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REVIEW ARTICLE

Prediction on distributional patterns of weeds under future climatic scenarios

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ABSTRACT

Biological invasion pose serious threat on the natural ecosystem, human health and the economy. It has become important part of today's global ecological change and major threat to native biodiversity, ecosystem stability and its services and give rise to numerous management and control issues. Furthermore, climate change has the potential to enhance the detrimental effect of these species on the natural ecosystem and agriculture globally. Climate change is expected to affect the distribution and occurrence of the weeds in future. It will have a profound effect on crop protection, including the effects on pests, diseases and weeds. Therefore, assessing the impact of climate change on the geographical distribution of the species under future climatic scenarios is of great importance. This information helps in understanding the impact of the species and in making informed decisions on the matter related to biodiversity, public health, agriculture and the economy. Apart from this, it also helps in early detection of the hot spots of the species enabling prompt actions in order to reduce management cost after its introduction in new places. Hence, in the present article, we reviewed the work studying the distributional patterns of different weeds under future climate scenarios. It is concluded that species distribution modelling is a powerful tool to evaluate the expansion risk of invasive alien weeds into non-native regions based on the information on their climatic niche. However, it is essential to consider limitations of the models and uncertainties behind the use of future climate change scenarios.

Keywords: Climate change, Distribution modelling, Geographical distribution, Prediction, Weed distribution

Weeds may be considered as undesirable plants interfering with agriculture and natural ecosystem and are one of the biggest problems in achieving the potential yield of the crops. If left uncontrolled, weeds can cause extreme yield losses in crops. Crop yield losses depend upon the types of weed species present in the field along with the farming practices being followed (Varanasi *et al*. 2016). Weeds put negative impacts on crop yields by competing for essential resources such as light, water, space and nutrients and they are responsible for deteriorating quality of produce by contaminating the seed and lowering the value of harvested crops (Boydston *et al*. 2008). Hence, weed management is the key component of successful crop production. Alien weeds are exotic, introduced, foreign and non-native those have been intentionally or accidently introduced by humans from one region to another. These plant species adversely influence the natural biodiversity, ecosystem and human well-being. These species pose a great challenge because of their capability of spreading fast, great competitiveness and ability to establish in new areas within a short period.

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Globally, there is a great concern about the negative effects caused by invasive alien species to the natural ecosystems and rates of their establishment increased with globalization and global warming (Huston 2004, Williams *et al*. 2015, Adhikari *et al*. 2020). Biological invasion pose serious threat on the economy, human health and the natural ecosystem. It has become important part of today's global ecological change and major threat to native biodiversity, ecosystem stability and its services (McGeoch *et al*. 2010) and also give rise to numerous management and control issues (Lodge *et al*. 2006, Hulme 2009). Many previous studies reported that the climatic factors are important driving factors behind the biological invasion into the non-native ranges. This is happened because invasive alien species normally spread into those areas who possess the similar climatic conditions to their native habitat (Petitpierre *et al*. 2012, Wang *et al*. 2017). Furthermore, climate change has the potential to enhance the detrimental effect of these species on agriculture globally (Wang and Wan 2020, Neve *et al*. 2009, Ziska 2016). In the past, climate change has occurred over hundreds or thousands of years, but recent changes in the climate have occurred just in few decades (Varanasi *et al*. 2016). It is observed that extreme weather phenomenon such as floods and droughts may occur due to the effects of climate change and cause massive impacts on the global ecosystem, changes in the habitat of species and their spread (Kwak *et al*. 2008, Pearson and Dawson 2003, Gharde *et al*. 2023a).

