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The impact of climate change on the distribution of wetland-associated invasive alien plant species in Western province, Sri Lanka

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ABSTRACT

Introduction: Climate change and invasive alien plant species (IAPS) severely threaten natural ecosystems globally.

Objective: To identify and assess climate suitability for seven wetland-associated species and predict their future distribution using shared socio-economic pathways (SSPs) 2 4.5 and 5 8.5 for 2050 and 2070.

Methods: The species selected were *Alstonia macrophylla*, *Annona glabra*, *Dillenia suffruticosa*, *Lantana camara*, *Leucaena leucocephala*, *Panicun maximum*, and *Sphagneticola trilobata*. Data on species occurrence were collected by field surveys in the Western province (Colombo, Gampaha and Kalutara districts), and this, together with climate data, were fed into the Maximum Entropy model (MaxEat model). Climate suitability area maps were developed for the seven IAPS for the current climate and four future scenarios.

Results: *A. glabra, L. camara*, and *L. leucocephala* showed an increase in climate-suitable areas for the years 2050 and 2070 under both climatic scenarios compared to the current distribution. *S. trilobata* showed a decrease in its range in the future compared to the current distribution. The climate-suitable area for *A. macrophylla* will also not expand under either scenario except for a modest rise in SSP2 4.5 in 2050. The current distribution of *D. suffruticosa* and SSP2 4.5 in 2050's distributions were almost identical, and the other two future scenarios showed comparatively low distribution. For *P. maximum* SSP2 4.5 indicated a slight increase in climate-suitable areas for 2070 compared to the current distribution.

Conclusion: *A. glabra, L. camara*, and *L. leucocephala* can become highly invasive as their ranges expand in response to future climate changes. The distribution of *S. trilobata* will be significantly reduced under future climate scenarios. As suitable areas for IAPS increase in the Colombo district over time compared to other districts in the province, its wetland-associated native plant species may face a greater risk of invasion by IAPS in future climatic scenarios.

Key words: temperature; range expansion; exotic; habitat shift; biodiversity.

RESUMEN
Impacto del cambio climático en la distribución de especies de plantas exóticas invasoras en humedales de la provincia occidental de Sri Lanka

Introducción: El cambio climático y las especies de plantas exóticas invasoras (EPI) amenazan gravemente los ecosistemas naturales a nivel mundial.
Objetivo: Identificar y evaluar la idoneidad climática de siete especies asociadas a humedales y predecir su distribución futura utilizando vías socioeconómicas compartidas (VSSP) 2 4.5 y 5 8.5 para 2050 y 2070.
Métodos: Las especies seleccionadas para el estudio fueron *Alstonia macrophylla*, *Annona glabra*, *Dillenia suffruticosa. Lantana camara*, *Leucaena leucocephala*, *Panicun maximum*, y *Sphagneticola trilobata*. Los datos sobre la presencia de especies se recopilaron mediante estudios de campo en la provincia occidental (distritos de Colombo, Gampaha y Kalutara) y estos, junto con datos climáticos, se incorporaron al modelo de máxima entropía (modelo MaxEnt). Se desarrollaron mapas de áreas de idoneidad climática para las siete EPIs para el clima actual y cuatro escenarios futuros.
Resultados: *A. glabra, L. camara* y *L. leucocephala* mostraron un aumento en las áreas adecuadas para el clima para 2050 y 2070 en ambos escenarios climáticos en comparación con la distribución actual. *S. trilobata* mostró una disminución en su rango en el futuro en comparación con la distribución actual. El área adecuada del clima para *A. macrophylla* tampoco se expandirá en ninguno de los escenarios, excepto por un aumento modesto en SSP2 4.5 en 2050. La distribución actual de *D. suffruticosa* y las distribuciones de SSP2 4.5 en 2050 fueron casi idénticas, y los otros dos escenarios futuros mostraron una distribución comparativamente baja. Para *P. maximum*, SSP2 4.5 indicó un ligero aumento en las áreas adecuadas del clima para 2070 en comparación con la distribución actual.
Conclusión: *A. glabra, L. camara* y *L. leucocephala* pueden volverse altamente invasivas a medida que sus áreas de distribución se expandan en respuesta a futuros cambios climáticos. La distribución de *S. trilobata* se reducirá significativamente en futuros escenarios climáticos. A medida que las áreas adecuadas para EPIs aumenten en el distrito de Colombo en comparación con otros distritos de la provincia, sus especies de plantas nativas asociadas a humedales pueden enfrentar un mayor riesgo de invasión por EPIs en futuros escenarios climáticos.

Palabras clave: temperatura; expansión de área de distribución; exóticas; cambio de hábitat; biodiversidad.

INTRODUCTION

Invasions due to the positive impact of global climate change on biological organisms are regarded as one of the key causes affecting biodiversity and ecological functioning, causing life on Earth to relocate globally (Bhagwat et al., 2012; Çoban et al., 2020; Thuiller et al., 2008). Further, biological invasions will cause changes in species distribution, extinctions, and habitat loss, which will affect natural, agricultural, and croplands (Çoban et al., 2020; Corlett & Westcott, 2013; Dang et al., 2021; Thuiller et al., 2008; Walther et al., 2009). Notably, within the last few decades, invasive alien plant species (IAPS) increased their distribution, competition for resources, hybridization with non-native species, homogeneity in ecosystems due to the displacement of native biota and alterations in genetic diversity (Abdelaal et al., 2020; Cao et al., 2021; Corlett & Westcott, 2013; Dang et al., 2021; Garcia et al., 2014; Walther et al., 2009). Identifying and predicting such impacts of invasive species and their distribution before they invade new environments under various climate scenarios is vital to reducing their future effects (Bhagwat et al., 2012; Garcia et al., 2014; Marambe & Wijesundara, 2021; Thapa et al., 2018). According to Essl et al. (2019) and Walther et al. (2009), as climate change has accelerated biological invasions, a more comprehensive and holistic management plan is required to restrict their spread and detrimental consequences.

Species distribution models (SDMs) are commonly utilized in ecology and conservation studies (Elith et al., 2010; Jiang et al., 2023; Thapa et al., 2018). They combine a set of known species occurrences data with environmental variables to forecast species' present and future distribution (Abdelaal et al., 2020). Such distribution models are very effective in evaluating the spreading of invasive species, for biodiversity conservation, and to assess the possible impact of climate change on species' distribution patterns (Thapa et al., 2018). The maximum entropy model, or MaxEnt model, is an open-source SDM that uses environmental grid data and geographic coordinates of species occurrences to predict the future distribution of species (Jiang et al., 2023; Nyairo & Machimura, 2020). Since its release in 2004, it has been widely used for modelling species distributions. MaxEnt model is a machine learning method to create species distribution maps from presence-only data (Franklin, 2010).

