



Effects of Climate Change on Weeds and Invasive Alien Plants in Sri Lankan Agro-Ecosystems: Policy and Management Implications

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Changes in the climate have worsened the problems caused by weeds and invasive alien plants (IAPs) in agro-ecosystems at global scale resulting from their changes in the range and population densities. Over the past six decades, Sri Lanka has experienced a slow but steady increase in annual environmental temperature by 0.01–0.03°C. Increasing extreme events of rainfall, wetter wet seasons, and drier dry seasons are some of the characteristic features of the changes in the climate observed in Sri Lanka over the years. The Ministry of Environment (MOE) in Sri Lanka has established a National Invasive Species Specialist Group (NISSG) in 2012 and adopted the National Policy on Invasive Alien Species (IAS) in Sri Lanka, Strategies and Action Plan in 2016. Further, the MOE has developed and adopted protocols to assess the risk of IAS at pre- and post-entry level to the country while incorporating climate change concerns. Periodic risk assessments have been carried out to prioritize actions against IAS in Sri Lanka. The Ministry of Agriculture has adopted a National Weed Strategy (NWS) and has identified the Weeds of National Significance (WONS) under different priority crops. A study done in 2014 has clearly shown that weed control costs in agricultural lands in several districts of Sri Lanka were nearly doubled during the years that experienced *El Niño* Southern Oscillation (ENSO). Further, studies have clearly indicated that IAPs also survive, expand and impact the continuously disturbed environments in agro-ecosystems. *Panicum trichocladum*, a species listed as a potential invasive based on the risk assessment done in 2016, has shown an increase in its population density and distribution in Sri Lanka during the last 2–3 years. However, weeds and IAPs in agro-ecosystems have drawn less attention of policy makers, scientists, and practitioners in relation to impact of climate change in island ecosystems. This paper focuses on the scientific evidence reported in agro-ecosystems in Sri Lanka on climate-related impacts on agriculturally important weeds and IAPs, and the efforts made to manage their introduction and spread across the country.

Keywords: agro-ecosystems, weeds, invasive alien plants, climate change, Sri Lanka

INTRODUCTION

Sri Lanka (7.8731° N, 80.7718° E), occupying a land area of 62,707 km² and water bodies of 2,905 km² (Department of Census and Statistics, 2020) is an island nation with a physically diverse geography and tropical climate. Four geographical and topographical features considerably influence the climate of Sri Lanka, namely being (1) a relatively small island in the Indian Ocean coupled with warm and humid air—resulting in a slower cooling in the nights in areas closer to the coastal belt, (2) located about 645 km north to the equator—resulting in hot environments owing to the fall of greater solar energy per unit area (3) existence of central highlands perpendicular to two monsoon wind streams—resulting in eastern and western slopes having contrasting climates at a given season (e.g., when western slopes of the central highlands are wet, the eastern slope experience a dry climate, and *vice versa*), and (4) the proximity to the Indian subcontinent with a vast landmass in the immediate north and northwest of the country—resulting in rapid cooling effect in the nights of the northern peninsular of Sri Lanka due to the buffering effect created from the release of long-range radiation with heat from the Indian sub-continent. The monsoonal winds originated from the surrounding oceans mainly determines climate patterns observed in Sri Lanka. Based on the annual rainfall, Sri Lanka is divided into Wet zone (>2,500 mm); Intermediate zone (1,750–2,500 mm); and the Dry zone (<1,750 mm). The country is further divided into seven agro-climatic zones and 46 agro-ecological regions (Punyawardena, 2007). The rainfall and cultivating seasons in Sri Lanka are shown in **Table 1** together with the vital atmospheric parameters.

The Intergovernmental Panel on Climate Change (IPCC, 2014) confirms that South Asia will experience a significant change in its climate during the 21st century. According to Abeyssekera et al. (2015, 2021) the frequency of occurrence of extreme rainfall events in Sri Lanka would increase in the future, resulting in excess soil moisture stress in the rainfed uplands, flood damages in lowland paddy fields and rapid drying out in cascade of tanks in the long-run, thus imposing a significant negative impact on Sri Lanka's agricultural productivity. Several reports have indicated an increase in the minimum and maximum ambient temperature in most districts of Sri Lanka and a decrease of rainy days resulting in prolonged dry spells and droughts (Premalal and Punyawardena, 2013; MMDE, 2016a; Naveendrakumar et al., 2018). Being a party to the United Nations Framework Convention on Climate Change (UNFCCC—1992) and to Paris Agreement (2016), Sri Lanka recognizes the need to accelerate addressing climate-related issues.

Weeds, including invasive alien plants (IAPs), are the major biological constraint in agro-ecosystems (Ghersa, 2013; Paini et al., 2016; Kariyawasam et al., 2017; Chauhan, 2020). Peters et al. (2014) reported that over the years, many weed species have increased their population densities, and expanded in their range of distribution, thus making them a major biotic component in agro-ecosystems. The impact of weeds and IAPs on productivity of food crops have been increasingly experienced

