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# Potential risks of invasive alien plant species on agriculture under climate change scenarios in Sri Lanka

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ABSTRACT

Invasive alien plant species (IAPS) have had a significant impact on agriculture in many countries in the world. Climatic suitability maps can be used to assess the vulnerability of agricultural areas for potential plant invasions. We used climatic suitability heat maps of IAPS to examine how potential climatic suitability for multiple IAPS invasion changes in eight agricultural land-use types in Sri Lanka under climate change scenarios for 2050. The findings of the study revealed that all evaluated agricultural land-use types are potentially vulnerable to invasion by different numbers of IAPS. In the majority of land-use types, the climatic suitability for multiple IAPS was predicted to increase under climate change scenarios. Out of all land-use types, coconut grown areas are expected to have the greatest suitability increase for more than three IAPS. Nearly all paddy lands were predicted to become suitable for two serious aquatic invaders (*Eichhornia crassipes* and *Salvinia molesta*) under current climatic conditions. However, a noticeable reduction in climatic suitability for IAPS was predicted in paddy lands by 2050. The study provides useful information that can be used by policy-makers to develop effective control and management strategies against the establishment of IAPS in agricultural land-uses in Sri Lanka.

## 1. Introduction

Biological invasion is considered as one of the most important direct drivers of global environmental change with significant ecological and socio-economic impact (Millennium Ecosystem Assessment, 2005). Invasive alien plant species (IAPS) have the potential to make a considerable impact on global agriculture, which continues to influence food security worldwide (Cook et al., 2011; Fleming et al., 2018). The economic cost of plant invasion to agriculture is growing due to the increasing number of new introductions, which create a tremendous impact on crop and pasture production (Seebens et al., 2017). Thus, in many countries, IAPS cause billions of dollars in agricultural losses each year (Pimentel et al., 2001; Sinden et al., 2004). For instance, in the USA, around one-fourth of gross national product of agriculture is diverted for controlling exotic invaders (Simberloff, 1996). In addition to the economic damage, IAPS add an additional cost of management to agriculture. The magnitude of impact can vary between countries or locations (Lovell et al., 2006; Paini et al., 2016); knowledge and understanding of such impacts on global agriculture and food security are limited and not properly evaluated in many countries (Paini et al., 2016). Many such evaluations are not uniform, perhaps due to differences in the cost estimation methods and criteria used (Pyšek and Richardson, 2010). Invasive species impact agricultural production and thus challenge achieving sustainable development goals (SDGs), particularly Goal 2 that aims to “end hunger, achieve food security and improved nutrition and promote sustainable agriculture”.

Warming of the earth surface is unavoidable due to anthropogenic influences (human-influenced greenhouse gas emission) and natural climatic variability (Cubasch et al., 2013; IPCC, 2012). The average temperature over the land surface has increased considerably (by 1.53 °C) from 1850–1900 to 2006–2015 which has impacted the growing seasons of crops, leading to reductions in crop yields (IPCC, 2019). According to climate predictions, there will be significant differences in the climate of South Asia by 2100 (IPCC, 2014). Many developing countries in the tropical region are susceptible to the climate change effects in the next century because of their relatively low capacity to adaptations (Achard et al., 2002; Lobell et al., 2008; Paini et al., 2016). Impacts of climate change are considerable and undoubtedly noticeable on agricultural productivity (Arora, 2019). Further, climate change as a key driver of geographical distribution of species strongly affects the spread of IAPS (Fandohan et al., 2015; Taylor and Kumar, 2013). Potential growth and distribution of IAPS are likely to be

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accelerated by several aspects of climate changes, such as increase in temperature, atmospheric carbon dioxide level, nitrogen deposition, severe weather conditions and changes in precipitation (Jia et al., 2016; Ziska et al., 2011). Recent developments in global trade and transport have facilitated pathways for IAPS to move in across natural barriers and geographic borders which has rendered managing biological invasions more challenging (Hulme, 2009).