Distribution impacts of IAPS are particularly severe on oceanic islands (Essl et al., 2019; Marambe & Wijesundara, 2021; Wijesundara, 2010), where species and ecosystems are distinct and vulnerable due to island plant syndrome caused by limited resources, weak predation, and decreased interspecific and intraspecific competition (Essl et al.,2019; Kariyawasam et al., 2019). The shortage of native plant species for utilitarian or ornamental uses on islands led to a significant increase in the cultivation of alien plants (Essl et al., 2019). Sri Lanka, a tropical island with one of the world's 36 hotspots, has a diverse topography and different climates, contributing to substantial plant richness, including 3 350 endemic plant species. The country's wet zone is home to 94 % of its endemic plant species (Green et al., 2009). However, climate change affects the country's rainfall distribution, resulting in a smaller wet zone region (Eeswaran, 2018; Marambe & Wijesundara, 2021). According to combined climate suitability maps created for 14 IAPS in Sri Lanka for the year 2050, biodiversity-rich zones with higher endemism are potentially at a higher risk of climate change (Kariyawasam et al., 2021).

Most invasive alien plants in Sri Lanka were initially introduced intentionally as ornamental or economically beneficial plants (Iqbal et al., 2014; Marambe & Wijesundara, 2021; Perera & Epa, 2023; Wijesundara et al., 2010). Due to their specific adaptations to rapid spread in new habitats, they eventually spread into human settlements, forests, agricultural areas and wetlands, causing a detrimental effect on all these habitats. Thirty-one plants are considered nationally important IAPS in Sri Lanka (Wijesundara et al., 2010), of which 27 are invasive weeds spreading in agroecosystems (Marambe & Wijesundara, 2021). Identifying and mapping invasive flora and vulnerable habitats is critical for successful invasive alien species (IAS) control, as baseline data on the distribution and abundance of IAPS in Sri Lanka are limited. Many studies focus on the rising vulnerability of biodiversity to IAS in temperate regions. However, the tropics, where most biodiversity hotspots are located, have gotten less attention (Iqbal et al., 2014).

This study was conducted in seven selected wetlands in the Western province of Sri Lanka using seven frequently found, *Alstonia macrophylla*, *Annona glabra*, *Dillenia suffruticosa*, *Lantana camara*, *Leucaena leucocephala*, *Panicum maximum*, and *Sphagneticola trilobata*. The objectives of the study were to identify and assess potential climate suitability for the Western province wetlands, predict possible distribution changes in wetlands using Shared Socio-economic Pathways 2 4.5 and 5 8.5 for 2050 and 2070, and assess the risk posed by the distribution of native plant species in wetlands of the Western province. Here, predictions were made for climate conditions in the years 2050 and 2070 using the current geo-referenced occurrence data of seven and climate data in the MaxEnt model.

MATERIALS AND METHODS

Study area: The wetlands selected for the study (Table 1) were in all three districts of the Western province, namely, Colombo, Gampaha, and Kalutara (6°49'59.99" N & 80°04'60.00" E). The Western province covers an area of 3 684 km^2, which represents 5.6 % of the country's total land area. It is in the country's Southwest and receives about 2 500 mm of rainfall yearly, with the Southwest monsoon playing a significant role. The average temperature varies slightly from month to month, ranging from 28 to 29 °C.

Table 1
The wetlands selected to assess the future distribution of invasive alien plant species under different climate change scenarios in the Western Province, Sri Lanka.

Name of the wetland	Area (Km^2)	District
Muthurajawela marsh-South	5.69	Gampaha
Bellanwila-Attidiya marsh	3.72	Colombo
Parliament road marsh	*2.94*	Colombo
Bolgoda wetland-East	2.45	Colombo
Thalawathugoda wetland park	0.24	Colombo
Diyata Uyana marsh	0.20	Colombo
Beddagana (Kotte) marsh	0.19	Colombo
Kotte rampart park	0.18	Colombo
Walauwatta Wathurana swamp	0.12	Kaluthara
Talangama tank	0.11	Colombo

The total sampled wetland area was 15.84 km^2.

Species occurrence data: For the study, seven IAPS that are frequently found and well-established in Sri Lankan wetlands were selected (Table 2). *A. macrophylla* is originally found in Southeast Asia and deliberately introduced to Sri Lanka from Malaysia (Jayawardhane & Gunaratne, 2022). This plant is famous as a pioneer plant that quickly colonizes disturbed land areas (Ministry of Mahaweli Development & Environment [MMD&E], 2015). According to (Nanayakkara, 2002), *A. glabra* was likely introduced to the country in the 19th century for unknown reasons. Crude extracts from *A. glabra* seed, pulp, or leaves are commonly used in traditional medicine in Mexico, China, and Japan but not in Sri Lanka. In 1882 *D. suffruticosa* was introduced to Royal Botanical Gardens of Sri Lanka from Boneo (Wickramathilake et al., 2014). *D. suffruticosa* is a species capable of affecting the nutrient absorption of native plants growing beneath it by altering the soil structure and functions (Wickramathilake et al., 2014). *L. camara* has been naturalized in approximately 50 countries and is regarded as one of the world's worst weeds (Qin et al., 2016). *L. camara* is an ornamental plant that was introduced to Sri Lanka back in 1926 (Fernando et al., 2016). *L. camara* can adjust and thrive in harsh environmental conditions due to its phenotypic plasticity and allelopathy (Day et al., 2003). *L. leucocephala* is among the top five invasive plant species with a global presence (Sharma et al., 2022). It is believed that this fast-growing Southeast Asian legume plant was brought to the island in 1970 as a multipurpose plant due to its nitrogen-fixing ability. Even though it raises nitrogen in the soil, it easily outcompetes native plant species with its ability to produce a higher number of seedlings and germination rate (Bambaradeniya et al., 2001; Liyanage et al., 1993; Weber, 2004). *P. maximum* is a very famous weed in Sri Lanka that was introduced in the 1820s and now causes significant issues in agriculture and forestry plantation establishment. This plant suppresses native flora through pest and disease transmission, resource domination, and alteration of ecosystems (Gajaweera et al., 2011; MMD&E, 2015). *S. trilobata*, is considered one of the world's 100 worst invasive species. This was introduced to Sri Lanka back in the 1980s as a cover crop for tea plantations (Prematilake & Ekanayake, 2004). The *S. trilobata* creates a

Table 2
The invasive alien plant species (IAPS) recorded during the study.

