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Invasive Plants Distribution Modeling: A Tool for Tropical Biodiversity Conservation With Special Reference to Sri Lanka

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Abstract

The potential threats and habitat preferences of noxious plants in tropical countries are poorly known. Species distribution modeling (SDM) is a robust tool that can be used in conservation planning for early detection of invasion risks. However, the use of SDM for the strategic management of increasing risks of such plant invasions in Sri Lanka has not been undertaken due to several underlying reasons including the long-lasting data gap, technical, technological, and financial issues. In addition, the literature relevant to SDM applications in the country is substantially poor, scattered, and unpublished. Therefore, in this article, we explore SDM applications relevant to invasive plants in Sri Lanka with implications similar to other countries in the tropics. We examine the challenges and potentials for utilization of SDM technology in conservation planning in Sri Lanka and discuss data gap as a major obstacle. We also identify the potential SDM interventions relevant to invasive plants control and management in Sri Lanka and recommend conservation planners to prioritize them and apply for the strategic management of invasive plants in Sri Lanka. Finally, we suggest some recommendations to make an enabling environment in relevant institutions for the utilization of SDM technology in ecosystem management planning in Sri Lanka.

Keywords

conservation planning, plant invasions, risk assessment, species distribution modeling, Sri Lanka

Introduction

Species invasions are recognized as a serious threat to the environment, economy, and social well-being of our planet (McNeely, Mooney, Neville, Schei, & Waage, 2001). It is considered as one of the most important drivers of biodiversity loss and native species extinction and endangerment (McNeely, 2004). The impacts of species invasions on native biodiversity and ecosystem services are considerable (Pysek & Richardson, 2010) and ranks second only to habitat fragmentation and degradation (Lowe, Browne, Boudjelas, & De Poorter, 2000). Therefore, the Convention on Biological Diversity (CBD; Article 8h), the key international instrument dedicated for conservation of biodiversity on earth, requests all contracting parties to take appropriate action to “prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species” (Secretariat of the Convention on Biological Diversity, 2005) p. 8. CBD and other international agreements, such as Sanitary and Phytosanitary

Measures (SPS Agreement), provide guidance to evaluate the risk of species and designate such species under national regulations.

At present, plant invasion is one of the increasingly important environmental challenges in Sri Lanka with significant impact on native biodiversity. Absence of effective early detection measures is one of the key hindrances to prevent introduction of potential invasive alien plant species (IAPS). The current control measures

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are mostly focused on extensively spread IAPS that make a noticeable impact. In some countries, species distribution modeling (SDM) technique is effectively used to assess potential risks of plant invasions and guide conservation decisions (Guisan et al., 2013). However, applications of SDM technique are very limited in tropical countries (Cayuela et al., 2009). Poor representation of tropical species is a major drawback from the conservation point of view, as responses of tropical and temperate plants to climate change are totally different and thus general inferences are not likely to be made (Feeley, Stroud, & Perez, 2017).

Therefore, the aims of this article were to (a) explore SDM applications relevant to plant invasions in Sri Lanka with implications similar to other countries in the tropics, (b) examine the potentials and challenges for successful implementation of SDM in the Sri Lankan context, (c) identify SDM potentialities with direct applications in Sri Lanka, and (d) provide recommendations to improve SDM applications for conservation planning in Sri Lanka. Therefore, this article will provide useful insights into the potential utilization of SDM technology to control and manage plant invasions.

Climate Change and IAPS Distribution

Climate change is an inevitable global phenomenon (Intergovernmental Panel on Climate Change [IPCC], 2012). A significant number of plant species are challenged with higher rates of extinction in the future, as climate change shifts the spatial distribution of many species (IPCC, 2014). Global climate change as a key determinant of species distribution significantly influences the IAPS dynamics in the future (Fandohan et al., 2015; Taylor & Kumar, 2013). Millennium Ecosystem Assessment [MEA] (2005) informs that the earth's temperature has been increased considerably (approximately 0.6°C) over the last 100 years; it also reveals that the projected rate of extinction of species will increase by 10-fold in the future compared with the current rate. Climate change predictions confirm that the climate of South Asia will change significantly in the 21st century (IPCC, 2014). The trend analysis conducted by long-term climate data of 19 meteorological stations in Sri Lanka indicated significant changes in the temperature and precipitation across the country (Jayawardena, Dharshika, & Herath, 2017). The analysis indicated that the annual averages of mean minimum temperature and precipitation of the country are increasing during the 1980–2015 period. Similarly, multimodel ensemble projections have suggested that both maximum temperature and minimum temperature of Sri Lanka will increase in the future under both moderate emission (RCP 4.5) and high emission (RCP 8.5) scenarios (Table 1) (Jayawardena et al., 2017). The observed

Table 1. Multimodel Ensemble Predictions of Maximum and Minimum Temperature for Sri Lanka Under Moderate Emission Scenario (RCP 4.5) and High Emission Scenario (RCP 8.5) for Different Time Periods (Jayawardena et al., 2017).