Climate change and distribution of weeds

Climate change, mostly known by the term "Global Warming", is now a well-accepted phenomenon which may be due to both natural and human intervention. According to Inter-governmental Panel on Climate Change (IPCC), "climate change refers to any change in the state of climate identified by fluctuations in the mean and/or the variability of its properties due to natural event or human activities, and that persists for a longer period like decades or more" (Anwar *et al*. 2021). Global climate model projects that in the 21st century, mean global surface temperature will increase by 1.5–4.5°C due to rise in CO_2 concentrations and also due to greenhouse effect (IPCC, 2001). Furthermore, IPCC (2007) has claimed that, since the nineteenth century, global mean annual surface temperature has already increased by 0.76°C. It is also stated that about 50% of the anthropogenic CO_2 emissions between 1750 and 2011 have already occurred in the last 40 years (IPCC 2014) of which, around 40% of the CO_2 emissions remain in the atmosphere and the rest on land and in oceans, which is an alarming situation. Climate change is also expected to affect the distribution and occurrence of the weeds in future. It will have a profound effect on crop protection, including the effects on pests, diseases and weeds. Furthermore, the physiology and biological cycle of the weeds and their competitive relationship with crops will also be affected significantly (Gonzalez 1995). Climate change may also affect the geographic distribution of a native species or invasion of crops by a new weed species (López-Tirado and Gonzalez-Andújar 2023). Sometimes future climate change can lead to shifts in the geographical distribution and richness of the species (Wang *et al*. 2018); their extinction (Bestion *et al*. 2015), and shift in their ranges (Bellard *et al*. 2012). Climatic change has already brought significant changes in the behaviour of the species, biodiversity, its spatial distribution and habitat (Weiskopf *et al*. 2020). Many previous studies focused on assessing the impact of climate change on the geographical distribution of the species under future climatic scenarios at global level as well as at regional level. This information helps in understanding the impact of the species and in making informed decisions on the matter related to biodiversity, public health, agriculture and the economy. Apart from this, it also helps in early detection of the hot spots of the species enabling prompt actions in order to reduce management cost after its introduction in new places (Dorji *et al*. 2022).

Species distribution modelling

To assess the impact of climate change on the distribution of weed species, species distribution modelling approach is widely used for prediction purposes. Predictive models used for the species distribution modelling are powerful tools that can assist in making the decision on the management of these invasive species under different climate scenarios. For studying the impact of future climatic scenarios on the species habitat and their distribution, various species distribution models are used. These models mainly includes MaxEnt, BIOCLIM, DOMAIN, Random forest, *etc*. which are known for their simplicity and the data accessibility (Katz and Zellmer 2018, Srivastava *et al*. 2019, Gharde *et al*. 2023a). Among these, MaxEnt is popular and widely adopted method, which can generate much more robust results even in the case of small sample sizes (Phillips *et al*. 2006). This modelling approach is a well-established approach to model and project the habitat suitability of a species based on their current distribution relative to climatic factors (Elith *et al*. 2006, Gharde *et al*. 2023b). This technique has gained importance in ecology, biogeography, biodiversity conservation and management of natural resources (Adhikari *et al*. 2019). Numerous studies have been conducted in the past to assess the impact of climate change on the potential distribution of the species and found the difference in the result (Merow *et al*. 2017) which is typically depend upon the climatic requirement of the species. In India, widespread obnoxious invasive alien weeds such as *Parthenium hysterophorus*, *Lantana camara*, *Chromolaena odorata*, *Cassia tora*, *Tridax procumbens*, *Ethulia gracilis*, *Calyptocarpus vialis*, *Phalaris minor* etc. have been studied for their probable geographical distribution in future climatic scenarios. Steps followed in the modelling process are depicted in the flow chart given as **Figure 1**.

Studies on species distribution modelling for invasive alien weeds in India

Species distribution modelling may aid in understanding the current and future invasion potential of the invasive alien weeds under climate change scenarios. Numerous studies have been