Family name	Species	Common name	Life form
Apocynaceae	*Alstonia macrophylla* Wall. ex G.Don	Hard milkwood	Tree
Annonaceae	*Annona glabra L.*	Pond apple	Small tree
Dilleniaceae	*Dillenia suffruticosa* (Griff ex Hook.f. & Thomson) Martelli	Shrubby Dillenia	Small tree
Verbenaceae	*Lantana camara L.*	Lantana	Shrub
Fabaceae	*Leucaena leucocephala* (Lam.) de Wit	White leadtree	Tree
Poaceae	*Panicum maximum* Jacq.	Guinea Grass	Grass
Asteraceae	*Sphagneticola trilobata* (L.) Pruski	Creeping ox eye	Creeper

The GPS Map Camera. (n.d.) was used to get live locations and capture photos.

very thick and crowded cover on the ground that prevents the germination of other plant species. So, it can suppress native flora in wetlands by creating unnecessary competition for nutrients, light, and water (MMD&E, 2015).

The Visual Encounter Survey was conducted from January 2023 to July 2023 in the ten selected wetlands (Fig. 1) to record current species occurrence data based on the accessibility to the location. Five 100 m length line transects were marked using lines and poles in each wetland, and GPS coordinates of sites were recorded using a handheld GPS (Etrex/Model: Garmin Summit). For each transect, 1 m^2 quadrats are arranged evenly with a 10 m distance along the line. There was a 20 m gap between each transect (du Toit et al., 2021).

Climate data: The MaxEnt model uses climate variables as the major predictors because its primary aspect is regulating the geographic distributions of species (Zhang et al., 2021). Nineteen bioclimatic variables used as environmental parameters in SDMs were downloaded from the WorldClim database for current and future climate scenarios (Fick & Hijmans, 2017). Historical data for the 1970-2000 period was considered at a 2.5 arc-min resolution using the sixth version of the atmosphere-ocean General Circulation Model (GCM), Model for Interdisciplinary Research on Climate (MIROC6). Selecting a suitable global climate model for species distribution modelling is difficult because the performance of the GCM depends on the study area and the bioclimatic variables used. However, previous studies suggest that MIROC6 performs well in South Asia (Kariyawasam et al., 2019). For the future climate prediction updated scenario of Representative Concentration Pathways (RCP),

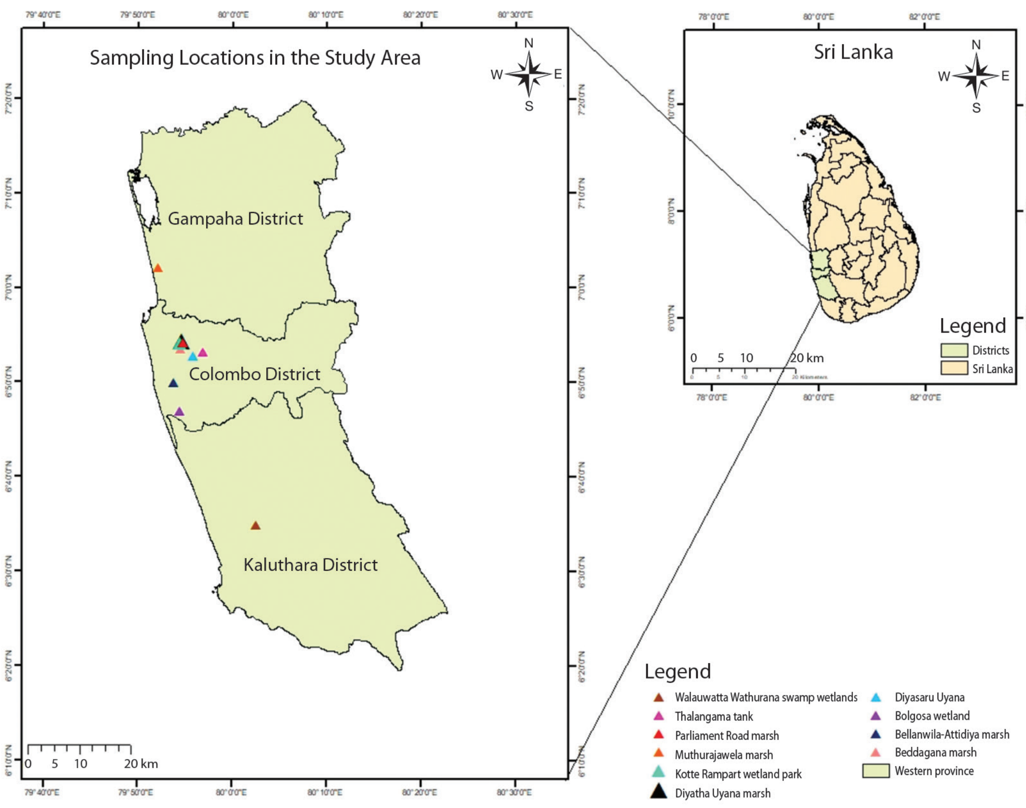

Fig. 1. The selected wetlands in the Western Province, Sri Lanka.

Table 3
The selected environmental variables used for MaxEnt modelling of seven in the wetlands of Western Province, Sri Lanka.

Variable	Abbreviation	unit
Mean Diurnal Range (Mean of monthly; max temp - min temp)	BIO 2	°C
Isothermality (BIO2/BIO7) (×100)	BIO 3	
Min Temperature of Coldest Month	BIO 6	°C
Mean Temperature of Wettest Quarter	BIO 8	°C
Mean Temperature of Coldest Quarter	BIO 11	°C
Precipitation of Warmest Quarter	BIO 18	mm

Shared Socioeconomic Pathways (SSPs) were considered, which were used for the Intergovernmental Panel on Climate Change (IPCC) sixth Assessment Report (AR6). Here, SSP2 4.5, a combination of SSP two and RCP 4.5, and SSP5 8.5, SSP five and RCP 8.5, were used as greenhouse gas emissions pathways for the years 2050 and 2070.

To remove highly correlated variables in 19 environmental variables in the MaxEnt model, Pearson Correlation Coefficients (r) among variables were calculated. The 'removeCollinearity' (version 1.5.1) function in R software (Leroy et al., 2015) was used to calculate the correlation, and the following six variables were selected to conduct the study (Table 3).