Time period	Temperature increase °C under RCP 4.5		Temperature increase °C under RCP 8.5	
	Minimum	Maximum	Minimum	Maximum
2020–2040	0.7–1.2	0.9–1.3	1.1–1.5	1.0–1.5
2040–2060	1.0–1.6	1.3–1.7	1.6–2.5	1.4–2.3
2070–2090	1.5–2.3	1.9–2.5	2.4–3.5	2.2–3.2

changes in climate in the past have already affected ecological systems; the projected increase in the future will undoubtedly make serious implications on the movement of species ranges in many countries, as species are vulnerable to climate change and respond by shifting their niches spatially and temporally (MEA, 2005). This can be intensified in tropical island countries which are highly vulnerable to the impacts of climate change due to low adaptive capacity (Achard et al., 2002; Lobell et al., 2008).

Invasive Plants Distribution Modeling—The Need

The economic, ecological, and social impacts of species invasion are enormous and well recognized (Gallardo & Aldridge, 2013). Plant invasions have negative impacts across several sectors such as agriculture, tourism, forestry, fishery, human health, water, and irrigation. IAPS directly impact on native biodiversity and agriculture through competition for resources and other ways, that is, predation, hybridization, and herbivory (Manchester & Bullock, 2000). Scientists can significantly improve the quality of ecosystems by preventing invasions of alien plants through two complementary strategies, early detection, and rapid response (Guisan et al., 2013). However, these two strategies are not properly integrated into decision-making process in many developing countries in the tropics. In view of that, understanding the pattern of the current and potential distribution of invasive plants is crucial for designing strategic control and management actions (Gormley et al., 2011; Ward, 2007).

Background to the SDM

SDM, the prediction of species' potential geographic distributions based on environmental variables and available records of species occurrence is a widely used technique in conservation decision-making today (Elith, 2015; Glor & Warren, 2010; Phillips, Anderson, & Schapire, 2006). It has the potential for use in a range of scientific applications, for example, reserve planning,

resource management, ecology, epidemiology, evolution, invasive species management, biogeography (Beaumont, Hughes, & Poulsen, 2005; Franklin, 2009; Phillips et al., 2006). Species distribution models provide useful information as a first step of assessing the potential risk of invasion of a species or a geographic area (Elith, 2015). A variety of statistical approaches are currently in use for developing SDMs for various applications (Franklin, 2009; Graham & Hijmans, 2006; Pearson & Dawson, 2003). Among these techniques, MaxEnt (Phillips et al., 2006) and CLIMEX (Sutherst & Maywald, 1985) are more popular for predicting potential ranges of invasive plants (Merow, Smith, & Silander, 2013; Phillips et al., 2006). However, no single modeling approach will be best performing than the others under all situations, and thus testing the predictive ability of several algorithms is always recommended (for details, see Qiao, Soberón, and Peterson, 2015). Theoretical limitations can remain between modeling tools which are always underpinned by ecological theories and assumptions (Guisan & Thuiller, 2005). Thus, predictive power and robustness can vary across the modeling techniques used. As a result, the potential geographic spread of an invasive plant can be an overprediction or an underprediction depending on the model used (Fandohan et al., 2015; Ward, 2007; Wearne, Ko, Hannan-Jones, & Calvert, 2013; Webber et al., 2011). Therefore, selecting the most appropriate model is important in any modeling study. Building a robust and accurate SDM model is important to provide reliable information to the policy-making process.