worldwide (Vilà et al., 2004; Paini et al., 2016), under variable and changing climate (Peters et al., 2014; Ramesh et al., 2017; Beaury et al., 2020). Recent reports identified IAPs as a serious threat to agricultural production and food security in Sri Lanka (Paini et al., 2016; Kariyawasam et al., 2017). Changes observed in the global environment could increase the risks of biological invasions worldwide (Ricciardi et al., 2017). Increasing concentrations of atmospheric CO₂, and other changes observed in the temperature and rainfall are considered as major issues related to managing weed populations in agro-ecosystems (Varanasi et al., 2016). Considering this future impact, and a country that rely heavily on agriculture sector for rural livelihood development (Central Bank, 2019), this review is focused on the climate change impacts on weeds and IAPs in agro-ecosystems in Sri Lanka. The objectives were to elucidate the climate impacts on the distribution and persistence of weeds and IAPs in agriculture, especially focusing on food crop production, and to identify a way forward in managing these troublesome species in a changing and variable climate, in Sri Lanka. In this effort, we carried out a thorough literature survey using the Google[®] search engine to scan the published information pertaining to the topic. A keywords search, which included “invasive alien plants,” “weeds,” “agro-ecosystems,” “agriculture,” “climate change,” “climate impacts,” “climate-weed interactions,” “climate-invasive alien plant interactions,” “policies,” and “Sri Lanka,” was done to increase the precision of the survey. The climate impact on weeds and IAPs in Sri Lanka was mainly focused on the 25 year period from 1996 to 2020. The following sections of this paper summarizes the climate change experienced in Sri Lanka and its impacts, major weeds and IAPs of the agro-ecosystems, implications of weeds, IAPs and climate interactions, and conclusion.

Climate Change and Overall Climate Impacts in Sri Lanka

The climate risk to South Asia could result in significant damage to the economies, social development, and environmental aspects (Ahmed and Suphachalasai, 2014), and Sri Lanka is not an exception. The INFORM Risk Index (EU, 2019), considering the climate-related natural disaster, has categorized Sri Lanka under “moderate disaster risk” by ranking the country in the 97th position in terms of overall risk, out of 191 countries. Further, the World Bank and the Asian Development Bank (WB and ADB, 2020) reported that Sri Lanka is positioned at 56th in terms of for exposure to flooding, 45th in the exposure to tropical cyclones and their associated hazards, and 76th for drought exposure. The WB and ADB (2020) have reported the projected changes in the Sri Lankan climate (**Table 2**). With an annual increment of ambient temperature at 0.01–0.03°C since 1960 (Marambe et al., 2015a), the daily minimum temperature (night time) has shown a rapid increases than that of daily maximum temperature (day time), which could facilitate establishment of more perennial weeds (Ziska, 2004) as explained in detailed later in this review. Analyzing the rainfall using data collected from 400 rain gauging station, Nissanka et al. (2011) reported that the seasonal annual rainfall in Sri Lanka does not show a discernible significant

TABLE 1 | Rainfall and cultivating seasons and vital atmospheric parameters of Sri Lanka (source: Punyawardena, 2007).

Cultivating seasons	Rainfall	Months
<i>Yala</i> season (minor cultivating season)	First Inter Monsoon (FIM) South East Monsoon (SEM)	March–April May–September
<i>Maha</i> season (major cultivating season)	Second Inter Monsoon (SIM) North East Monsoon (NEM)	October–November December–February
Atmospheric parameters		
Average annual temperature	26.5–28.5°C—at altitudes <1500 m 15°C—at altitudes >1500 m	
Average annual precipitation	5,500 mm—in the south-western slopes of Central Highlands 900 mm—southeastern part of the Dry zone of country (Hambantota)	
Monthly relative humidity	55–90%	
Pan evaporation	3–8 mm— <i>Yala</i> season 205 mm— <i>Maha</i> season	

TABLE 2 | Projected changes in climate of Sri Lanka (source: WB and ADB, 2020).

Parameter	Projected change
Temperature	<ul style="list-style-type: none"> Under RCP8.5 scenario, increase by 2.9–3.5°C by the year 2090s (compared to 1986–2005 baseline) Under RCP2.6, increase by 0.8–1.2°C by the year 2090 (compared to 1986–2005 baseline) Rise of minimum temperatures faster than rises in average temperatures.
Heat	<ul style="list-style-type: none"> Under RCP8.5, more than 100 days of a year surpassing 35°C (baseline of 20 days) by the 2090s. Extreme heat events threatening human health and living standards, especially in urban areas without adequate cooling systems
Rainfall	<ul style="list-style-type: none"> Frequency and intensity of extreme precipitation events would increase posing a huge risk on human and animal lives, livelihoods, and infrastructure, due to riverine flooding, flash floods, and landslides.

trend, except in few locations. However, the extreme rainfall events, as reported by Premalal and Punyawardena (2013) and WB and ADB (2020) would affect the floristic composition in ecosystems (Jewitt et al., 2014), including weeds and IAPs, which is discussed later in this review. All these results indicate the need for prioritization of climate actions in Sri Lanka focusing on the exposure to the climate risk factors.

MAJOR WEEDS OF THE AGRO-ECOSYSTEMS OF SRI LANKA

Weeds are an important biotic constraint to achieve increased productivity (Chauhan, 2020) having direct and/or indirect interferences with the crop production. Analysis done by Bambaradeniya et al. (2001), Rajapakse et al. (2012) and Rao et al. (2017) clearly indicate that weeds have caused about 50% of crop yield losses, in addition to reducing the quality of the crop harvest and threatening the native biodiversity of Sri Lanka. For example, paddy yield in Sri Lanka is reduced by about 20–40% (Herath Banda et al., 1998) or even by 80–90% (Marambe, 2009; Chauhan et al., 2013) due to weed competition. Availability of water plays an important role in determining the level of the weed interference where Amarasinghe and Marambe (1998) reported that paddy cultivated in rainfed lowlands are more susceptible to weed competition compared to that in irrigated lowlands. Furthermore, the climatic zone will also determine the competitive pressure exerted by weeds on crops as reported

by Weerakoon et al. (2000), where the weed pressure higher in moisture-stressed Dry zone than that in the Wet zone. Abeysekera et al. (2006) showed that the floristic composition of weeds have changed in paddy fields due to the method of crop establishment, where wet-seeding has resulted in a shift of weed flora from annuals to perennials. The perennial weeds such as *Isachne globosa* are more difficult to control in paddy fields due to their multiple propagation techniques, by using sexual (seeds) and vegetative (stolons) propagules.