MaxEnt model settings: MaxEnt version 3.4.4 (Phillips et al., n.d.) was used to get a random test percentage setting in the model. This model option divides the uploaded species' occurrence data into two parts. A certain percentage of data (called test data) will be used to evaluate the model's performance. The remaining percentage of training data will be used to develop the model. The random test percentage in the settings folder was changed to 25 %. This automatically sets presence data to be used as training (75 %) and test data (25 %) (Ding et al., 2022). Species occurrence data collected through a field survey included 21 points for *A. macrophylla*, 40 for *A. glabra*, 21 for *D. suffruticosa*, 23 for *L. camara*, 30 for *L. leucocephala*, 26 for *P. maximum*, and 20 for *S. trilobata*. In the basic settings, "replicate run type" was selected as "subsample" and "regularization multiplier value" as one. In advanced settings, maximum iterations were increased to 5 000. Replicates were set as 15 so that MaxEnt would run the model multiple times and create averaged suitability maps (Tesfamariam et al., 2022). Other default settings were kept in the MaxEnt software (Ding et al., 2022). The species occurrence data CSV file and ASCII format of historical environmental layers were uploaded for species *A. macrophylla*, and the program was run. Then, the same species model was run separately for the ASCII format of future environmental layers of SSP2 4.5 for the year 2050, SSP2 4.5 for the year 2070, SSP5 8.5 for the year 2050, and SSP5 8.5 for the year 2070. The same procedure was carried out for the rest of the six species.

Development of climatic suitability maps: The 'reclassify' tool of ArcMap 10.8 was used to split the current distribution output raster layer of one species into three categories: low suitable area, suitable area, and highly suitable area. The areas were classified based on the number of invasive alien plant species (IAPS) present: low suitability with 1 IAPS, moderate suitability with 1.000000001 to 2 IAPS, and high suitability with 2.000000001 to 3 IAPS. Then, for the same species raster layer, SSP2 4.5 for the year 2050, SSP2 4.5 for the year 2070, SSP5 8.5 for the year 2050, and SSP5 8.5 for the year 2070 were reclassified. This procedure was applied to the seven selected.

For the quantitative evaluation of the suitability area changes for the years 2050 and 2070, the class “suitable area” was calculated using the following formula.

$$\text{Original area reduction or expansion} = \text{Original area} - \frac{\text{(New area)}}{\text{(Original area)}} \times 100$$

Then, potentially suitable areas change for each class of seven species under SSP2 4.5 and SSP5 8.5 for the years 2050 and 2070 were further analyzed as an area reduction or expansion. The following formula was used to calculate the percentage of the proportion of area increase regarding the original area.

Thus, area expansions were expressed as negative values, while reductions were defined as positive (Kariyawasam et al., 2019).

Statistical analysis: The MaxEnt model supplied statistical tests for the modelling process. One was the receiver operating characteristic (ROC) curve or area under the curve (AUC) value, a default setting. AUC value is essential to quantitatively evaluate the predictive performances of the model for each model run (Kariyawasam et al., 2019). AUC value helps to assess the performance of the model in each run. This value can range between 0-1. An AUC value below 0.2 will indicate the model’s poor performance, and AUC values between 0.5 and 0.7 are moderate. The value above 0.7 shows the model’s high performance (Thapa et al., 2018).

RESULTS

MaxEnt model prediction accuracy: The overall accuracy for each run of the model was quantitatively assessed by area under the curve (AUC) value. When considering the present and future periods of seven, AUC values ranged between 0.87 (lowest) and 0.98 (highest) with training data and 0.74 (lowest) and 0.98 (highest) with test data. The average training value was 0.96, and the average test value was 0.93. The highest AUC value of 0.98 was obtained for *S. trilobata* for the year 2070 in SSP2 4.5. The lowest AUC value, 0.87, was obtained for *Dillenia suffruticosa* in the year 2050 in SSP2 4.5. Six out of seven had AUC values > 0.9.

Current and future distribution of wetland-associated invasive alien plant species: Under the current climate, larger suitable predicted areas were recorded for D. suffruticosa (1 703.73 km^2) and A. macrophylla (1 172.06 km^2). The species L. leucocephala had the lowest suitable predicted area, 16.24 km^2 (Table 4).

Three species, namely *A. glabra, L. camara, and L. leucocephala,* showed an overall increase in climate-suitable areas for years 2050 and 2070 under both climatic scenarios than the current distribution (Fig. 2). *S. trilobata* was the only species that showed a decrease in climate-suitable areas for the years 2050 and 2070 under both climatic scenarios compared to the current distribution. For *A. macrophylla,* SSP2 4.5 for 2050 was the only scenario that showed a higher climate-suitable area than the current distribution. The distribution of *A. macrophylla* in SSP5 8.5 will decline by 85.1 % in 2050 (Table 5). Even though the highly suitable area of *A. macrophylla* will be reduced in the year 2050 for SSP5 8.5, its highly suitable area will expand into the Southern part of the province (Fig. 3A). The climate-suitable areas of *A. glabra* will significantly increase from 30.76-47.42 % in 2050 and 2070. The highly suitable area of *A. glabra* (2 06.33 km^2) will also increase by 9.54 % for SSP2 4.5 in 2025 and 0.42 % for SSP5 8.5 by 2070.

D. suffruticosa’s current distribution and SSP2 4.5 for 2050’s future distribution were almost identical, and other future scenarios showed less distribution than these two. The highly suitable area (285.95 km^2) of *D. suffruticosa* will expand by 16.47 % in SSP2 4.5 in 2050 and 2.6 % in SSP5 8.5 in 2070. Under future climate circumstances, *D. suffruticosa* will be

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Table 4
Projected area of suitability (km^2) of the seven IAPS of three classes (low suitable, suitable, and highly suitable) under the current climate and SSP2 4.5 and SSP5 8.5 for 2050 and 2070.

Species	Distribution class	Current	2050		2070	
			SSP2 4.5	SSP5 8.5	SSP2 4.5	SSP5 8.5
Alstonia macrophylla	Low suitable	2 361.25	2 359.54	3 434	2 385.23	2 391.23
	Suitable	1 172.06	1 181.48	174.65	1 130.11	1 091.587
	Highly suitable	187.5	179.79	112.16	259.41	199.48
Annona glabra	Low suitable	3 016.2	2 773.92	2 787.61	2 868.1	2 877.51
	Suitable	498.28	720.88	734.57	651.53	636.12
	Highly suitable	206.33	226.02	198.63	201.19	207.19
Dillenia suffruticosa	Low suitable	1 731.13	1 679.76	2 063.31	2 028.21	1 907.5
	Suitable	1 703.73	1 708.01	1 382.68	1 450.31	1 523.94
	Highly suitable	285.95	333.04	274.82	242.29	289.38
Lantana camara	Low suitable	3 036.75	2 660.9	2 794.46	2 697.72	2 717.41
	Suitable	474.31	835.6	657.52	775.67	803.07
	Highly suitable	209.76	224.31	268.83	247.43	216.34
Leucaena leucocephala	Low suitable	3 398.9	3 065	2 781.62	2 821	2 551.32
	Suitable	16.24	504.27	722.59	688.34	942.62
	Highly suitable	156.68	155.54	216.61	211.47	226.88
Panicum maximum	Low suitable	2 843.26	3 433.15	2 858.67	2 820.15	3 100.11
	Suitable	678.07	161.81	673.79	689.2	447.77
	Highly suitable	199.48	125.85	188.35	211.47	172.94
Sphagneticola trilobata	Low suitable	2 767.07	2 855.25	3 462.26	3 420.31	3 428.87
	Suitable	757.69	698.62	142.98	151.54	167.81
	Highly suitable	196.06	167.81	115.58	148.97	124.14