Several factors may influence model performance, such as the number, quality (i.e., biased or unbiased) and type (i.e., presence-only or presence/absence) of occurrence data (Franklin, 2013; Glor & Warren, 2010), range (i.e., entire, native or invasive) of occurrence data (Romero-Alvarez, Escobar, Varela, Larkin, & Phelps, 2017), number of background points and the method used to select them (Barbet-Massin, Jiguet, Albert, & Thuiller, 2012; Elith, 2015), choice of environmental parameters and resolution (Beaumont et al., 2005; Franklin, 2013), settings or feature types (Romero-Alvarez et al., 2017), modeling species of concern (Kriticos et al., 2011), study area (Elith & Graham, 2009), and spatial extent of study (Barbet-Massin et al., 2012). Various methodologies and approaches are being developed rapidly to address the uncertainties associated with the modeling techniques. Ensemble forecasting approach, which is a collection of modeling techniques, is widely used for better accuracy of model predictions (Araújo & New, 2007). BIOMOD (Thuiller, Lafourcade, Engler, & Araújo, 2009) is a popular program for ensemble forecasting of species spread implemented in an open source package R (R Development Core Team, 2013). Increasingly, modelers compare results across several

modeling techniques, owing to differences between modeling techniques and also for cautious interpretation. Good understanding of the concepts of SDM and underlying assumptions on which models are built will facilitate modelers to select the best model that generates the most robust prediction to the species of concern. However, in reality, model selection is mostly based on availability or accessibility to modeling software and also on local expertise (Elith, 2000) that may lead to imperfect predictions. Therefore, comprehensive guidance is needed for selection of the most applicable method for a particular application (Elith & Graham, 2009).

SDMs basically need two types of data: georeferenced species occurrence data and environmental data. Occurrence data can be presence-only, presence and absence, abundance, or richness according to the modeling method in use (Miller, 2010). Presence-only data (e.g., herbarium data) are frequently used when absence data are not available, especially in less intensively sampled tropical countries (Phillips et al., 2006). Bioclimatic variables are popularly used as environmental parameters in SDMs as reliable, high resolution, updated climate data are freely accessible (Adhikari, Tiwary, & Barik, 2015; Fandohan et al., 2015). The importance of the contribution of ecophysiologically significant nonclimatic variables predicting suitable areas has been frequently discussed in the literature (Beaumont et al., 2005; Elith, 2015). However, the ecophysiologically important complete and consistent layers across the study area are not commonly available at the required resolution, especially in developing countries (Mod, Scherrer, Luoto, & Guisan, 2016).

SDM Applications Relevant to IAPS

Invasive plants distribution modeling can be used in the conservation decision-making process to achieve various objectives. Many SDM studies have been conducted to predict areas where an invasive plant could potentially occur in the future. The focus of these studies is to examine the likely distribution of selected invasive plant or a group of taxa at a local scale to classify areas for future strategic management. For instance, Lamsal, Kumar, Aryal, and Atreya (2018) modeled the ecological niches of five IAPS *Ageratum conyzoides*, *Parthenium hysterophorus*, *Ageratina adenophora*, *Chromolaena odorata*, and *Lantana camara* in the Himalayan foothills and investigated how the predicted invasion ranges vary with elevation gradient. This study revealed that the climate responses of these invasive plants are different under the projected climate change; thus, such invasion dynamics may result in negative impacts on biodiversity and ecosystem services in the region. In another example in Nepal, Shrestha, Sharma, Devkota, Siwakoti, and

Shrestha (2018) modeled the potential distribution of six IAPS, *Ageratum houstonianum*, *C. odorata*, *Hyptis suaveolens*, *L. camara*, *Mikania micrantha*, and *P. hysterophorus*, across the country under climate change scenarios and found that these species will expand in the future. The study findings provide valuable insights into potential ranges of six noxious IAPS in Nepal, and this information is useful for control and management efforts. Kariyawasam, Kadupitiya, Ratnayake, Hettiarachchi, and Ratnayake (2017) modeled five priority IAPS of Sri Lanka, namely, *Mimosa pigra*, *Annona glabra*, *L. camara*, *Prosopis juliflora*, and *P. hysterophorus* across the country. The explicit objective of this study was to identify and prioritize high-risk agroecological regions in order to take information-based decisions to control and manage IAPS. Likewise, Thapa, Chitale, Rijal, Bisht, and Shrestha (2018) modeled the potential distribution of 11 IAPS in western Himalaya and found that most of the species will expand the ranges in the future. By doing this, the study identified the ecosystems at potential invasion risk, and thus immediate conservation efforts need to be focused on for cost-effective planning and management. Majority of these IAPS are common invaders in the region and have a considerable impact on native biodiversity. Taylor and Kumar (2016) used SDM to examine the impacts of climate change on the potential distribution of invasive vine *Merremia peltata* on some of the archipelagos in the South Pacific and found a decreasing trend of climatic suitability in some islands and an increasing trend in some others. These findings can be used to design policy measures more broadly for island settings.