Apart from the specific weeds identified under different cropping systems, Sri Lanka has periodically identified the Weeds of National Significance—WONS (SLCARP, 2011, 2017; Table 3) to support prioritization of weed management in different agro-ecosystems in the country in terms of allocation of finances for research and practical application of weed control strategies. The WONS of Sri Lanka have been identified for different crops including more than 30 troublesome weeds in paddy, which is the major staple crop of Sri Lankans.

INVASIVE ALIEN PLANTS IN AGRO-ECOSYSTEMS

Alien plants have become invasive in their introduced habitats due to the absence of natural enemies, and outcompete the native species in the ecosystem (Hornoy et al., 2011), showed rapid reproduction rates (Richardson et al., 2000), higher adaptability to new and changing environments (Pyšek et al., 2012), and

TABLE 3 | Weeds of National Significance in Sri Lanka (source: SLCARP, 2017).

Weed	Habitat	Crop	Weed	Habitat	Crop
<i>Aeschynomene indica</i> L.	Semi-aquatic	Paddy	<i>Eclipta alba</i> (L.) Hassk.	Semi-aquatic	Paddy
<i>Anredera cordifolia</i> (Ten.) Steenis	Upland	Tea	<i>Eichhornia crassipes</i> (Mart.) Solms.	Aquatic	Paddy
<i>Brachiaria brizantha</i> (SM.) Griseb.	Upland	Rubber	<i>Eleusine indica</i> (L.) Gaertn.	Semi-aquatic	Paddy
<i>Cyperus difformis</i> L.	Semi-aquatic	Paddy	<i>Fimbristylis dichotoma</i> (L.) Vahl.	Semi-aquatic	Paddy
<i>C. iria</i> L.	Semi-aquatic	Paddy	<i>F. mileacea</i> (L.) Vahl.	Semi-aquatic	Paddy
<i>C. rotundus</i> L.	Upland	Paddy, Horticultural crops, Tea, Sugarcane	<i>Hedyotis auricularia</i> (L.) Bremek.	Upland	Rubber
<i>Caladium</i> spp. Vent.	Upland	Tea	<i>Hyptis suaveolens</i> (L.) Poit.	Upland	Coconut
<i>Chromolaena odorata</i> (L.) R.M.King and H.Rob	Upland	Coconut, Rubber	<i>Imperata cylindrica</i> (L.) Raeus.	Upland	Horticultural crops, Rubber, Sugarcane
<i>Commelina benghalensis</i> L.	Semi-aquatic	Paddy	<i>Ipomoea obscura</i> (L.) Ker Gowl.	Semi-aquatic	Paddy
<i>C. diffusa</i> Burm.f.	Semi-aquatic, upland	Paddy, Tea	<i>M. pudica</i> L.	Upland	Floricultural crops
<i>Conyza sumatrensis</i> (Retz.) E.Walker	Upland	Tea	<i>Murdannia nudiflora</i> (L.) Bren.	Semi-aquatic	Paddy
<i>Crassocephalum crepidioides</i>	Upland	Tea	<i>Oryza sativa</i> sp. Spontanea (L.)	Semi-aquatic	Paddy
<i>E. crus-galli</i> (L.) P.Beavuv.	Semi-aquatic	Paddy	<i>I. violacea</i> L.	Upland	Coconut, Flower crops
<i>E. glabrescens</i> (Munro) ex. Hook.f.	Semi-aquatic	Paddy	<i>Ipomoea</i> spp. L.	Upland	Sugarcane
<i>Isachne globosa</i> (Thunb. Kuntze.	Semi-aquatic	Paddy	<i>Panicum maximum</i> (Jacq.)	Upland	Coconut, Sugarcane, Spice crops, Floricultural crops, Fallowed agricultural land
<i>Ischaemum rugosum</i> (Salisb.)	Semi-aquatic	Paddy	<i>P. repens</i> L.	Upland	Paddy, Tea, Sugarcane
<i>Ischnocarpus frutescens</i> (L.) W.T. Aiton	Upland	Sugarcane	<i>Panicum trichocladum</i> Hack. ex Engl.	Upland	Tea
<i>Lantana camara</i> L.	Upland	Coconut, Floricultural crops, Fallowed agricultural land	<i>Parthenium hysterophorus</i> L.	Upland	Upland food crops, Fallowed agricultural land
<i>Leptochloa chinensis</i> (L.) Nees	Semi-aquatic	Paddy	<i>Paspalum distichum</i> L.	Semi-aquatic	Paddy
<i>Limnocharis flava</i> (L.) Buch.	Semi-aquatic	Paddy	<i>Pennisetum polystachion</i> L.	Upland	Spice crops
<i>Ludwigia octovalvis</i> (Jacq.) Raven.	Semi-aquatic	Paddy	<i>Salvinia molesta</i> D.Mitch	Aquatic	Paddy
<i>L. perennis</i> L.	Semi-aquatic	Paddy	<i>Scirpus supinus</i> L.	Semi-aquatic	Paddy
<i>Mikania cordata</i> (Vahl.) Willd	Upland	Rubber	<i>Spermacoce</i> spp. L.	Upland	Tea
<i>M. micrantha</i> Kunth.	Upland	Rubber, Spice crops	<i>Sphaeranthus indicus</i> Linn.	Semi-aquatic	Paddy
<i>Marsilea aquadrifolia</i> L.	Semi-aquatic	Paddy	<i>Sphagneticola trilobata</i> (L.) Pruski	Semi-aquatic, Upland	Paddy, Fallow agricultural land
<i>Mimosa pigra</i>	Semi-aquatic, upland	Paddy, Fallowed agricultural land	<i>Sphenoclea zeylanica</i> Gaertn.	Semi-aquatic	Paddy
<i>Monochoria vaginalis</i>	Semi-aquatic	Paddy	<i>Syngonium</i> spp. L.	Upland	Tea
			<i>Vernonia zeylanica</i> (L.) Less.	Upland	Coconut