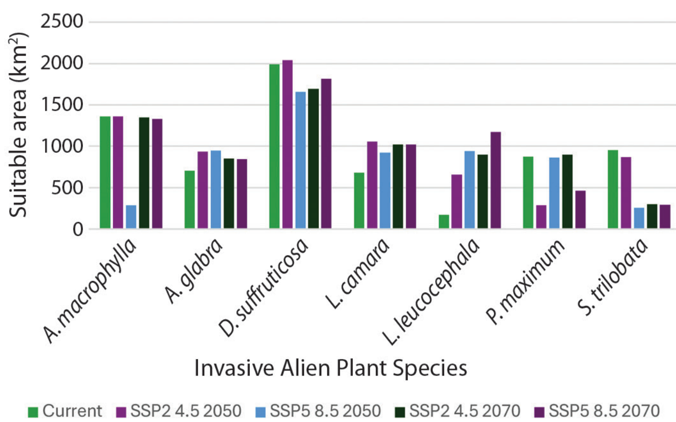

Fig. 2. Projected suitable area (km^2) of the seven selected IAPS in Western province wetlands in Sri Lanka under current climate and MIROC6 SSP2 4.5 and SSP5 8.5 for 2050 and 2070.

dispersed from 1 382.68 km^2 to 1 708.01 km^2, extending into all three districts. In all future climate scenarios, the suitable and highly suitable areas of *L. camara* in the western province will increase. According to the species distribution maps, this species will mainly be distributed in the Colombo and Gampaha districts in future.

Table 5
Percentage area variation (km^2) of invasive alien plant species (IAPS) under current climate and SSP2 4.5 and SSP5 8.5 for 2050 and 2070.

Species	Distribution class	SSP2 4.5		SSP5 8.5	
		2050	2070	2050	2070
Alstonia macrophylla	Low suitable	-0.072	1.01	45.43	1.27
	Suitable	0.80	-6.87	-85.1	-3.58
	Highly suitable	-4.11	38.35	-40.2	6.39
Annona glabra	Low suitable	-8.03	-4.91	-7.58	-4.6
	Suitable	44.67	30.76	47.42	27.66
	Highly suitable	9.54	-2.49	-3.73	0.42
Dillenia suffruticosa	Low suitable	-2.97	17.16	19.19	10.19
	Suitable	0.25	-14.87	-18.84	-10.55
	Highly suitable	16.47	-15.27	-3.89	1.2
Lantana camara	Low suitable	-12.38	-11.16	-7.98	10.52
	Suitable	76.14	63.53	38.63	69.31
	Highly suitable	6.94	17.96	28.16	4.49
Leucaena leucocephala	Low suitable	-9.82	-17.00	-18.16	-24.94
	Suitable	3005.12	4138.53	4349.45	5704.31
	Highly suitable	-0.73	34.97	38.25	44.80
Panicum maximum	Low suitable	20.75	-0.81	0.54	9.03
	Suitable	-76.14	1.64	-0.63	-33.96
	Highly suitable	-36.91	6.01	-5.58	-13.30
Sphagneticola trilobata	Low suitable	3.19	23.60	25.12	23.92
	Suitable	-7.80	-80	-81.13	-77.85
	Highly suitable	-14.41	-24.01	-41.05	-36.68

For *P. maximum* SSP2 4.5 for 2070 was the only scenario that showed a higher climate-suitable area than current distribution. In the Colombo district, *P. maximum* has its highly suitable areas (199.48 km^2), which reduce in 2050 SSP2 4.5, 2050 SSP5 8.5, and 2050 SSP5 8.5 but show an increment for the 2070 SSP2 4.5 by 3.01 %. In current climate conditions, *P. maximum* has a suitability area of 678.07 km^{2,} but this reduces significantly for SSP2 4.5 by 76.14 % in 2050. In the year 2050, SSP5 8.5 and 2070 SSP2 4.5 show suitable area increments, while 2070 SSP5 8.5 show a reduction. The current highly suitable areas (156.68 km^2) of *L. leucocephala* in the Colombo district will reduce slightly for SSP2 4.5 in 2050 but increase for the other three scenarios. In current climate conditions, *L. leucocephala* has a very low suitability area of 16.24 km^2, but this expands significantly in both scenarios for the years 2050 and 2070. The currently suitable area is spread out only in the Colombo district, but in the future, it will expand to both the Kaluthara and Gampaha districts. When considering *S. trilobata* highly suitable areas (196.06 km^2) in the Colombo district, it is reduced for all future scenarios. In current climate conditions, *S. trilobata* has a noticeable suitability area (757.69 km^2) that covers Colombo and Kaluthara districts. This area was slightly reduced for SSP2 4.5 by 7.80 % in 2050 and significantly reduced for 2050 SSP5 8.5, 2070 SSP2 4.5, and 2070 SSP5 8.5.

Fig. 3 shows the maps of climatic suitability for selected under the current climate and SSP2 4.5 and 5 8.5 for 2050 and 2070. The projected maps of all seven species under the current climate showed a highly suitable region in the Western part of the Colombo district, including Bellanwila-Attidiya Marsh, Bolgoda Wetland, and Colombo Wetland City. In the future, the