Plant invasion is increasingly recognized as a challenging issue in protected area management, as vulnerability of some areas to colonization by invaders is likely to increase under climate change (Foxcroft, Pyšek, Richardson, & Genovesi, 2013). SDM technology can be used in conservation planning to assess and improve the effectiveness of protected areas through spatial prioritization (Taylor, Cadenhead, Lindenmayer, & Wintle, 2017), that is, demarcate areas potentially vulnerable to high risk of invasion (Fandohan et al., 2015; Wan, Zhang, & Wang, 2018; Wearne et al., 2013). Directing limited financial resources to an area without such prioritization would be difficult and challenging. The information generated by SDMs has been used to identify hot spots of biological invasion across countries or regions (O'donnell et al., 2012). Invasion hot spots are areas potentially suitable for multiple invasive species establishment, and thus, the cumulative impact made by several species can be comparatively severe and significant (Gallardo & Aldridge, 2013). Delineation of hot spots provides useful information for conservation planners to take action immediately in risk situations. Furthermore, it is a powerful tool to prioritize limited resources in

evidence-based conservation decision-making process (Gallardo & Aldridge, 2013). SDM technology has been successfully used to define invasion hot spots in several countries (Adhikari et al., 2015; Gallardo & Aldridge, 2013; Ibanez, Silander, Allen, Treanor, & Wilson, 2009; O'donnell et al., 2012), as it is an important strategy for setting priorities for the allocation of scarce resources (Coates & Atkins, 2001).

SDM studies investigate how invasive plants shift their ecological niche spatially and temporally under climate change. The behavior of invasive plants in novel climates is expected to have different and inconsistent; thus, potential responses under climate change scenarios should be studied and understood in order to advance our understanding (Ibanez et al., 2009). In light of poor and incomplete knowledge of the behavior of invasive plants in current and future climates, understanding the potential threats before they become unmanageable would be important to develop cost-effective control strategies (Kriticos, Yonow, & McFadyen, 2005). Biodiversity-rich tropical countries have the potential to integrate SDM into their conservation decision-making process for better surveillance, control, and management of IAPS in the region. By doing so, much-needed policy implications can be stipulated for the short-term and long-term strategic management of natural resources.

Present Status of SDM in Sri Lanka

SDM is one of the most leading research fields relevant to environmental science facet in the world today (Renner & Warton, 2013). The scientific literature relevant to this subject is fast growing; however, the practical utilization of this technology in conservation science problems is rare and not understood (Guisan et al., 2013). Literature shows that the use of SDM technology is not uniform and mostly limited to the Western world. Cayuela et al. (2009) report that studies based on SDM is not satisfactory in the tropics despite the recognition given to the high level of biodiversity richness of the region. In the Sri Lankan context, applications of SDM in spatial planning and decision-making relevant to plant invasion is nearly untouched.

We searched online databases, Google Scholar and several other sources and explored the literature on predictive modeling of invasive plants in Sri Lanka and realized that the practitioners and policymakers have not utilized this important tool in strategic control and management of invasive plants. Our findings were limited to one publication which has focused on the potential ranges of nationally significant five invasive plant species to identify the high-risk agroecological zones of the country (Kariyawasam et al., 2017). Therefore, SDM applications in Sri Lanka were broadly reviewed without

limiting to plant invasions. Online database, the Web of Science Core Collection (search date June 22, 2018) was searched using the keyword *species distribution modeling* and then refined to Sri Lanka. Out of the 19 results that were received, none of the papers focused on SDM relevant to plants. Three publications were found relevant to the potential habitat suitability of selected animal groups, that is, the Sri Lankan leopard, an endangered and endemic subspecies *Panthera pardus kotiya* (Kittle, Watson, Cushman, & Macdonald, 2018; Silva et al., 2017), three bufonid species belonging to the endemic genus *Adenomus* (Meegaskumbura et al., 2015) and two sea cucumber species belonging to the genus *Holothuria* (Dissanayake & Stefansson, 2012). Furthermore, literature given in the Web of Science CAB Abstracts were searched (search date June 22, 2018) using search terms *species distribution modeling and Sri Lanka*. Out of the 32 results received, only two papers focused on SDM applications. These two studies were on habitat suitability of Travancore flying squirrel, *Petinomys fuscocapillus* (Kumara & Suganthasakthivel, 2011) and Carnivore species richness and distribution in two protected areas in Sri Lanka (Ratnayeke & Van Manen, 2012). Although, the SDM studies are limited, several studies have been conducted using approaches of geographic information system (GIS) and remote sensing technologies to map the spatial distribution and vulnerable areas for certain invasive plants, for example, *Austroeupatorium* (*Austroeupatorium inulifolium*) in Knuckles Forest Reserve (Piyasinghe, Gunatilake, & Madawala, 2018), Mesquite (*P. juliflora*) in North western coastal belt (Gunawardena, Fernando, Nissanka, & Dayawansa, 2015). We understand that several studies undertaken at undergraduate and postgraduate thesis level are not published and mostly not accessible. Results of such studies can be used to verify SDM outcomes.