Sri Lanka, with a land area of 65,610 km$^2$, is predominantly an agrarian-based country with rich biodiversity. Greater number of population of the country are rural dwellers and they rely on agriculture for livelihood (FAO/WFP, 2017). Agriculture that contributes 7.1% of Sri Lanka's GDP, is a key source of revenue to the country (Central Bank of Sri Lanka, 2020). At present, around 43% of the area of Sri Lanka is set apart for agriculture (Gunawardana, 2018). The main intensive agricultural lands in the country include paddy lands, plantations (i.e., tea, rubber, and coconut), vegetable cultivations and home gardens. Rice is the single most important crop in Sri Lanka. Key plantation crops occupy a prominent place in the economy of the country. Home gardens, one of the diversified agricultural systems in the country provides an important source of fruits, medicines, timber and other raw materials. Despite many control and management efforts, the pressure from IAPS on agriculture is growing (Early et al., 2016; Paini et al., 2016).

Invasive alien plants may reduce agricultural productivity through several mechanisms: competition (for light, nutrients, water), allelopathy and parasitism, and decrease the yield of crops and quality of pasture (Bajwa et al., 2019; Fried et al., 2017). Tall IAPS shade out the crops, particularly young plants, and hamper their growth (Burgos and Ortuoste, 2018). Experimental studies reported the potential risks of IAPS to agriculture, i.e., severe yield losses (Pratt et al., 2017; Tamado et al., 2002); inhibition of seed germination and growth of crops and pastures (Gnanavel and Natarajan, 2013; Koodkaew et al., 2018); allelopathy effects and direct competition (Shackleton et al., 2017); disturbance to the movements of livestock (Gouldthorpe, 2006) and block irrigation canals (Spencer and Coulson, 1976).

Identifying agricultural areas with higher potential for invasion by multiple IAPS under climate change scenarios is challenging. A review of literature reveals that how IAPS impact on agriculture under scenarios of climate and how these risks vary across different agricultural land-use types remains understudied. Thus, prediction of potentially suitable habitats for IAPS establishment and prioritizing areas where urgent attention would be required are important for assessing the risks of IAPS invasion in agricultural lands. Species distribution models are commonly used to define geographical areas potentially suitable for IAPS invasion under climate change scenarios; however, only a limited number of studies have used this tool for assessing the climatic suitability of IAPS in agricultural land-uses (Wang and Wan, 2020). A few studies have been undertaken in Sri Lanka to develop potential climatic suitability maps for priority IAPS under scenarios of climate (Kariyawasam et al., 2019a; Kariyawasam et al., 2021b). However, these studies have not investigated the likely impacts of IAPS invasion on agricultural land-uses under changing climatic conditions. We believe that there is a need to extend these results with the aim of evaluating the potential risks of plant invasions to agricultural areas as invasive plants adversely impact agriculture, leading to food insecurity. Thus, this research aims to quantify the risks from multiple IAPS invasion in eight different agricultural land-uses in Sri Lanka and compare the findings under various climate change scenarios. Using MaxEnt habitat suitability modeling technique, Kariyawasam et al. (2019a) developed combined maps of climatic suitability ("heat maps") of 14 priority terrestrial IAPS under current climate and future climate scenarios, representative concentration pathways 4.5 and 8.5 (RCP4.5 and 8.5) for 2050. We used these combined climatic suitability maps to assess the climatic suitability in each of the seven terrestrial agricultural land-use types, namely; chena, cropland, homestead, tea, rubber, coconut and grassland. In addition, Kariyawasam et al. (2021b) developed climatic suitability maps of the worst aquatic IAPS, *Eichhornia crassipes* and *Salvinia molesta* using the same modeling technique for current and future climate scenarios (RCP4.5 and 8.5) for 2050. These two IAPS are widespread in aquatic habitats of Sri Lanka and they are considered as the most serious aquatic IAPS in the country. In the present study, we used these maps of climatic suitability for assessing the suitability in paddy lands under current and future climate scenarios for 2050. Paddy is the major aquatic-based agricultural land-use type in Sri Lanka. The approaches used in the above two modeling studies are briefly described under the methods section. The objective of this study was to assess the vulnerability of agricultural land-use types in Sri Lanka for multiple plant invasions through assessing potential climatic suitability for different numbers of IAPS and understanding how the suitability changes spatially and temporally under climate change scenarios.