Data collection and pre-processing

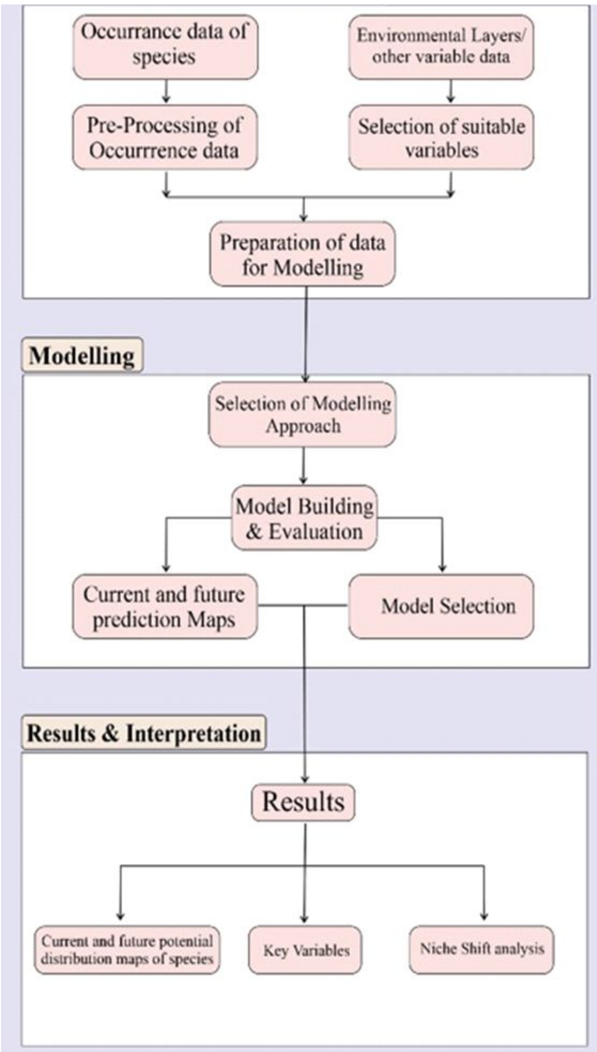

Figure 1. Steps followed in the species distribution modelling for projecting the distributional patterns of species

conducted in the past to show the invasion potential of the species in the world as well as in India. for instance, potential distribution of three obnoxious weeds in north-western Ghats of India, *viz*. *Chromolaena odorata*, *Lantana camara* and *Parthenium hysterophorus* have been studied by Patil and Janarthanam (2013) using 32 environmental variables and MaxEnt modeler. They observed that the weeds might have adapted to different sets of environmental conditions throughout their distributional range. In case of Parthenium, most of its potential distribution was shown on the eastern side of Western Ghats. Whereas, the distribution of *L. camara* and *P. hysterophorus* was not predicted along the western coastal regions. In case of *C. odorata*, its potential distribution starts from coastal areas and extends up to the hilly regions of Western Ghats in Goa and in border areas of Karnataka and Maharashtra states; the potential distribution is predicted only to the hilly areas towards north and south. Distribution of *L. camara* was also studied by Tiwari *et al*. (2022) in Jharkhand, eastern India for its climatic niche under future scenarios. Study predicted the area expansion by 20-26% by 2050 in all RCPs as compared to the current invasion (~13%). In another study, Panda *et al*. (2017) revealed that the distributions of annual *Senna tora* (*Cassia tora*) and *Lantana camara* (perennial) would depend on the precipitation of the warmest quarter and moisture availability. According to this study, in future climate, *C. tora* may invade central India, while *L. camara* is expected to invade the Western Himalaya, parts of the Eastern Himalaya and the Western Ghats. Analysis revealed that the distribution ranges of both species could shift in the northern and north-eastern directions in India, due to the changes in moisture availability in these regions. Similarly, Kishore *et al*. (2024) revealed the large invasion and spread of species, *viz*. *Chromolaena odorata* (33.01%) and *L. camara* (30.33%) in the Western Ghats, especially the Nilgiri Biosphere Reserve (NBR) under the current scenario. The future projections confirmed a significant reduction in the invasion of *C. odorata*, while expansion in the invasion of *L. camara* excluding a few exceptions in the study area. *C. odorata* was also studied by Panda and Behera (2019) and found that it could invade the biodiversity-rich regions of India *viz*. the Eastern Ghats, the Western Ghats, the Eastern Himalaya and the north-eastern regions. They also studied the distribution of *Tridax procumbens* and revealed that it will be more prevalent in Central India due to its dependencies on precipitation seasonality and radiation rather on temperature. It is expected that these species will spread in those regions not utilized by others.