Cayuela et al. (2009) studied 123 articles relevant to SDM, published in leading international scientific journals over a 12-year period (1995–2007) and found that representation of applied SDM interventions in conservation decision-making in the tropics was remarkably low, that is, which was limited to two articles. We reviewed the above 123 articles and found that around 10% were relevant to species invasion issue. However, these 123 publications contained only five papers from the South and South-East Asian region and, surprisingly, none of these five papers addressed plant invasion issue or more broadly the species invasion issue. This is an unfortunate situation, given the high richness of biodiversity and endemism in the region and the significant threat posed by species invasion on native biodiversity.

SDM Challenges and Potentialities

At present, SDMs are not integrated into the conservation decision-making process in Sri Lanka. The recently developed policy documents (e.g., national invasive species policy, strategy and action plan, the national biodiversity strategies and action plans—NBSAPs) have clearly identified the importance of early detection, rapid response, and monitoring thereby addressing invasive alien species issue. However, the role of predictive modeling has not been recognized as an important tool in national conservation policies of the country adequately. We are not certain about the level of awareness on the practical utility of SDMs for invasive plants management among practitioners and policymakers in the country, as it has not been assessed. However, it is more likely that they do not have a proper understanding about how, when, and for what purpose SDMs can be used for the management of invasive plants as local expertise relevant to climate change modeling of species distribution is exceptionally limited. To what extent SDMs are incorporated into conservation science modules in local universities is also not known. Therefore, awareness creation among the above key people on potential uses of SDMs would be important after a proper preassessment. Donor-funded conservation projects can play a significant role in this regard, as these projects can hire foreign experts to train local counterparts. Strong linkages between policymakers and modelers are strongly encouraged to channel the research requirements of the country for better and meaningful application of this technology (Guisan et al., 2013). Similarly, research outcomes are not efficiently conveyed to policymakers for timely conservation decision-making. This may be due to several reasons including absence of a proper coordination mechanism, weak institutional and financial capacity, and technical and technological issues.

Absence of reliable species occurrence data is a key reason for the poor application of SDMs in developing tropical countries. Often invasive species are not considered in plant research studies and surveys, and hence, they are poorly documented. Most of the old collections of species data available at national- or local-level plant repositories, such as herbaria, are not georeferenced. Therefore, data are still scarce, fragmented, and incomplete. In Sri Lanka, inadequate willingness to share data is also a critical issue that hampers data sharing and accessibility. Although the Government enacted a new policy for sharing data to promote harness and timely delivery of data, the access to data and information is still a tedious task and a lengthy process. Furthermore, most of the data forms required for SDM studies are not readily available in required specifications. This is mainly due to lack of technical awareness of data

processors and also relevant institutions have not been given a mandate for processing of such data. The issue is critical at subnational level. In addition, several other factors, that is, inadequate financial and institutional capacities, poor technical assistance, and lack of access and security may also drive the data limitations (Meyer, Kreft, Guralnick, & Jetz, 2015). Therefore, Sri Lanka still needs to identify institutional and legal gaps for effective handling of specific environment data and establish specific legal enactments to ensure processing and dissemination of such data. However, positive trends can be observed in many institutions. The national herbarium of Sri Lanka, located at the Royal Botanic Gardens, Peradeniya has taken action to georeference all its new collections. Alternatively, georeferenced species occurrence data are increasingly available through data sharing initiatives across the scientific community (Trainor, Schmitz, Ivan, & Shenk, 2014). Global Biodiversity Information Facility (GBIF) is a very good open access data portal that contains nearly one billion georeferenced location data for all kinds of living beings on earth. Today, invasive plants distribution modeling is one of the most popular research disciplines where GBIF-mediated data are extensively applied. A large number of modeling studies have been conducted successfully using data extracted from the GBIF resource portal (Adhikari et al., 2015; Fandohan et al., 2015; Lamsal et al., 2018; Webber et al., 2011). We extracted the occurrences available at GBIF for 20 nationally significant IAPS in Sri Lanka (Table 2; search date December 20, 2018). Remarkably, occurrence data of selected invasive alien plants were poorly represented in GBIF. Several species had no occurrence records and none of the species had more than 15 records. Poor mobilization and use of biodiversity data in Sri Lanka and many other countries could be contributed by several underlying reasons. Data collection for scientific studies and documentation are not satisfactory in many countries which may lead to difficulties in processing data at internationally accepted standards. Other contributory factors are inadequate field data collection, language barriers, lack of a proper mechanism for sharing scientific data, and weak technical and financial capacity.