## 2. Methods

### 2.1. *Invasive plant species considered by the modeling studies*

We considered climatic suitability of 14 terrestrial and two aquatic IAPS (Table 1). These plant species have been recognized as priority IAPS of Sri Lanka and included in the national list of 20 plant species declared by the Government in, 2015 (MoMD&E, 2015).

### 2.2. *Preparation of climatic suitability maps*

#### 2.2.1. *MaxEnt species distribution modeling of 14 terrestrial IAPS*

MaxEnt models were calibrated for 14 terrestrial IAPS using geo-referenced species records from Sri Lanka and bioclimatic variables, which are at 30 arc-seconds resolution. Occurrence data of 14 terrestrial IAPS was acquired from various sources, such as published and unpublished literature, online databases and expert consultations. Sampling bias was reduced using spatial filtering of occurrences which resulted in 1460 occurrence records for 14 IAPS (Fig. S1). Bioclimatic variables extracted from Worldclim database (version 1.4) for current and future climatic conditions were used as environmental variables. Collinear variables were removed using the package 'virtual species' in R. This method groups variables into clusters, which allows selecting the most responsive single variable from each cluster. Thus, a set of seven non-correlated environmental variables was selected for model run (Table S1). The fifth version of the Model for Interdisciplinary Research on Climate (MIROC5) general circulation model (GCM) was used for future climate projections under Representative Concentration Pathways (RCPs) 4.5 and 8.5 for 2050. Linear, quadratic and hinge features, and 1000 maximum iterations were selected with other default settings. Ten-fold cross-validation was used, enabling the models to use all occurrence data for validation. The performance of MaxEnt models of 14 species was evaluated using threshold-independent AUC (area under the receiver operating characteristic curve) and threshold-dependent TSS (true skill statistic) measures. Satisfactory performance of both measures was ensured while validating models for the intended use. Suitability maps were classified using maximum training sensitivity plus specificity threshold approach. Combined maps of climatic suitability (heat maps) were developed by aggregating 14 individual climatic suitability maps for current and future scenarios and these combined climatic suitability maps were further classified into five classes based on the number of overlapped IAPS: very low (0 IAPS), low (1–2 IAPS), moderate (3–4 IAPS), high (5–6 IAPS) and very high (7–8 IAPS). See Kariyawasam et al. (2019a) for full details of the modeling of 14 terrestrial IAPS.

#### 2.2.2. *MaxEnt species distribution modeling of two aquatic IAPS*

MaxEnt models for two aquatic IAPS, *E. crassipes* and *S. molesta* were calibrated using geo-referenced occurrence records from the entire world and a set of environmental variables, which are at 30 arc-seconds resolution. Occurrence data of the two species was obtained from online databases, such as Global Biodiversity Information Facility, Atlas of Living Australia, CABI Invasive Species Compendium, published and

**Table 1**
Details of IAPS considered by the two modeling studies. Adapted from MoMD&E (2015).

| | No | Species | Habitat type | Family | Common name |
|---|---|---|---|---|---|
| Terrestrial | 1 | *Alstonia macrophylla* Wall. | Terrestrial | Apocynaceae | Hard milkwood |
| | 2 | *Annona glabra* L. | Terrestrial | Annonaceae | Pond apple |
| | 3 | *Austroeupatorium inulifolium* (H.B.K.) R. M. King & H. Rob | Terrestrial | Asteraceae | Austroeupatorium |
| | 4 | *Clidemia hirta* (L.) D. Don | Terrestrial | Melastomataceae | Soapbush, Koster's curse |
| | 5 | *Dillenia suffruticosa* (Griff ex Hook.f. & Thomson) Martelli | Terrestrial | Dilleniaceae | Shrubby Dillenia |
| | 6 | *Lantana camara* L. | Terrestrial | Verbenaceae | Lantana |
| | 7 | *Leucaena leucocephala* (Lam.) de Wit | Terrestrial | Fabaceae | White lead tree |
| | 8 | *Mimosa pigra* L. | Terrestrial | Fabaceae | Giant Mimosa |
| | 9 | *Opuntia dillenii* (Ker-Gawl.) Haw | Terrestrial | Cactaceae | Prickly pear cactus |
| | 10 | *Panicum maximum* Jacq. | Terrestrial | Poaceae | Guinea grass |
| | 11 | *Parthenium hysterophorus* L. | Terrestrial | Asteraceae | Parthenium |
| | 12 | *Prosopis juliflora* (Sw.) DC. | Terrestrial | Fabaceae | Mesquite |
| | 13 | *Sphagneticola trilobata* (L.) Pruski | Terrestrial | Asteraceae | Creeping ox-eye |
| | 14 | *Ulex europaeus* L. | Terrestrial | Fabaceae | Gorse |
| Aquatic | 15 | *Eichhornia crassipes* (Mart.) Solms | Aquatic | Pontederiaceae | Water hyacinth |
| | 16 | *Salvinia molesta* D.S. Mitch | Aquatic | Salviniaceae | Salvinia |