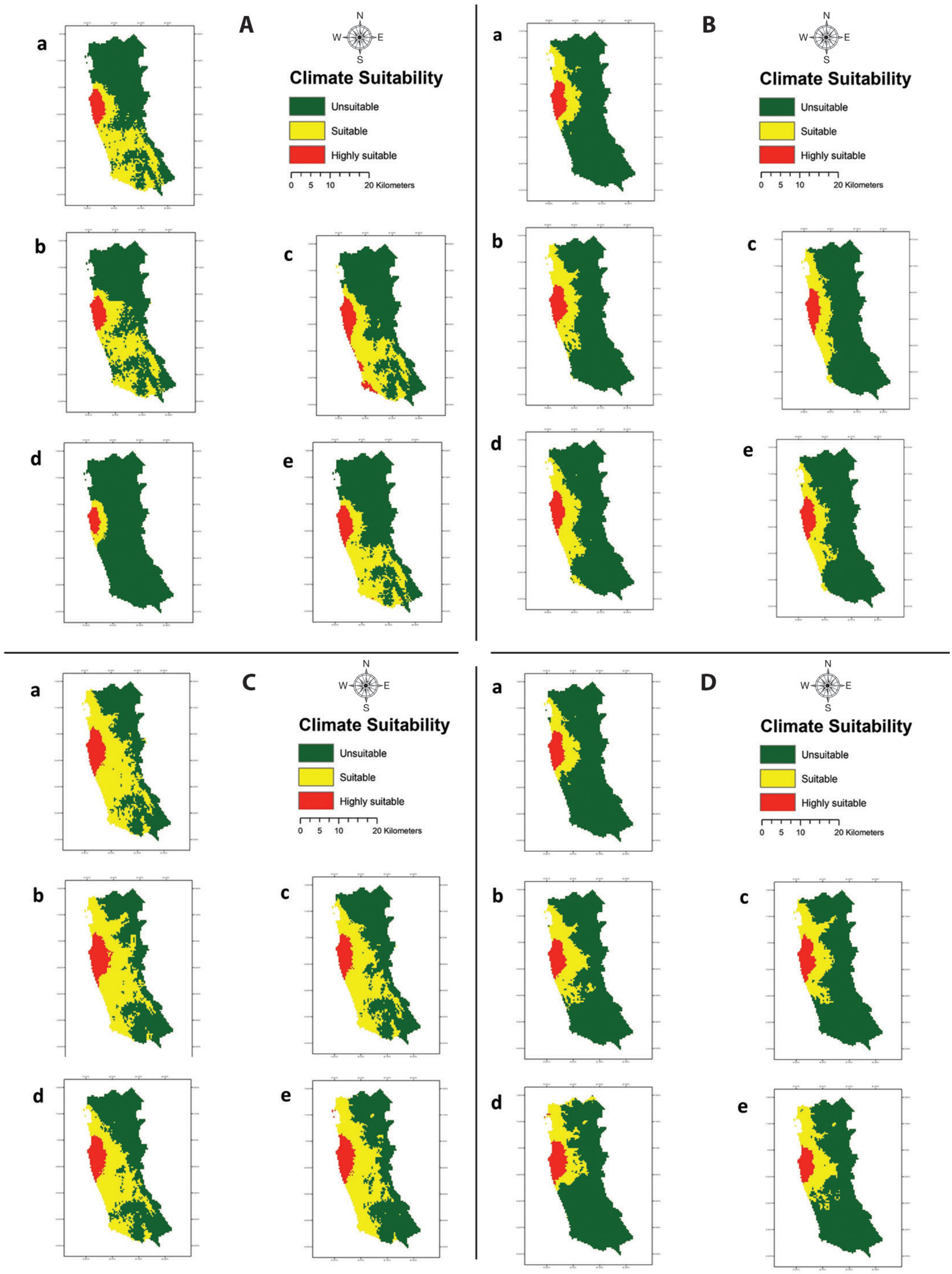

Fig. 3. Continue in next page.