Spatial and temporal differences in available environmental data sets are major challenges in preparing climate data for SDM models at a finer scale. For generations, the presence of gaps in meteorological data has been an impediment for accurate projection of SDMs for the future. In Sri Lankan context, collection of thematic data at administrative unit levels, that is, district level or divisional secretariat level, create problems for the consistency of data. Relating to temporal differences, values over different time periods on different variables create incompatibilities in data.

Table 2. Number of Georeferenced Occurrences Available at the GBIF Global Data Portal for Nationally Significant Invasive Plants in Sri Lanka.

No.	Species	Family	No of records in GBIF ^a
1	<i>Prosopis juliflora</i>	Fabaceae	00
2	<i>Salvinia molesta</i>	Salviniaceae	02
3	<i>Eichhornia crassipes</i>	Pontederiaceae	12
4	<i>Panicum maximum</i>	Poaceae	04
5	<i>Clusia rosea</i>	Clusiaceae	00
6	<i>Typha angustifolia</i>	Typhaceae	02
7	<i>Lantana camara</i>	Verbenaceae	14
8	<i>Annona glabra</i>	Annonaceae	00
9	<i>Austroeupeatorium inulifolium</i>	Asteraceae	00
10	<i>Dillenia suffruticosa</i>	Dilleniaceae	01
11	<i>Cuscuta campestris</i>	Convolvulaceae	0
12	<i>Alstonia macrophylla</i>	Apocynaceae	02
13	<i>Leucaena leucocephala</i>	Fabaceae	03
14	<i>Clidemia hirta</i>	Melastomataceae	11
15	<i>Parthenium hysterophorus</i>	Asteraceae	00
16	<i>Mimosa pigra</i>	Fabaceae	00
17	<i>Opuntia dillenii</i>	Cactaceae	01
18	<i>Ulex europaeus</i>	Fabaceae	03
19	<i>Sphagneticola trilobata</i>	Asteraceae	03
20	<i>Cestrum aurantiacum</i>	Solanaceae	00

^aSearch date December 20, 2018.

In addition, inconsistencies generated due to methodological differences in the collection of data (i.e., different sample sizes) create problems in validation. (Meyer et al., 2015) report that there is a severe data limitation across Asia. Data gaps as the main hindrance for poor representation of SDM work in tropical countries have been discussed by Cayuela et al. (2009) previously.

There are several open source climate databases (free to download) that provide the most comprehensive and reliable suite of environmental data which are accurate enough for SDM applications at the national level. Table 3 provides sources of species occurrence and environmental data that may be explored by the practitioners for future SDM applications relevant to invasive plants. Species occurrence data extracted from online databases can be improved through data cleaning, for example, removal of duplicates and outliers. This is further reinforced by data filtering that ensures the geospatial accuracy. MaxEnt is a very good open source software that can be freely downloaded for spatial distribution modeling of invasive plants. R language environment is popularly used to implement SDM in different ways with the help of appropriate functions in R packages (i.e., *dismo* and *raster*). There are user-friendly open source GIS software, such as QGIS (<https://qgis.org/>) that has strong potential to be used

Table 3. Potential Data Sources for Species Distribution Modeling Applications.