unpublished materials (Fig. S2). Spatial thinning was undertaken other than spatial filtering to minimize the sampling bias. This resulted in 4704 occurrence records for two species. Models used bias correction files in order to reduce sampling bias. Bioclimatic variables from Worldclim database (version 2) for current and future climatic conditions were used as environmental variables along with two non-climatic variables, human footprint and elevation. Ten non-correlated variables were selected after removing collinear variables using the package 'virtual species' in R (Table S2). While selecting variables, special consideration was paid to selecting temperature variables that are highly responsive in determining distribution of aquatic IAPS. Average of two well tested GCMs, MIROC5 (fifth version of the Model for Interdisciplinary Research on Climate) and MPI-ESM-LR (Max Planck Institute for Meteorology) was used for future projections under RCPs 4.5 and 8.5 for 2050. Ten replicates were used with auto features, 1000 maximum iterations and other default settings. Subsampling was employed as there were moderate to many occurrences for the species of interest. Performance of MaxEnt models of current and future climates was evaluated using threshold dependent and threshold independent evaluation metrics: AUC, TSS and sensitivity. Suitability maps of individual IAPS were classified using maximum training sensitivity plus specificity threshold approach. See Kariyawasam et al. (2021b) for full details of the modeling of two aquatic IAPS.

### 2.3. *Assessment of risks of IAPS on terrestrial agricultural land-use types*

In this study, we considered seven agricultural land-use types, namely; (i) chena (traditional practice of rain-fed agriculture), (ii) cropland (vegetable and fruit cultivations), (iii) homestead (home-gardens), (iv) tea, (v) rubber, (vi) coconut and (vii) grassland, based on 1:50,000 digital maps of Sri Lanka by the Survey Department published in 1996. The study was undertaken using ArcMap (10.4.1 version) software (ESRI, Redlands, CA, USA). As described in section 2.2.1, classified combined maps of climatic suitability of 14 terrestrial IAPS contain five classes of different levels of IAPS richness (i.e., very high to very low). In ArcMap, we overlaid each of the seven agricultural land-use maps on classified combined map of climatic suitability of the current climatic conditions. Then, we calculated the area of five classes within each land-use type. We assumed that agricultural areas which potentially support for higher numbers of IAPS can have relatively greater risks. Thus, the risk was quantified using areas acquired by the five classes within a particular land-use type. This exercise was carried out with future climatic conditions (RCP4.5 and 8.5) for 2050 as well. Our aim was to assess the potential climatic suitability changes across individual agricultural land-use types under climate change scenarios to understand how climate change influences potential risks of plant invasions.

### 2.4. *Assessment of risks of IAPS on aquatic agricultural land-use types*

Paddy lands, which is the main aquatic agricultural system in Sri Lanka was considered in this exercise. Climatic suitability maps of *E. crassipes* and *S. molesta* were used in this assessment (described in section 2.2.1). In ArcMap, we developed combined climatic suitability maps of these two species for current and future scenarios, RCP4.5 and 8.5 for 2050. These maps were classified into three classes (risk categories) as the number of species that can support at a given place was ranged from zero to two. Thus, the three classes used were high (2 IAPS), moderate (1 IAPS) and low (0 IAPS). In Arc Map, the paddy lands map was overlaid on the classified combined map of climatic suitability of two aquatic IAPS in the current climate. The areas of each of the three classification classes that come inside paddy lands were quantified. Same exercise was undertaken for future scenarios as well.