Gharde *et al*. (2023a) used MaxEnt model to predict the invasion potential of *Phalaris minor* in India under current and future climatic scenarios in RCPs 4.5 and 8.5 for the years 2050 and 2070. They found that currently, 21% area of the country is either highly (9%) or moderately (12%) suitable as habitat for the species. Model predicts approximately 90% contraction in the area considered highly or moderately suitable climatically under both moderate and high emissions scenarios. Aravind *et al*. (2022) worked on identifying potential habitats of *Ethulia gracilis* which was recently found for the first time in India growing along the roadside as well as in fallow lands. They found that the regions with risk are warmer and thus, temperature is the factor affecting the species more compared to precipitation. They concluded through their study that this species has potential to be the invasive or at least attain the status of pest in Peninsular India. In the similar study, Thapa *et al.* (2018) projected the potential distribution of eleven invasive alien plant species (*Ageratina adenophora*, *Ageratum conyzoides*, *Ageratum houstonianum*, *Amaranthus spinosus*, *Bidens pilosa*, *Erigeron karvinskianus*, *Lantana camara*, *Parthenium hysterophorus*, *Senna occidentalis*, *Senna tora* and *Xanthium strumarium*) in the part of Kailash sacred landscape region in Western Himalaya under future climatic conditions. They projected that distribution of most of these invasive plants is going to expand under future climatic scenarios. They might pose a serious threat to the native ecosystems through competition for resources in the infested area. Native scrublands and subtropical needle-leaved forests will be the extremely affected ecosystems by the expansion of these species in the future. A detailed study on probable distribution of *Parthenium hysterophorus* in current and future climatic scenarios was conducted by Ahmad *et al.* (2019). The study revealed that 65% of the total area of the country is suitable for species potential invasion under current climate. They found three invasion areas *viz.* Western Himalaya, North-East and parts of Peninsular India as hotspots for the species. However, they predicted overall decrease in habitat suitability for *P. hysterophorus* under future climate but some of the region currently invaded will remain equally (North-east) or will be at high risk (Western Himalaya) to its invasion under future climate. Similarly, *Calyptocarpus vialis*, an emerging invasive weed in the north-western Indian Himalayan Region (IHR), was studied by Lal *et al.* (2024) for its possible habitats under current climatic scenarios and potential range expansion under future climatic scenarios. Study revealed that unlike the current condition, areas with "high" and "very high" suitability status would rise while less-favourable areas would contract. All RCPs (2.6, 4.5, 6.0, and 8.5) indicate the expansion of *C. vialis* in "high" suitability areas, but RCP 4.5 predicts contraction, and RCPs 2.6, 6.0, and 8.5 predict expansion in "very high" probability areas. The current distribution of *C. vialis* is 21.59% of the total area of the state, with "medium" to "high" invasion suitability, but under the RCP 8.5 scenario, it might grow by 10% by 2070. The study also reveals that *C. vialis* may expand its niche at both lower and higher elevations. Some of such studies based on species distribution modelling for revealing the probable geographical distribution of the weeds in future climatic scenarios are compiled and listed in **Table 1**. Similarly, distribution and abundance of aquatic plants are greatly affected by the variations in the environmental factors; however, these plants assimilate the temporal, spatial, physical, chemical and biological characteristics of the ecosystem. In the previous studies, it was demonstrated that environmental interaction play an important role in deciding the distribution and abundance of the aquatic plant species (Berendregt and Bio 2003, Bernez *et al.* 2004) in addition to other factors such as competition, predation and disease. Some of the distributional studies of aquatic plants are listed in **Table 2**.

