as a primary management action.

Conserving the endemic organisms inhabiting gorse while managing the land cover with gradual suppression of weeds would be a better option to

tackle the invasion of gorse in the HPNP. The areas where the gorse has a long-established population (e.g. at the Race Course and Gregory lake areas of Nuwara Eliya) need to be brought under immediate control, because of the opportunities for gorse to further intrude on agricultural lands and adjacent forest areas. Tourists arriving in Nuwara Eliya, dubbed "*Little England*" because of its temperate environment and colonial-era homes, frequent the lake's surroundings. Heavy use of the area by both local and overseas tourists may encourage gorse spread to nearby regions.

Sri Lanka should dedicate more research to establish the life history characteristics and population dynamics of gorse and other IAPs and evaluate their spread under a changing climate. Ecological studies must include the reproductive behaviour of gorse and its interrelationships with other fauna and flora. Research should also not ignore how the plant's genetic make-up and metabolism may change in response to various biotic and abiotic stressors in its environment and responses to disturbances. Further, investigations on applications of biological, and herbicidal control in Sri Lankan gorse populations are important to develop an integrated, sustainable management plan. Integrated weed control techniques may offer the best prospects for the long-term control of gorse in the Central Highlands, where they do play a significant ecological role.

ACKNOWLEDGEMENTS

The authors are grateful to Dr. Nimal Chandrasena, Editor-in-Chief of the journal *Weeds*, and two anonymous reviewers for valuable comments and suggestions for improving this article. The main author (PM) acknowledges a Ph.D. scholarship grant (AHEAD/PhD/R3/Tech/406), funded by the World Bank and administered by AHEAD Operations of the Ministry of Higher Education. This review was part of PM's studies, which are continuing.

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