## 3. Results

### 3.1. *Assessing the risks of IAPS on terrestrial agricultural land-use types*

Findings reveal that under projected climate scenarios, all agricultural areas are potentially at risk from plant invasions at varying magnitude (Fig. S3). The area represented by five climatic suitability classes vary across agricultural land-use types over climate change scenarios (Fig. 1; Table S3). Climatic suitability for IAPS is likely to be increased by 2050 in several agricultural areas, namely; chena, coconut, cropland, homestead and grassland. Cropland shows potentially lowest climatic suitability for IAPS under all scenarios due to greater representation of 'very low' climatic suitability class and thus, is relatively safer from potential risks of IAPS. However, under current climatic conditions, rubber and tea plantations show greater suitability for multiple IAPS, as 94% and 80% of their total area support establishment of more than three IAPS respectively (Table 2). Under future scenarios, the suitability of IAPS in rubber and tea land-uses is predicted to decrease, but the suitability remained relatively at higher levels. Under climate change scenarios, coconut shows greatest suitability increase for more than three IAPS.

### 3.2. *Assessment of risks of IAPS on aquatic agricultural land-use types*

Under projected climate scenarios, paddy land-use is expected to have decreasing risks from aquatic plants, *E. crassipes* and *S. molesta* invasions (Fig. S4). The area represented by three climatic suitability classes in paddy land-use vary under climate change scenarios (Fig. 2; Table S4). Under current climatic conditions, the greater representation of 'high' suitability class (area suitable for both aquatic invasive plants) signifies the potentially increased risks to paddy growing areas