Variable	Source	Description
Species data	Global Biodiversity Information Facility https://www.gbif.org/	Georeferenced occurrence records for all life forms. 985,190,182 results (search date June 19, 2018).
	Global Invasive Species Database http://www.iucngisd.org/gisd/	Invasive species data at country-level.
	Global Register of Introduced and Invasive Species http://www.griis.org/	Invasive species data at country-level with references for additional information.
	CABI Invasive Species Compendium www.cabi.org/isc	Invasive species data at country-level with references for additional information.
	Pacific Island Ecosystems at Risk (PIER) http://www.hear.org/Pier/	Invasive plants data on Pacific islands.
	Global Compendium of Weeds (GCW) http://www.hear.org/gcw/index.html	Invasive species data at country-level records with references for additional information.
	Tropicos http://www.tropicos.org/Home.aspx	Species data (nearly 1.3 million scientific names).
	ALA—The Atlas of Living Australia https://biocache.ala.org.au	Georeferenced occurrence records. ALA covers all taxonomic groups that occur in Australia.
	National/university/institutional herbaria	Generally contains georeferenced species occurrence records for all plant groups.
	Publications of workshops/symposia	Invasive species records at local or regional level.
Environmental data	WorldClim—Global climate data http://www.worldclim.org	Average monthly climate data for minimum, mean, maximum temperature and precipitation for 1960–1990 (version 1) or 1970–2000 (version 2, current climate only). Resolution: Several resolutions: 10 min, 5 min, 2.5 min, 30 s (~1 km ²).
	GCM Downscaled Data Portal http://www.ccafs-climate.org/	Global and regional level data for bioclimatic, diurnal temperature change, maximum temperature, mean temperature, minimum temperature, precipitation, solar radiation for future (1970–2080). Resolution: 30 s.
	CliMond climate data https://www.climond.org	All variables given in Kriticos et al. (2012). Resolution: 10 or 30 s.
	CHLSA Climate data http://chelsa-climate.org	Monthly mean temperature and precipitation for 1979–2013 period. Resolution: 30 s.
	LP DAAC—USGS https://gdex.cr.usgs.gov/gdex/	Elevation (ASTER GDEM) for 2000–2008 (version 2). Resolution of 1 s (30 m).
	ISRIC World soil information http://data.isric.org/geonetwork/srv/eng/catalog.search#/home	WISE derived soil properties. Resolution: 30 s.
	UN Environment https://unepgrid.ch/en/platforms	High-quality geospatial data at global, continental, national, and subnational levels.
	CGIAR—CSI http://www.cgiar-csi.org/	Global Potential Evapo-Transpiration and Global Aridity Index, Resolution: 30 s.
	Socio-economic Data and Application Centre https://beta.sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-adjusted-to-2015-unwpp-country-totals	SRTM digital elevation, Resolution: 90 m at the equator. Soil water balance, Resolution: 30 s. Global population density (2000, 2005, 2010, 2015, 2020). Resolution: 30 s.

as decision support mapping tools for invasive plants management at the local or national level. By analyzing all the above information, it can be implied that a high range of potentialities are becoming available for future SDM studies in developing tropical countries where this technology has not been adequately explored.

Potential SDM Interventions

Plant invasions undergo a series of consecutive steps before the impacts are realized. Hellmann, Byers, Bierwagen, and Dukes (2008) identified four distinct phases in the process of plant invasion, introduction, colonization, establishment, and spread or dispersal. During this pathway, a species will have to overcome all confronted obstacles for an invasion to have happened successfully. Therefore, improved tools and techniques should be applied to prevent the movement of species through this pathway to avoid the introduction or control plant invasions. SDM technology can play a crucial role in this regard at several stages of the invasion process. Guisan et al. (2013) identified potential SDM entry points in the structured decision-making process that can be applied more broadly in four conservation fields including species invasions.

SDM can be applied consecutively in the plant invasion process for the strategic control and management of invasive plants. Early detection through preentry risk assessment can be used to block the introduction, the very first step of the invasion process. Once an invasive plant is established, eradication is extremely difficult and not feasible financially; thus, prevention is widely accepted as the most effective and economically feasible management strategy (McNeely, 2004; McNeely et al., 2001). Through the preentry risk assessment, relevant authorities can evaluate the risk of a new plant becoming invasive before they are allowed entry into the country (Guisan et al., 2013; McNeely et al., 2001). The resulting potential invasive plants can be placed under an *Alert List* for vigilance to avoid possible future invasions. Preentry risk assessment is an important tool used by the border control agencies (i.e., customs service) to screen the introduction of potential invaders and safeguard the country. Maps developed through predictive modeling can be used to assess the likelihood of species invasions in the future and be incorporated into risk assessment protocols to improve its effectiveness. Every year, Government authorities in Sri Lanka receive a number of requests in search of permission to import plants to the country for various purposes. In most cases, decision-making is not easy due to the lack of information relevant to the species' response to the climate. Potential distribution can be an important criterion of preentry risk assessments, and SDMs provide this most critical information for decision-making purpose