aggressive growth and spread with early maturity. The IAPs have continued to affect the biodiversity of the natural ecosystems (Pyšek et al., 2012) and food security (Paini et al., 2016). The socio-economic impacts of IAPs have been extensively reviewed by Raj and Singh (2020). Wijesundara (2015) reported that invasive plants have caused a loss of ~US\$ 23 billion in USA due to their impacts on agriculture, industry, recreation and the environment. Shackleton et al. (2017) reported an economic loss of US\$ 500–1,000 per household per annum due to *Opuntia stricta* invasion in the African continent. The losses due to *E. crassipes*, a WONS in Sri Lanka (Table 3), in South Africa was estimated to be US\$ 58,195 per year (Wise et al., 2007). All studies on record clearly indicate that biotic invaders are a significant component of the anthropogenic environmental change. It is important to note that the mechanisms of such invasions could depend on many factors other than climate such as the resilience of the ecosystem and biotic interactions, and natural dispersal mechanisms, man-made pathways and vectors of IAPs, etc.

Invasive Alien Plants Reported in Sri Lanka

Internal trade, aid, and travel and transportation have helped movement of IAPs into natural and man-made ecosystems in Sri Lanka (Marambe et al., 2015b), which could have been facilitated by the liberalized economic policies adopted in Sri Lanka since 1978. The first official publication of the IAPs was released in Sri Lanka in 1999 (MEFR, 1999), with a list of such species in Sri Lanka. However, such listing were based mainly on the limited available literature, and perceptions of scientists/environmentalists without a scientifically valid risk assessment process. Sri Lanka conducted its first nation-wide risk assessment in 2009–2010 using a post-entry risk assessment (PERA) protocol developed, where 28 IAPs have been identified (Ranwala et al., 2012). The second effort to assess the impact of IAPs was carried out in 2015, by the NISSG of the MOE, using an updated PERA protocol, where 20 species were identified (Table 4) as nationally important priority IAPs. Further to those, 15 potential IAPs have also been recognized (Wijesundara, 2015).

The IAPs are a significant and growing threat to the natural and agro-ecosystems, and economy of Sri Lanka (Marambe et al., 2015b; Marambe and Silva, 2016; Kariyawasam et al., 2021). For example, Marambe et al. (2002a) reported of yield losses of 72% in tomato (*Solanum lycopersicum*) and 29% in chili (*Capsicum annuum*) due to the parasitic weed *Cuscuta* spp. Jayasinghe et al. (2004) reported that *Cuscuta* spp. lives on 161 host plants of which 27 are crops and 22 are other weeds, highlighting the threat of this holo-parasitic IAP in agro-ecosystems. Munasinghe et al. (2008), in their studies carried out in selected man-made reservoirs in the Anuradhapura district of the north central province of Sri Lanka, suggested that *S. molesta* and *E. crassipes* covered the water surfaces by 35 and 45%, respectively. This would negatively affect the aquatic life and increase water losses, including irrigation water, due to high rates of evapotranspiration.

About US\$ 1.61 million has been spent by the Department of Irrigation of Sri Lanka since 2008 to clean reservoirs, irrigation canals and other waterways invaded by IAPs (Dharmasena, 2018). In mid 1980s, *S. molesta* invasion has cost the rice

production in Sri Lanka by about US\$ 163,000–375,000 per annum (Doeleman, 1989).

INTERNATIONAL CONVENTIONS AND NATIONAL POLICIES

The Ministry of Foreign Affairs of Sri Lanka, through its Ocean Affairs, Environment and Climate Change Division, promotes and coordinates projects and activities in relation to international conventions treaties entered into agreement by the country. It further ensures consistency and coherence in the engagement of Sri Lanka at international level in ocean affairs, environment and climate change, and provide relevant guidance to line ministries and agencies of the government of Sri Lanka.

The Biodiversity Secretariat (BDS) and the Climate Change Secretariat (CCS) of the MOE is the Sri Lankan focal point for the Convention on Biological Diversity (CBD; <https://www.cbd.int/countries/nfp/?country=lk>), and the UNFCCC including Paris Agreement (<https://unfccc.int/process/parties-non-party-stakeholders/parties/national-focal-point>), while the Department of Agriculture (DOA) of the Ministry of Agriculture (MOA) is the focal point for the International Plant Protection Convention (IPPC; <https://www.ippc.int/en/countries/all/contactpoints/>). All three conventions are of prime importance in the subjects concerned in this review paper. Sri Lanka has also enacted the Plant Protection Act No. 35 of 1999 to regulate the entry of weeds including IAPs, while the National Invasive Species Act is currently in the making, providing more authority to regulatory officers to deal with the entry to, and spread of IAPs in Sri Lanka (Source: Ms. Pathma Abeykoon, BDS, MOE).