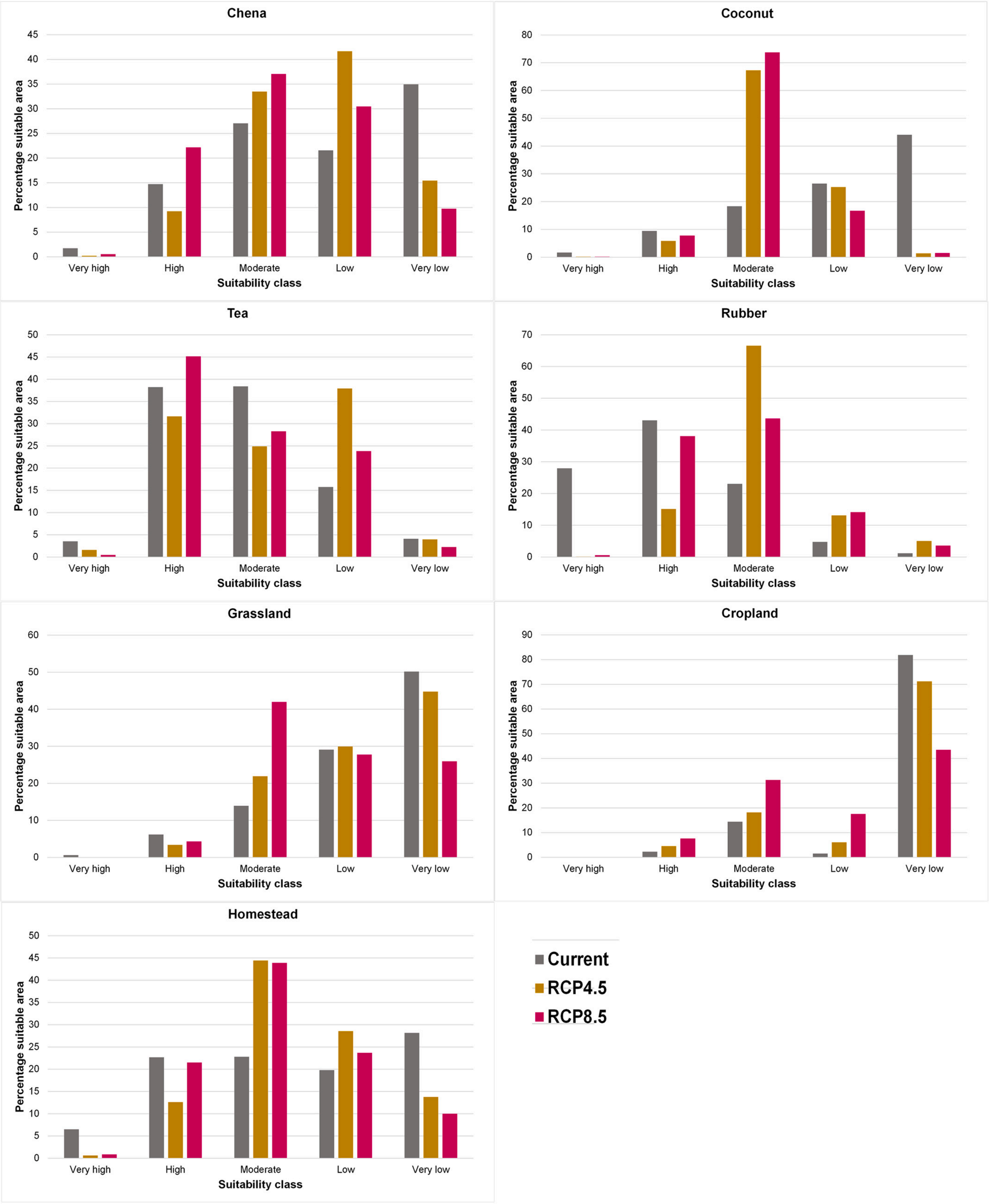

**Fig. 1.** Representation of five climatic suitability classes of 14 terrestrial IAPS in seven agricultural land-use types under current and future climate scenarios for 2050.

**Table 2**
Percentage area potentially suitable for more than three IAPS in seven terrestrial agricultural land-use types under current and future climate scenarios for 2050 (percentage area is relevant to the total area of the land-use type).

| Climate Scenario | Land-use type | | | | | | |
|---|---|---|---|---|---|---|---|
| | Chena | Coconut | Tea | Rubber | Grassland | Cropland | Homestead |
| Current | 43 | 29 | 80 | 94 | 21 | 17 | 52 |
| RCP4.5 | 43 | 73 | 58 | 82 | 25 | 23 | 58 |
| RCP8.5 | 60 | 82 | 74 | 82 | 46 | 39 | 66 |

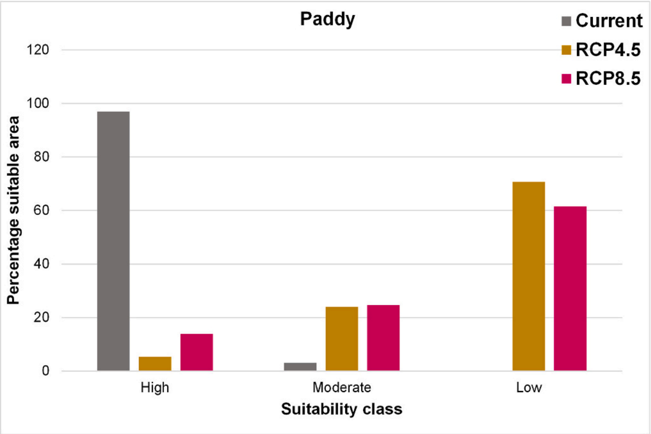

**Fig. 2.** Representation of three climatic suitability classes of two aquatic IAPS in aquatic agricultural land-use type (paddy) under current and future climate scenarios for 2050.

**Table 3**
Percentage area that represents more than one aquatic IAPS in paddy land-use type under current and future climate scenarios for 2050 (percentage area is relevant to the total area of the land-use type).

| Climate scenario | Land-use type Paddy |
|---|---|
| Current | 100 |
| RCP4.5 | 29 |
| RCP8.5 | 38 |

(Table 3). Under climate change scenarios, by 2050, the areas suitable for both aquatic invasive plants will reduce significantly, while the area potentially free from both aquatic IAPS (low suitability) will increase extensively. Results also revealed that the entire paddy areas are currently suitable for the establishment of at least one invasive plant; however, this will reduce to 29% and 38% under RCP4.5 and 8.5 climate change scenarios respectively, suggesting decreased risks from aquatic plant invasions.