Thus, species distribution modelling is a powerful tool to evaluate the expansion risk of invasive alien weeds into non-native regions based on the information on their climatic niche. It has become an essential method in biogeography, ecology and natural resource management. This modelling is based on the information about the species occurrence data along with their climatic requirement. Most of the studies include invaded range data as the species occurrence data, however, it is suggested that the modelling potential distribution of invaded species should preferably be based on occurrence data of the native range along with invaded range data since the species might not reach its full potential of habitable space on invaded region. Additionally, each modelling work should include the selection of parameter value carefully and critical assessment of model results if they are biologically sound and easy to interpret. Furthermore, it should always keep in mind that species do not necessarily distribute across the suitable environment as predicted by models. There are multiple reasons responsible for limiting the species to cover all the suitable habitats, which includes geographical barriers, competition with native species, variable dispersal ability of the species *etc*. Hence, species distribution modelling should be used keeping all these facts in mind for forecasting invasion hotspots to enable the implementation of early detection and fast response systems, and development of successful scientific policies to avoid the future invasions of the species.

Table 1. Studies on Species distribution modelling and prediction of weeds' invasion under future climate scenarios

Weed(s)	Region	Prediction about Contraction/expansion in areas	Reference	Prediction for future scenarios	Model used
Ageratina adenophora (Spreng.) R. M. King & H. Rob.	China	Expansion in new areas	Tu *et al*. 2021	SSP 245 and 585 for 2050, 2070 and 2090	MaxEnt
	China	Expansion of the dispersal zone towards the northeast and coastal areas, and a slight contraction in the Yunnan–Guizhou plateau	Zhang *et al.* 2022	SSP126, 245, 370, and 585 for the year 2050 and 2090	MaxEnt
	Global	Contraction globally but increase in six biodiversity hotspot regions	Changjun *et al*. 2021	RCP 2.6, 4.5, 6.0, and RCP 8.5 in 2050 and 2070	MaxEnt
	Chitwan–Annapurna Landscape (CHAL), Nepal	Expansion in the suitable areas	Poudel *et al.* 2020	RCPs 2.6, 4.5, and 8.5 in 2050 and 2070	MaxEnt
Alternanthera philoxeroides (Mart.) Griseb.	China	Expansion	Tu *et al*. 2021	SSP 245 and 585 for 2050, 2070 and 2090	MaxEnt
Ambrosia artemisiifolia L.	China	Expansion	Tu *et al*. 2021	SSP 245 and 585 for 2050, 2070 and 2090	MaxEnt
	South Korea	Expansion	Adhikari *et al*. 2022	RCP 4.5 and 8.5 for the year 2070	ANN, GLM, MARS, MaxEnt, and RF
Mikania micrantha Kunth	China	Expansion	Tu *et al*. 2021	SSP 245 and 585 for 2050, 2070 and 2090	MaxEnt
	South and Southeast Asia, Australia, Oceania and parts of the USA	Expansion toward cold and dry areas of the invasive range	Banerjee *et al*. 2019	RCPs 2.6 and 8.5 for the years 2050 and 2070	MaxEnt
	India	Expansion	Banerjee *et al*. 2017	-	MaxEnt
Parthenium hysterophorus L.	World and Oman	Contraction in areas in 2081–2100 at global level. Expansion for 2021-40 and a contraction for 2081–2100	Ruheili *et al*. 2022	SSP6–8.5 for the years 2030 and 2090	MaxEnt
	Bangladesh	Expansion	Masum *et al.* 2022	RCPs 2.6 and 8.5 for the year 2070	MaxEnt
	Bhutan	Expansion	Dorji *et al*. 2022	RCPs 4.5 and 8.5 for the years 2050 and 2070	MaxEnt
	Chitwan Annapurna Landscape, Nepal	Expansion in the suitable habitat under RCP 4.5 for 2050 and 2070, and decrease in suitable areas under RCP 8.5 in 2050 and 2070	Maharjan *et al.* 2019	RCPs 2.6, 4.5 and 8.5 for the years 2050 and 2070	MaxEnt
	Sri Lanka	Contraction in the areas under very low class and expansion for moderate class of suitability.	Kariyawasam *et al.* 2019	RCPs 4.5 and 8.5 for the years 2050	MaxEnt
	China	Expansion towards northward	Guan *et al.* 2020	RCPs 2.6 and 8.5 for the years 2050	Ensemble approach
	India	Overall decrease in habitat suitability with some highly vulnerable (Western Himalaya) region to its invasion	Ahmad *et al*. 2019	RCP 2.6 and RCP 8.5 for the years 2050 and 2070	Ensemble approach
Cynodon dactylon, Cyperus rotundus, Echinochloa colona, Echinochloa crus-galli, Eichhornia crassipes, Eleusine indica, Imperata cylindrica, Panicum maximum, and *Sorghum halepense*	World	Expansion in new areas	Wang and Wan 2020	RCPs 4.5 and 8.5 for the years 2050 and 2080	MaxEnt
Ambrosia trifida, Symphyotrichum pilosum, Ageratina altissima, Hypochaeris radicata, Lactuca serriola, Paspalum dilatatum, Paspalum distichum, Rumex acetosella, Sicyos angulatus, Solanum carolinense, Solidago altissima	South Korea	Expansion in new areas	Adhikari *et al*. 2022	RCP 4.5 and 8.5 for the year 2070	ANN, GLM, MARS, MaxEnt, and RF
Spartina alterniflora Loisel	China	Expansion in new areas	Yuan *et al*. 2021	RCPs 2.6 and 8.5 for the years 2050 and 2070	MaxEnt
Verbesina encelioides (Cav.) Benth. & Hook. Fil ex Gray	South Africa	Expansion in new areas	Moshobane *et al.* 2022	SSP 585 for the years 2030, 2050, 2070 and 2090	Ensemble approach
Apium leptophyllum, Astragalus sinicus, Bromus unioloides, Chenopodium ambrosioides, Coronopus didymus, Gnaphalium calviceps, Lolium multiflorum, Modiola caroliniana, Oenothera laciniata, Paspalum dilatatum, Sida rhombifolia, Silene gallica, Sisymbrium officinale, Sisyrinchium angustifolium, Spergularia rubra, Malva parviflora	South Korea	Expansion in new areas	Hong *et al*. 2021	RCPs 4.5 and 8.5 for the years 2050 and 2080	MaxEnt
Urochloa panicoides P. Beauv.	World	Area contraction in Brazil, Australia, India, and Africa, and an expansion in Mexico, the United States, European countries, and China	Duque *et al*. 2022	-	CLIMEX