The National Climate Change Policy (NCCP) of 2012 (MMDU, 2012), National Adaptation Plan for Climate Change Impacts in Sri Lanka (NAP-CC) in 2016 (MMDE, 2016a) and Nationally Determined Contributions (NDCs) in 2016 (MMDE, 2016b) have been adopted in Sri Lanka to tackle the climate change. The NAP-CC identifies the need to assess the impacts of enhanced levels of atmospheric CO₂ on biomass production of natural vegetation and spread of IAPs as priority actions under the theme food security (MMDE, 2016a). The Sri Lanka Council for Agriculture Research Policy (SLCARP, 2017) of the MOA has also published a National Weed Strategy (NWS) to deal with the WONS in agro-ecosystems. The NWS also focuses on the weed control under main food and export crops in relation to climate change (Rajapakse et al., 2012). The Ministry of Environment (MMDE, 2016c) has adopted the National Policy on Invasive Alien Species (IAS) in Sri Lanka, Strategies and Action Plan as the guiding document to control IAPs, in Sri Lanka. The National Agriculture Policy (NAP) of 2007 (MOA, 2007) and the National Agricultural Research Policy and Strategies 2018–2027 (SLCARP, 2018) of the MOA make provisions to management of weeds and IAPs and related research in Sri Lanka, respectively. A weed list, identifying list of weeds that are prohibited to be imported to Sri Lanka in addition to the WONS is expected to be adopted toward late 2021 under the Plant Protection Act No. 35 of 1999 (Source: Dr. W.A.R.T. Wickremarachchi, National Plant Quarantine Service, DOA).

TABLE 4 | Invasive alien flora in agro-ecosystems of Sri Lanka (source: updated from Wijesundara, 2010).

Plant species	Family	Country/Region/from which the species was introduced to Sri Lanka	Ecosystems affected	Reason of introduction	Year of introduction
<i>Salvinia molesta</i>	Salviniaceae	India	Island wide; Tanks, ponds, marshes, streams, paddy fields	Educational/Scientific study	1939
<i>Panicum maximum</i>	Poaceae	Africa	Islandwide; Disturbed forests and scrubland, roadsides, agricultural land	Fodder	1801
<i>Cuscuta campestris</i> Yunck	Convolvulaceae		Islandwide, except in upper montane zone; wastelands, agricultural land in low country	Accidental: Contaminant of grains	Unknown
<i>Clidemia hirta</i>	Melastomataceae	Tropical America	Sub-montane Wet zone; open areas in lowland, rainforest edges, tea fields	Ornamental	1894
<i>Parthenium hysterophorus</i>	Asteraceae	India	Dry and Intermediate zones; wastelands, irrigation canals, agricultural land	Accidental: Contaminant in imported chili and onion seeds	1980s
<i>Mimosa pigra</i>	Fabaceae		Dry and Intermediate zones; wastelands, agricultural lands, river banks	Protecting river banks	1980s
<i>Sphagneticola trilobata</i>	Asteraceae		Wet and intermediate zone; wastelands, roadsides, abandoned paddy fields		