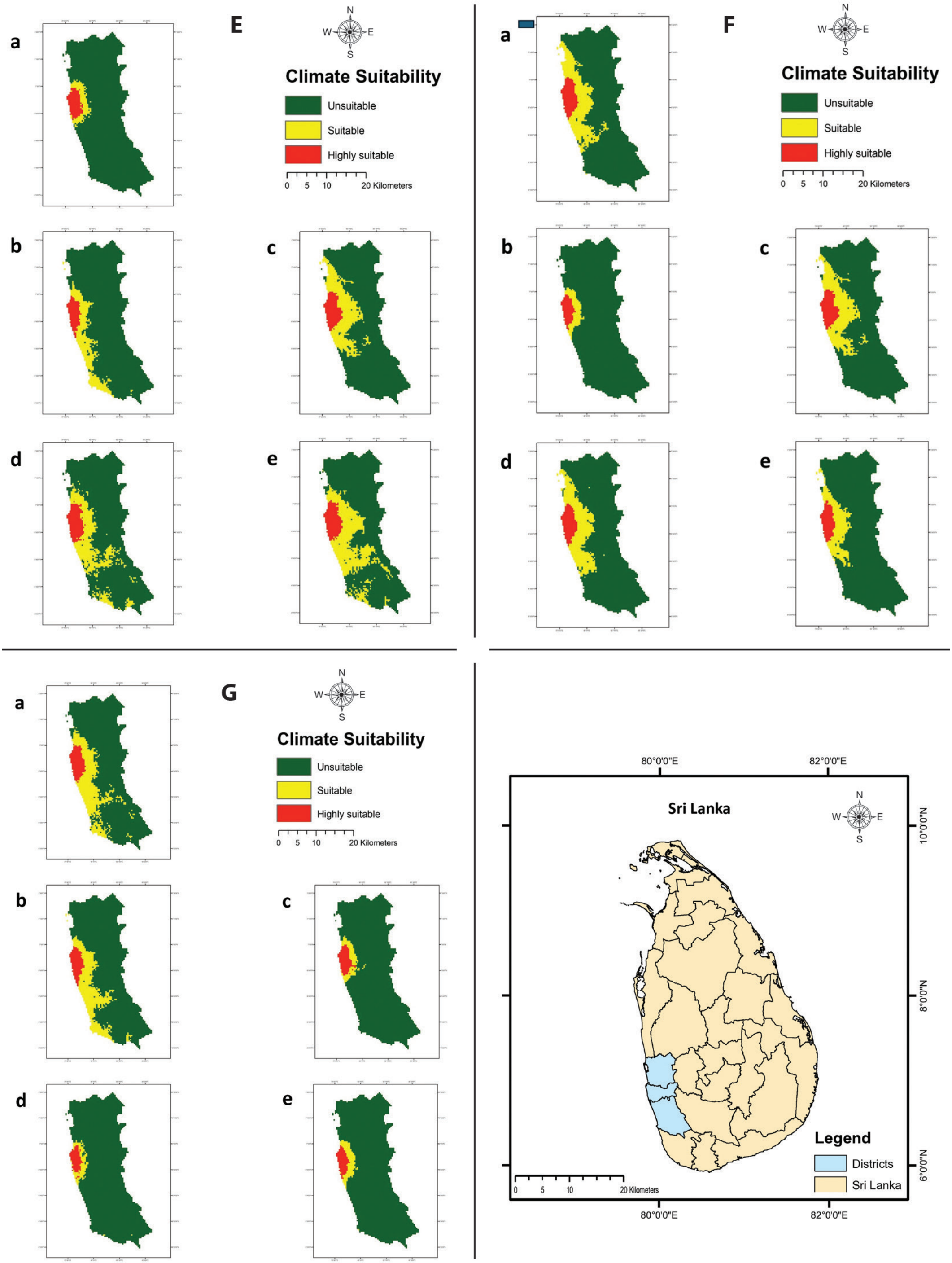

Fig. 3. Map showing current and future projected climate suitability for seven IAPS in the Western province of Sri Lanka. **A.** *Alstonia macrophylla*, **B.** *Annona glabra*, **C.** *Dillenia suffruticosa*, **D.** *Lantana camara*, **E.** *Leucaena leucocephal*, **F.** *Panicum maximum*, **G.** *Sphagneticola trilobata*. a: Current climate, b: MIROC6 SSP2 4.5 for 2050; c: MIROC6 SSP2 4.5 for 2070; d: MIROC6 SSP5 8.5 for 2050 and e: MIROC6 SSP5 8.5 for 2070.

native biodiversity in this area could be highly affected by the range expansion of wetland-associated IAPS.

DISCUSSION

The seven wetland-associated invasive plant species evaluated differed significantly in terms of biological characteristics and belonged to the following Families: Annonaceae, Apocynaceae, Asteraceae, Dilleniaceae, Fabaceae, Poaceae, and Verbenaceae. The results show that their responses to different climatic scenarios also vary. Recent studies, including those by Bezeng et al. (2017) and Jiang et al. (2023), indicate that the impact of climate change on invasive alien plant species (IAPS) is highly species-specific. In Sri Lanka's Western wetland ecosystems, species like *A. glabra, L. camara* and *L. leucocephala* are predicted to expand their range under SSP2 4.5 and SSP5 8.5 climate scenarios, posing threats to native biodiversity. The distribution models show temperature-related variables, especially those linked to cold-season temperatures, as critical drivers of this expansion. For *A. glabra*, the mean temperature of the coldest quarter (BIO11) contributed 73.1 % to the 2050 model under SSP2 4.5, suggesting potential range expansion as cold temperatures rise. *L. camara*'s model showed a 90.6 % contribution from BIO11, highlighting its sensitivity to cold-season temperatures and the likelihood of invading new areas. *L. leucocephala*, with a 98.1 % contribution from BIO11 under the SSP2 4.5 scenario for 2070, is also expected to significantly expand its range as cold temperatures become less restrictive. These findings underscore the importance of cold-season temperatures in shaping the future distribution of these invasive species.

Two scenarios with two distinct time periods suggested that *A. glabra*'s suitability area increased by more than 27 % (table 5) from the current distribution. The highly suitable area for this species fluctuates between 198.63-226.02 km^2 within both scenarios in 2050 and 2070. Under SSP5 8.5 in 2050, *A. glabra* suitability area is likely to increase by 47.42 % compared to the current distribution. Birds and mammals disperse *A. glabra* seeds, which may survive in fresh and saltwater for up to 12 months (Setter et al., 2002), enhancing their ability to invade new habitats like wetland ecosystems, particularly in the wet zone because *A. glabra* can successfully grow as dense clusters in both freshwater and brackish water wetlands (MMD&E, 2015; Nanayakkara, 2002) *A. glabra* form dense monocultures spreading in wetlands, riparian zones, coastal foreshores, and other natural and manmade drainages in Australia, creating a biodiversity conservation issue (Setter et al., 2002). Initiating eradication measures now will better prepare us for future challenges. If the SSP5-8.5 scenario occurs in 2070, these early actions will make it more feasible to manage and potentially eradicate the species from its established habitats in Sri Lanka.

It produces allelopathic compounds and frequently creates dense monospecies stands by interrupting the regeneration process of indigenous plant species (Kato-Noguchi & Kurniadie, 2021). The immediate introduction of control measures is highly recommended for *L. camara* as in all future climatic scenarios in 2050 and 2070; this species showed more expansion than the currently suitable area in Sri Lanka. The highest suitability to spread was shown under SSP2 4.5 in the year 2050, which could increase the suitability area by 76.14 %. The lowest future suitability is shown under SSP5 8.5 in the year 2050, in which the suitability area can increase only by 38.63 %. As a result, unless a proper plan is implemented to prevent this species' continuing range expansion, it will benefit from climate change scenarios and establish itself in new places, posing conservation challenges. According to Qin et al. (2016), MaxEnt model predictions through 2050 indicated an overall global expansion of *L. camara* despite future suitability varying considerably among continents.

It is widely used in agroforestry, livestock, and restoration operations, leading to its invasion of natural ecosystems in Asia. Out of seven plants studied, *L. leucocephala* had the lowest current distribution in the wetland environments in Sri Lanka. The plant primarily invades wastelands, roadsides, riverbanks, agricultural lands, and forest edges, inhibiting the growth of other woody and herbaceous species (Sharma et al., 2022). The highly moist soil in a wetland environment and the current climate may not be very positive for the distribution of *L. leucocephala*. However, future climate scenarios are highly advantageous for the range expansion of these species. According to MaxEnt model prediction, *L. leucocephala* will have a suitability area increase of more than 3 005 % for all four future climatic scenarios. Although *L. leucocephala* has limited natural dissemination by mechanical means, its persistent seed bank likely assures dispersal through the soil, which is common around disturbed sites (Nghiem et al., 2015). The highest suitability is presented under SSP5 8.5 in 2070 when the suitability area can increase by 5 704.31 % and the highly suitable area by 44.8 %. The warmer future climate in the wet zone in Sri Lanka (Kariyawasam et al., 2021) may be favorable for the growth and dispersal of *L. leucocephala*. So, this species' alarming, expected rate of rapid range expansion must be stopped before it further affects the local biodiversity. The current period will be the most suitable time to eradicate *L. leucocephala* if selected as a management option.

A. macrophylla is widely distributed in several Asian countries, including Sri Lanka, India, Thailand, Cambodia, Indonesia and Vietnam. It is a drought-resistant, wind-dispersed tree that thrives even on poor soil. According to the results, SSP5 8.5 in 2050 was the most unfavorable climate for *A. macrophylla* because its suitability area will be reduced by 85.1 %. In SSP5 8.5 in 2070, the suitability area will also be reduced by 3.58 % compared to the current suitability area. So, future climate conditions in the western province can be unfavorable for *A. macrophylla. A. macrophylla* is expected to experience climatic unsuitability by 2050 under the SSP5 8.5 scenario, presenting an opportunity to control its spread in vulnerable ecosystems in the Western province. Nonetheless, eradication and containment plans should be prepared in advance, even if future conditions may facilitate these efforts. *A. macrophylla* has been naturalized on Sentosa Island in Singapore since 1879 but has yet to spread beyond its original location (Nghiem et al., 2015), which shows its slow range expansion in invaded habitats.