## 4. Discussion

The potential risks from IAPS on global agriculture under changing climatic conditions is considerable and widely acknowledged (Wang and Wan, 2020). However, this important area of research remains unattended and understudied in many countries including Sri Lanka, perhaps due to data limitations and scientific and financial constraints (Kariyawasam et al., 2019b). In this study, we quantified the potential risks from priority IAPS on agriculture in Sri Lanka through an approach that assesses the potential climatic suitability for their establishment.

Our findings implied likely increased risks of plant invasions on several agricultural land-use types, such as chena, coconut, cropland, homestead and grassland, under climate change scenarios. These potentially increasing risks are revealed by the noticeable reductions in the area of suitability of 'very low' (0 IAPS) class and increased area of suitability, particularly in 'high' (5–6 IAPS) and 'moderate' (3–4 IAPS) classes. The "competitive exclusion principle" states that no two species can inhabit the same ecological niche at a given time in the same environment (Hutchinson, 1965). As such, if two or more species invaded the same niche, one will thrive and the others will be excluded due to competition. However, if a certain ecological niche is suitable for many IAPS, it implies a possibility of potentially high risks from invaders. Those niches will not remain vacant for long as many IAPS can invade and establish. Therefore, in our analysis, the area occupied by the 'very high' suitability class potentially unveils greater risks from IAPS. However, the contribution of 'very high' class is relatively low in all agricultural land-use types except rubber. Therefore, though 'very high' suitability is denoted by 7–8 IAPS richness, the relative risks can be low compared to the risks contributed by the low species richness classes (i.e., 'high' or 'moderate').

Invasive alien plants spread easily in areas where management efforts have become less intensive or terminated in recent times (Hejda and Pyšek, 2006). Commercial agriculture involves intensive farming practices, high inputs and outputs. In such managed landscapes, IAPS receive less chance to establish. As such, the potential risks could be relatively less in the well-managed agricultural lands compared to the unmanaged landscapes. Therefore, in agriculture lands, if such practices are continued, plant invaders cannot exert a considerable impact though there are potentials for successful invasion (i.e., climatic suitability). However, once these areas are abandoned or management actions weaken, IAPS can invade and establish in such areas easily. Unmanaged landscapes or uncultivated lands, in particular disturbed habitats, where continuous management interventions are not occurring, provide a conducive environment for plant invaders to establish and thrive in (Lozon and MacIsaac, 1997). Therefore, continuous crop growing with proper land management techniques should be practiced to safeguard the areas from IAPS.

In this study, we considered only the agriculture-related land-use types identified by the Survey Department, Sri Lanka. Crop wild relatives (CWR) and neglected and underutilised species (NUS) are two categories of agriculturally important plants that are freely grown in the wild without any management intervention (Hunter, 2012; Padulosi et al., 2013). The contribution of NUS and CWR of Sri Lanka in addressing food security and human nutrition is substantial (Liyanage, 2010; Ratnayake et al., 2020). However, majority of such plant-growing areas are not included under any of the above agricultural land-use types. Thus, perhaps these plants can have likely severe risks from plant invasions compared to the plants in well-managed agricultural lands. We examined the distribution of occurrences of seven endemic and threatened CWR species belonging to the genus *Cinnamomum* and found that these species are highly localized in south west Sri Lanka, where Kariyawasam et al. (2019a) found an invasive species concentrated area (Fig. S5).

Analysis of long-term climate data of the past three decades has implied that the temperature and rainfall in some areas of the country are increasing (Kariyawasam et al., 2021a). A study by Jayawardena et al. (2017) forecasted that temperature of the country is expected to continue to rise in the next few decades significantly. Accordingly, the country is expected to be warmer by the end of this century. Further, literature confirms that there is a direct link between climate variability and change and species range expansions (Bellard et al., 2013; Walther et al., 2009). Dukes and Mooney (1999) predicted that changing climates (i.e., temperature and water level increases) have the possibility to facilitate the prevalence of IAPS. Using a case study, Kariyawasam et al. (2021a) showed that the coverage of aquatic IAPS seems to have an increasing trend under long-term climate change and variability (Kariyawasam et al., 2021a). Thus, in consideration of the relationship between climate variability and the spread of IAPS, a continued expansion of the ranges of IAPS can be expected in the future in Sri Lanka under climate change. This can have potentially increased risks from IAPS on agriculture and thus, control and management of IAPS in agricultural lands would be a challenging issue for land managers.