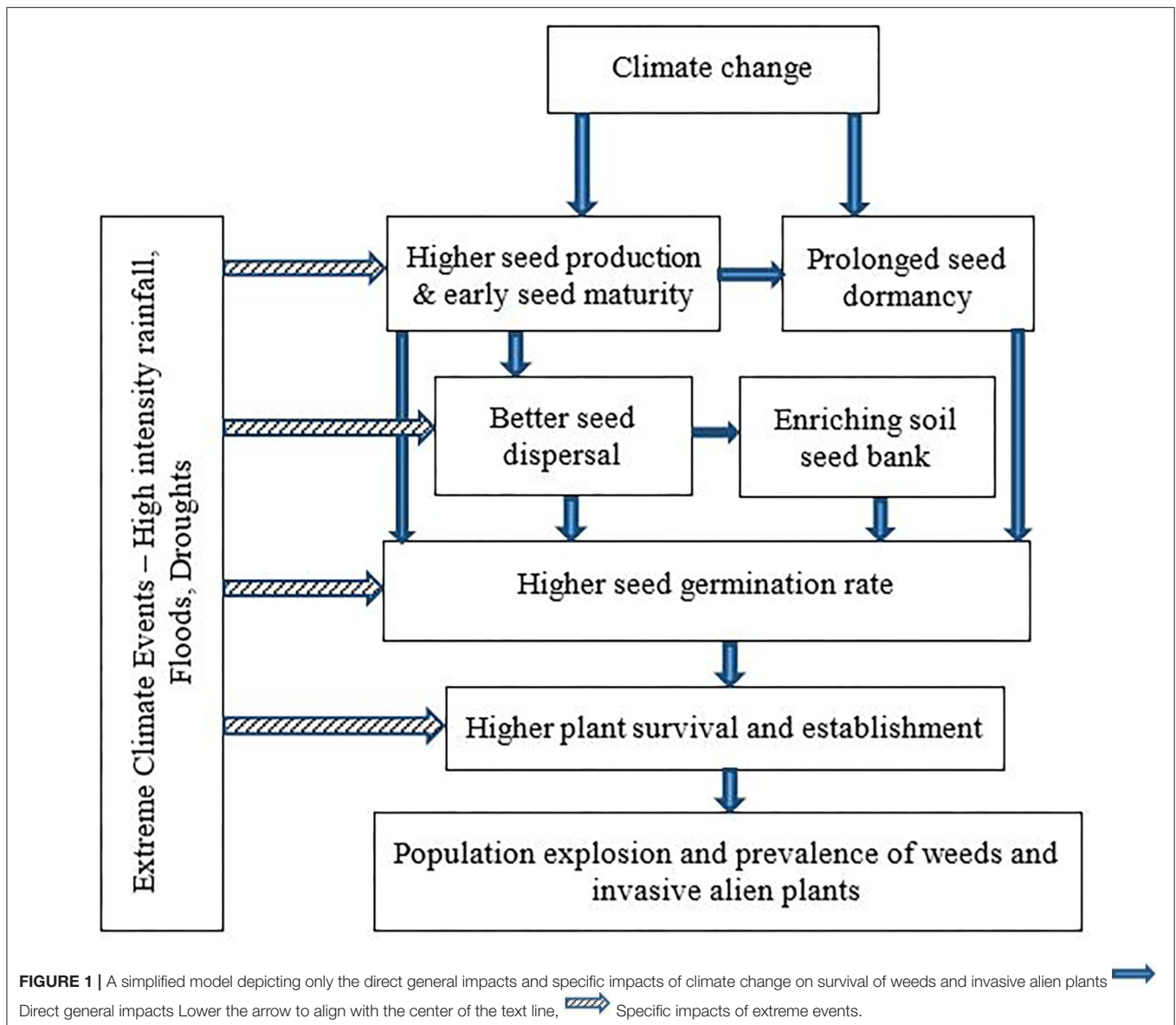
Other national policies and action plans that have made provisions for the management of weeds and IAPs in Sri Lanka are the National Environment Policy and Strategies of 2003 by the Ministry of Environment (MENR, 2003), National Wildlife Policy for Sri Lanka 2007 of the Department of Wildlife Conservation (DWLC, 2007), and National Biodiversity Conservation Action Plan (NBSAP) of the Ministry of Environment (MMDE, 2016d). From among its actions, the NBSAP has identified priority interventions targeting to prevent the entry and the spread of IAPs as a key activities to safeguard the environment of the country.

WEEDS, INVASIVE ALIEN PLANTS, AND CLIMATE IMPACTS - IMPLICATIONS

Global climate change would significantly influence the population dynamics of IAPs in the future (Fandohan et al., 2015). The conceptual framework (Figure 1) illustrates the climate impact on ecosystems services and the survival and population explosion of weeds and IAPs in agro-ecosystems. The efforts to identify biological invasions and predicting their impacts on ecosystems under changing climate have yielded inconsistent results (Hulme, 2016). Some studies have reported that the current distribution of IAPs may not be in equilibrium with the current climate, nor that their potential establishment and/or spread be determined primarily by climate. For example, Sathischandra et al. (2014) used rainfall and temperature data for a period of 40 years from 1982 to 2012 in Sri Lanka, while using cost of weed control as the proxy to assess pest incidences.

They reported the absence of a linear correlation between the occurrence of weeds and insect pests with climate variables. However, Sathischandra et al. (2014) further reported that the occurrence of weeds and insect pests can be relatively higher with extreme climate events that occur during *El Niño* and *La Niña* (ENSO) years. With such complexities, Kariyawasam et al. (2019a) highlighted the need for accurately predicting dynamics of IAPs under future climate change/global warming scenarios for more informed decision making to manage the IAP populations.

In a changing climate, the C₃ crops are expected to be benefitted by elevated CO₂ levels in the atmosphere, especially during their vegetative stages, compared to that of C₄ crops (Patterson, 1995). The C₃ food crops are expected to become less competitive compared to C₄ weeds in a changing climate (Korres et al., 2016) as the C₄ photosynthesis pathway is more effective and efficient at higher temperatures compared to that of plants with C₃ photosynthesis (Carter and Peterson, 1983; Ziska and Bunce, 1997). However, Ziska (2000) also reported that yield losses in C₄ crops such as *Zea mays*, *Saccharum officinarum* and *Sorghum bicolor* are affected by weeds having C₃ photosynthetic mechanism, indicating that such impacts would enhance with increasing levels of CO₂ in the environment. Weeds and IAPs are also known to have a greater physiological plasticity (Treharne, 1989), while perennial weeds may become more noxious under elevated CO₂ levels (Ramesh et al., 2017). Ziska and Runion (2006) reported that growth of weeds is benefitted from elevated CO₂ thus outcompeting crops even when the photosynthetic pathway of both crop and weeds are the same. As depicted in Figure 1, Ziska and George (2004) also reported that weeds with



invasive behavior and reproduce vegetatively have shown a more positive response to increasing CO₂ levels than crops. These findings highlight the greater level of complexity in predicting weed-crop interaction in a climate change scenario rendering it more difficult to design and adopt management strategies to overcome such problems in agro-ecosystems.

The IAPs have been reported to adapt to climate change showing plasticity in their growth patterns. For example, Patterson (1995) reported that *Bromus tectorum* has shortened its life span under drought conditions and extended its root system to deeper soil layers thus, demonstrating better adaptation of IAPs compared to most of the native plant species. In India, evidence for a rapid population expansion of IAPs was evident under higher environmental temperatures with a synchronized mass scale seed germination of *Trianthema*

portulacastrum (Masters and Norgrove, 2010), a noxious weed that is also reported in Sri Lanka (Kaur and Aggarwal, 2017). Several reports have also shown differential performance by weeds in a changing environment especially in terms of seed germination. Studies carried out by Huxman et al. (1998) reported of delayed germination and slower growth rate of seeds of an IAP (*Bromus* spp.) grown under elevated CO₂ levels compared to those obtained from plants that have grown under ambient environment.