D. suffruticosa, a native of East Asia, has the highest distribution in the current climate and four future scenarios compared to the other six studied. The presence of this species is considered a sign of forest degradation (Heng et al., 2014). According to Wijesundara (2010), the population size of *D. suffruticosa* has rapidly increased in Sri Lanka owing to optimum environmental conditions. However, only SSP2 4.5 in 2050 showed a slight increase in the suitability area (0.25 %) for *D. suffruticosa.* All the other three scenarios showed a decrease in the suitable area of over 10 % compared to the current suitability area. Even though the suitability area is predicted to be low in the future, the area it occupies will be considerably higher than the other six invasive species. Therefore, managing the spreading of *D. suffruticosa* in the future needs' special attention. It has spread to several areas of the country, including natural ecosystems, abandoned or degraded lands, and forest plantations. When considering the predictions of *P. maximum*, only 2070 SSP2 4.5 could increase the area by 1.64 %. All the other three scenarios showed a decline in the suitability area. The SSP2 4.5 in 2050 will have the highest drop in the area, 76.14 %. So, the future climate is not more advantageous for *P. maximum* than the current climate. According to Jiang et al. (2023), climate change may negatively affect the global distribution pattern of another Guinea grass species, *P. milliaceum*.

The present climate is the most suitable condition for *S. trilobata* because it has the highest distribution compared to most future climate scenarios. For SSP2 4.5 in 2050, the suitability area of the species reduced slightly by 7.08 %. For all the other future scenarios of the species, it shows a suitable area decline of more than 77 % compared to the current suitability area. The SSP5 8.5 in 2050 will be the species' most unfavorable scenario, showing 81.13 %

suitable area reduction. Also, it will be the best phase to manage the abundance of this species with the help of adverse environmental conditions of nature. *S. trilobata* thrives in moist areas like marshes and riverbanks, frequently impacted by human activity (Kato-Noguchi & Kurniadie, 2021; Perera et al., 2023). The expected lesser distribution of this plant under future climatic scenarios could be ascribed to the rising temperature in the environment. To leverage potential future climate unfavourability, appropriate eradication measures should be implemented now. Also, it will be the best phase to manage the abundance of this species with the help of adverse environmental conditions of nature. *S. trilobata* thrives in moist areas like marshes and riverbanks, frequently impacted by human activity (Kato-Noguchi & Kurniadie, 2021; Perera et al., 2023). *S. trilobata* currently thrives in stable, moist environments, with isothermality (BIO3) contributing 66.5 % to its distribution model, highlighting its reliance on consistent temperature patterns. However, as the climate warms, the species' distribution is expected to shift. By 2070, under the SSP2 4.5 scenario, the mean temperature of the coldest quarter (BIO11) becomes overwhelmingly dominant, contributing 99.3 %, indicating a growing dependence on cold-season temperatures. Similarly, under the SSP5 8.5 scenario for 2070, BIO11 and BIO6 (Min Temperature of Coldest Month) together account for over 33 % of the model, reflecting the species' increasing sensitivity to warming trends. As cooler, stable conditions become less common, *S. trilobata* may struggle to maintain its current distribution, potentially limiting its spread in the Western Province of Sri Lanka.

It is well known that invasive plants frequently inhabit human-modified ecosystems, which are different from their native habitats (Bhagwat et al., 2012; Çoban et al., 2020; Corlett & Westcott, 2013; Dang et al., 2021; Thuiller et al., 2008; Walther et al., 2009). Western Province is Sri Lanka's most populous province, so anthropogenic activities have significantly impacted the natural ecosystems. Disrupted habitats in the Western province include barren land, garbage dumping sites, agricultural lands, human settlements, industrial and construction sites and manmade wetlands. Due to these disturbances and future climate suitability, the wetlands in this environment can be highly susceptible to IAPS invasions. Meteorological data analysis in Sri Lanka indicates considerable changes in climate parameters, supporting future climate change (Iqbal et al., 2014). Since most native plants cannot evolve and change their distribution area quickly or spread fast like, it is necessary to take precautionary measures to manage the range expansion of in Sri Lanka. Island biogeography, small size, and expanding anthropogenic disturbances may significantly impact the spread of across the country. The projected maps of all seven species under the current climate showed a highly suitable region for IAPS in the Western part of the Colombo district, including Bellanwila-Attidiya Marsh, Bolgoda Wetland, and Colombo Wetland City. In the future, the native biodiversity in this area could be highly affected by the range expansion of wetland-associated IAPS.

The findings of this study provide scientific information emphasizing areas that should be managed more carefully. Because unfavorable environmental conditions limit the establishment and distribution of (Walther et al., 2009), most management measures used to control or remove invasive species are effective when plant distribution is minimal (Bhagwat et al., 2012). However, the ability of plants to invade depends not only on environmental factors but also on the species invasive potential and propagule pressure (Kariyawasam et al., 2019) which should also be considered in selecting strategies to control the future distribution of. Invasive plants provide significant environmental and socio-economic challenges. Sri Lanka, a signatory to the Nations Framework Convention on Climate Change (United Nations, 1992) and the Paris Agreement (United Nations Framework Convention on Climate Change, 2016), identifies with the urgency of solving climate-related challenges (Marambe & Wijesundara, 2021). This work is the first to predict wetland-associated dispersal under future climatic conditions in Sri Lanka, potentially assisting decision-makers in optimal planning and management.

The MaxEnt model was used to estimate the distribution of suitable climatic conditions associated with wetlands in Sri Lanka's Western province under shared socio-economic pathways SSP2 4.5 and 5 8.5 for 2050 and 2070. The results provide qualitative and quantitative evidence along with temporal and spatial locations where they are possibly distributed or that can be distributed in the future. *A. glabra, L. camara,* and *L. leucocephala* can become highly invasive as their ranges expand in response to SSP2 4.5 and 5 8.5 for both years. *S. trilobata* is vulnerable to climate change as its distribution will significantly reduce under future climate scenarios. SSP5 8.5 in 2050 will be the species' most adverse scenario, with an 81.13 % reduction in suitable territory. *A. macrophylla, D. suffruticosa*, and *P. maximum* will respond differently to future climatic scenarios, increasing and decreasing their distribution in response to climate fluctuations. Comparatively, native plant species and ecosystems in Colombo are at higher risk than in the Gampaha and Kaluthara districts. The findings can be utilized to design future conservation efforts for native plant biodiversity, reducing economic and environmental costs.

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