The economic loss by IAPS in agriculture is enormous and its contribution to national economies around the world is considerable (Fried et al., 2017). Thus, prevention of introduction or eradication through immediate response at early stages of invasion is crucial for their management (McNeely et al., 2001). Once IAPS are established, it is extremely difficult to control or eradicate them. Thus, early detection of potential risks through habitat suitability modeling provides the most needed information for strategic control and effective management of IAPS in agricultural areas to safeguard crop production. The study implied that the paddy lands have greater climatic suitability for the two worst aquatic invaders in the country under current climatic conditions, which is expected to decline considerably under climate change scenarios. Thus, we recommend short-term management actions addressing aquatic invaders in paddy lands. Findings also provide understanding about the spatial and temporal dynamics of IAPS in the agricultural land-use types. Decision-makers can make use of these findings to understand the most vulnerable land-use types in the current and projected climatic conditions. Early identification of risk areas is vital for designing effective control actions (Kariyawasam et al., 2019b).

### *4.1. Limitations of the study*

Crops grown in the agricultural lands are likely to shift their ranges with time and it may result in slight changes in the boundaries of respective land-uses. In this study, the crops have not been modelled for future climate scenarios. We considered that the boundaries of agricultural land-use types are stable and not changing in the future by 2050. However, IAPS will adapt to the changing climate and invade much faster than other plants, i.e., crops (Davidson et al., 2011; Ibanez et al., 2009). Thus, we believe that this limitation is not expected to have a major impact on the results. In this analysis, we assumed that potential risks from plant invasions are positively related to the increasing numbers of IAPS. However, the invasion risks may not be consistent across species and may vary depending on the invading taxa and their habitat type (Bezeng et al., 2017; Kariyawasam et al., 2020; Pyšek et al., 2012). As such, one particular IAPS may pose a more severe risk rather than the combined risk of two or more species. Thus, the risks from IAPS on agriculture may not always tend to enhance with the number of species. Further, invasion risks may also depend on the relative density of invading species as well (Herron-Sweet et al., 2016). Therefore, in our analysis too, the low suitability class (1–2 IAPS) may cause a greater invasion risk compared to the invasion risk of moderate (3–4 IAPS) or high (5–6 IAPS) suitability classes. In this analysis, we did not consider the climatic suitability of individual IAPS as our focus was on identifying the suitability of multiple IAPS inside agricultural land-use types. Thus, our analysis does not provide information relevant to the performance of individual species in agricultural lands. Though there are limitations, climatic suitability analysis is widely considered as an important approach to quantify the invasion risks in natural and managed landscapes (Kariyawasam et al., 2020; Wang and Wan, 2020).

## 5. Conclusion

Under climate change scenarios, IAPS are projected to impact agriculture at varying magnitudes. We used classified combined climatic suitability maps of terrestrial and aquatic IAPS to quantify the suitability in eight agricultural land-use types in Sri Lanka for multiple plant invasions. The study quantified the risk areas and prioritized vulnerable agricultural land-uses for plant invasions under climate change scenarios. Our findings highlighted that the vulnerability for multiple plant invasions across agricultural land-use types is varied and the risk of plant invasions is predicted to increase in the majority of land-use types in the future. This can have a negative consequence on food production in many agricultural land-use types in the country. Climate modelers suggest a favorable environment for the expansion of IAPS under climate change scenarios. Therefore, land managers need to be vigilant to use proper land management practices continuously to avoid plant invasions in agricultural lands. Decision-makers can utilize this key information for developing strategic actions to control and manage IAPS. Further, the findings highlight the importance of assessing the potential climatic suitability of IAPS in agricultural lands for better understanding of invasion risk in response to climate changes. Findings of this study can be significant for developing suitable mitigation and adaptation strategies for future climate change-related IAPS invasion for Sri Lanka as well as tropical countries.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crsust.2021.100051.

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