Increasing flooding depth is known to affect the germination and seedling growth of many weeds. For example, a study done in the Philippines (Chamara et al., 2018) has shown a decrease in seedling emergence of *Echinochloa crus-galli* and *Ludwigia hyssopifolia* from 53% to 95% thus, reducing the competitive pressure on paddy plants. However, they also reported that the

seedling emergence of *Cyperus difformis* is increased by 49–68% with increase in flowing depth from 2 to 5 cm, thus, indicating the differential performance of weeds and a potential shift in weed flora in paddy fields for changing climates, especially under extreme climate events. Both *E. crus-galli* and *C. difformis* are listed under WONS (Table 3) while *L. hyssopifolia* is also reported as troublesome weed in rice-growing environments (Perera and Dahanayake, 2015) in Sri Lanka. Experimental data of Chamara et al. (2018) also suggest that *C. difformis* would dominate paddy fields with increasing rainfall intensity in a changing climate.

Movement of propagules of IAPs to different locations and the loss of capacity of the native plants to tolerate IAPs has been identified as the primary processes that biological invasion could take place due to climate change (Diez et al., 2012). Marambe et al. (2002b) reported that river water flow helps dispersal of *Mimosa pigra* seeds, suggesting that flooding due to extreme weather events could help spread of this IAP further. We also have observed a marked increase in population sizes of *Clidemia hirta*, an identified IAP of Sri Lanka (Table 4), during the past several decades in tea plantations in the country. However, there has been no quantitative ecological studies to compare its population sizes at different time intervals. Peters et al. (2014) reported of the difficulty in quantifying the niche shifts of arable weeds. Recently, a climate suitability study carried out by Kariyawasam et al. (2019b) considering 14 IAPs under RCP 4.5 and 8.5 scenarios concluded that species-specific patterns of spread of IAPs depend on their existing growing environments in Sri Lanka. They also predicted that the southern and western parts of Sri Lanka are climatologically more suitable for IAPs. Potential impacts of climate change on the spread of IAPs, including that of agriculturally important weeds (Table 5).

Ramesh et al. (2017) reported that an increase in rainfall would increase the cost of production of crops owing to increased weed pressure. For example, increase in rainfall frequency and intensity would adversely affect the efficacy of soil-applied herbicides (Rodenburg et al., 2011). Further, Patterson (1995) reported that drought conditions would increase the cuticle thickness and leaf pubescence of weeds and reduce the entry of herbicides through leaves. These scenarios will increase cost of weed management and thus the total cost of crop production. Growth, reproduction and invasiveness of *Parthenium hysterophorus*, a WONS (Table 3) and an IAP (Table 4) in Sri Lanka, has been favored by changing climate (Bajwa et al., 2016), especially under changing rainfall patterns, and increasing temperatures and atmospheric carbon dioxide (CO₂) levels. Moreover, Javaid et al. (2010) reported of prolonged seed dormancy in *P. hysterophorus* with increasing temperature. Lopez et al. (2015) reported that the germination process of plant species is generally synchronized within the optimum temperature range. These results indicate that IAPs such *P. hysterophorus* could enhance its persistence in the environment and opportunity for developing into new invasions by temporal variations in seed germination due to non-synchronized breaking of seed dormancy.

The IAPs readily germinate with better seedling growth at high temperature compared to the native plant species (Xu et al., 2019). For example, Hou et al. (2014) reported that IAPs

are more tolerant in terms of seed germination and seedling growth. These results suggest the risk of seed bank enrichment by weeds and IAPs, and potentially high biological invasions with global warming.

Furthermore, non-existence or weak implementation of the IAP management plans, none to poor financial commitments for IAP control, absence of an information management system resulting in non-availability of reliable data, and poor institutional coordinating mechanism are the other key challenges affecting successful IAP management. Bambaradeniya et al. (2006) reported that, apart from climate change, the natural disasters such as Tsunami in 2004 has led to a rapid expansion of IAPs such as Siam weed (*Chromolaena odorata*) in the southern coastal belt of Sri Lanka bordering agricultural lands.

The IAPs are often equipped with mechanisms to disperse their seeds and other propagules through wind or animals over long distances (Pyšek and Richardson, 2007). Invasive flora has been reported for their rapid colonization ability after an extreme climate event, after maintaining low profile under strong inter-specific competition (Groves, 1999; Grice and Ainsworth, 2003). Finch et al. (2021) reported that extreme climate events could assist the movement of IAP propagules from one location to another, facilitating their establishment and spread within a region. This suggest that climate extremes would help rapid expansion in the geographic distribution of IAPs, and their establishment at higher population densities in new and favorable environments. For example, warmer-region palms such as *Trachycarpus fortunei* have successfully established in open fields in temperate European ecosystems while surviving the winters (Walther et al., 2007; Finch et al., 2021). Climate change has increased the spread of the aquatic weed *Ranunculus trichophyllus* into new lakes in the Himalaya region (Lacoul and Freedman, 2006). In Sri Lanka, the aquatic invasives *S. molesta* and *E. crassipes*, which are also in the list of WONS (Tables 3, 4) have been reported in Gregory's lake in the Nuwera Eliya city of Sri Lanka (Shirantha et al., 2010), a location that has recorded an increase of annual air temperature at a rate greater than the global average during the period 1906–2005 (De Costa, 2008). These results have indicated the threats of alien plants becoming IAPs with range expansion in a warming world, in turn impacting irrigated agro-ecosystems.