(Guisan et al., 2013). Postentry-level risk assessment provides an idea about the potential current and future spread of a species. Early detection and rapid response through SDM are important strategies for eradication and control of emerging invasive plants at an early stage before they are widespread and become uncontrollable. The distribution maps generated by SDMs are good tools for identifying spatial patterns of spread of invasive plants. These maps can be used to develop species or site-specific programs to prevent the introduction of an invasive plant to unoccupied areas (Kriticos et al., 2011). They are useful tools that provide vital information to prepare management plans for high conservation value areas and production landscapes. In Sri Lanka, there is a huge potential to use these predictive maps in protected area planning, as SDM identifies areas potentially susceptible to invasions. Likewise, land managers can use SDMs to identify high-risk areas across the country for potential distribution of weeds, as weeds are a challenging problem in agriculture. Early identification of risk areas helps to prioritize lands for control and management actions, that is, management plans and conservation plans (Franklin, 2009; Guisan et al., 2013). For instance, it would be important to consider the potential distribution of noxious plant *Ulex europaeus* while preparing the strategic management plan for Horton Plains National Park, as this plant has invaded certain areas in and around the park, and the range expansion under the projected climate change is not known. Predictive maps can also be used to strengthen the research data collection efforts when observations of species distribution are scarce, especially in areas unsurveyed or not easily accessible (Franklin, 2009, 2013; Pearce & Ferrier, 2000). For instance, during the time of ecophysiographic survey of crop wild relatives (CWR) of Sri Lanka, potential CWR localities where occurrences likely to be found were predicted using Diva GIS and FloraMap programs before field exploration start due to lack of CWR distribution data (Liyanaage, 2010). Therefore, models suggested that distribution areas were useful for field sampling, to identify new occurrences. Eradication can be the management objective for recent invaders with limited population size. For more established invasive plants, risk assessment information may be used for containment or control measures (McNeely et al., 2001). The risk assessment also helps invasive plants to be placed on the nationally important lists (i.e., the national list of invasive alien plants, plants of national significance, noxious weeds) to raise awareness among policymakers, environmental planners, and the general public. For instance, the Government of Australia has considered the current and potential area of suitability of individual invasive plant species as key criteria to identify Australia's Weeds of National Significance (WoNS; Thorp &

Lynch, 2000). The potential area of spread can be included as a key criterion of defining the national list of IAPS of Sri Lanka too, as it is an important consideration of risk assessment. SDMs are widely used to examine the behavior of invasive plants in novel climates to identify potential risk areas in the future. If the plants are potentially invasive under future climate (increased spread), more concerted management efforts and more resources should be employed to control them. Short-term management measures are appropriate if the plant shows decreased future spread. Such information is important to employ climate change adaptation strategies as well. Moreover, the information generated by the SDM techniques can be used to define *plant invasion hot spots* or the invasive plants concentrated areas. Therefore, conservation actions can be focused on those areas where prioritized management interventions are needed as financing is a critical factor in conservation planning. The growth and spread of any plant species can be reduced by limiting the most wanted factor or factors. This is common to invasive plants too. Modeling techniques generate vital information relevant to environmental factors that can be used to develop strategies in control programs. Thus, the spread of an invasive plant can be reduced or stopped by limiting certain factors that are contributing highly in the model prediction. Therefore, it is the duty of relevant authorities to use this most needed information for relevant actions in order to safeguard the natural environment.

We encourage the scientific community to take action to bridge the data gap of SDM and apply this technology for effective control and management of plant invasions in Sri Lanka. Also, hands-on training on different SDM techniques with underlying concepts can be incorporated into the conservation biology modules of universities at undergraduate and postgraduate level. This will undoubtedly enhance the utilization of SDM technology in various applications relevant to conservation science. We also recommend conservation planners to prioritize the potential SDM interventions and evaluate them in the country context to support conservation decisions. The success of these applications needs coherent linkages, concerted actions, and long-term commitments of all relevant stakeholders, such as the academia, conservation planners, policymakers, and decision-makers.

Conclusion

Alien plant invasions are one of the challenging environmental issues that make a severe impact across several sectors. SDM is a robust approach that can play a crucial role by generating much-needed information to control and manage invasive plants. At present, SDM

technology is hardly integrated into the conservation applications relevant to plant invasions in many tropical countries. Our findings revealed that representation of literature relevant to SDM technology in Sri Lanka is substantially limited, scattered, and not published. We identified several obstacles that contribute to weak practical utilization of SDM in Sri Lanka. However, there are emerging potentials for future use of this technology. We identified a range of SDM applications that can be practiced at various stages of the decision-making process relevant to control and management of invasive plants in Sri Lanka which should have implications for practitioners and policymakers in the regional tropical setting. We strongly suggest that the conservation planners and decision-makers need to be aware of the practical utilization and potential interventions of SDM technology for better management of invasive plants in Sri Lanka. Therefore, findings of this study are an important step toward mainstreaming SDM into the national conservation decision-making process.

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