Furthermore, as reported by Hou et al. (2014), the seed germination and seedling growth stages of *Mikania micrantha*, a WONS in Sri Lanka (Table 3), have better tolerated day/night temperatures of 34/29°C by allocating more biomass to shoot growth compared to that of native plant species. Hou et al. (2014) also reported that *M. micrantha* seedlings had short-term tolerance to extreme high day/night temperature (40/35°C). These results suggest that IAPs have higher chances of survival and rapid colonization in a changing climate with different growth stages showing differential responses to high environmental temperature regimes.

Some IAPs could also indirectly support the spread of other alien invasives. For example, *Arundo donax*, gorse (*Ulex europaeus*), kikuyu grass (*Pennisetum clandestinum*), and old world climbing-fern (*Lygodium microphyllum*), with their ability to increase fire loads and heat intensity, could result in higher

TABLE 5 | Invasive behavior of alien plants as affected by climate change and resulting changes in the environment (this is a representative list; the outcomes are based on scientific studies and observations).

Parameter	Influence on weeds and IAPs	Source
Higher environmental temperatures	Increases seed production and population densities of <i>E. crus-galli</i>	Marambe and Amarasinghe, 2002
Higher CO ₂ levels	Increased prevalence of <i>M. pigra</i> and <i>P. juliflora</i>	Marambe et al., 2003; Wijesundara, 2010
RCP 4.5 and 8.5 emission scenarios	A projected increase in population sizes by 2050 of <i>M. pigra</i> and <i>P. hysterophorus</i>	Kariyawasam et al., 2019a
RCP 4.5 and 8.5 emission scenarios	A projected decrease in population sizes by 2050 of <i>P. maximum</i> and <i>L. camara</i>	Kariyawasam et al., 2019a
Climate change induced disequilibrium in the ecosystem	Facilitate spread into protected areas: <i>C. odorata</i>	Iqbal et al., 2014
Floods	Facilitate spread into new habitats: <i>M. pigra</i> , <i>M. invisa</i> , <i>E. crassipes</i> , <i>S. molesta</i>	Iqbal et al., 2014
Increase in diurnal temperatures	Facilitate extension of temperature boundaries for growth: <i>Tithonia diversifolia</i> , <i>Eupatorium riparium</i>	Iqbal et al., 2014
<i>El Nino La Nina</i> (ENSO) years	Increase weed infestation in paddy	Sathischandra et al., 2014
Temperatures above 35°C	Enhanced seed germination and growth of paddy field weeds: <i>E. crus-galli</i> , <i>L. chinensis</i> , <i>Lindernia rotundifolia</i> , and <i>Monochoria vaginalis</i>	Bandara et al., 2017
High temperatures and moisture limited conditions	Higher population densities: <i>P. repens</i> , <i>Echinochloa</i> spp., <i>C. rotundus</i> , <i>L. chinensis</i> , and <i>Ischaemum rugosum</i>	Malaviarachchi et al., 2019
Increasing environmental temperature	Shift of weed flora from annuals to perennials in sugarcane	Witharama et al., 1997
Variation in rainfall	Changes critical period of weed competition in pole bean	Premalal et al., 1999

mortality rates in some fire-intolerant native species thus opening up more space for invasion by IAPs (Wijte et al., 2005). Though a direct inference cannot be drawn, *P. trichocladum* is a potential IAP (Wijesundara, 2015) that has shown a rapid spread in the central province of Sri Lanka over the past few decades.

At the global scale, the cost of IAS including IAPs was recently estimated to be around US\$ 1.288 trillion for the period 1970–2017 (Diagne et al., 2021). These estimates clearly indicate an unprecedented pressure to the economies, with annual average cost of US\$ 26.8 billion. Diagne et al. (2021) also reported that in 2017 alone the global cost of IAS was US\$ 162.7 billion. Furthermore, Cleland et al. (2007) showed that climate change could provide opportunities for aliens to become invasive by changing plant growth rates, reproductive capacity, and the plant physiology and phenology thus shifting their range.

CONCLUSION

Many agro-ecosystems in Sri Lanka are vulnerable to the changes in climate. Such vulnerable ecosystems with already low biodiversity, would be the first to demonstrate interactions between weeds, IAPs and climate change. Determination of the relationship between the environment parameters and species

characteristics is important to estimate the spread and persistence of agriculturally important weeds and IAPs under changing and variable climate. Detailed studies on niche shifts of weeds and IAPs are a necessity to understand the underline processes of such changes in agro-ecosystems. Continuous monitoring of the shifts in species populations of weeds and IAPs are thus a necessity. As highlighted by Iqbal et al. (2014) and Marambe et al. (2009, 2015a), climate impacts could be aggravated further by IAPs, if they are not considered as a significant component of the environment, especially in the climate action dialogue in Sri Lanka. Prioritizing actions against weeds and IAPs under a changing and variable climate, especially using the provisions granted by the NWS, NAP-CC, and National Invasive Alien Species Policy, Strategy and Action Plan is an urgent need in order to protect its fragile agro-ecosystems and ensure optimum use of its agro-biodiversity.

AUTHOR CONTRIBUTIONS

BM developed the initial concept and outline. BM and SW collectively expanded the content, contributed, and edited the manuscript. Both authors contributed to the article and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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