MaxEnt- Maximum entropy

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Weed(s)	Region	Prediction about Contraction/expansion in areas	Reference	Prediction for future scenarios	Model used
Amaranthus palmeri	USA	Northward range expansion and significant increase in suitability across large portions of the U.S. overall	Briscoe Runquist *et al*. 2019	CliMond and PRISM	Maxent and Boosted Regression Trees
Lantana camara L.	World	Contraction in the global suitable areas. Some areas in North Africa, Europe and Australia may become climatically suitable. In South Africa and China, its potential distribution could expand further inland.	Taylor *et al.* (2012)	-	CLIMEX
	World	Expansion in new areas	Wang and Wan 2020	RCPs 4.5 and 8.5 for the years 2050 and 2080	MaxEnt
	Sri Lanka	Contraction in the areas of very low class and expansion in the moderate class of suitability	Kariyawasam *et al.* 2019	RCPs 4.5 and 8.5 for the years 2050	MaxEnt
	China	Species expansion northward	Guan *et al.* 2020	RCPs 2.6 and 8.5 for the years 2050	Ensemble approach
	Queensland, Australia	Reduction in climatic suitability	Taylor and Kumar 2013	A1B and A2 scenarios for the years 2030, 2070 and 2100	CLIMEX
	Jharkhand, eastern India	Expansion up to 20–26% by 2050	Tiwari *et al.* 2022	RCP 2.6, 4.5, 6, and 8.5 for the year 2050	MaxEnt
Butomus umbellatus	North America	Decrease in suitable areas, though two of three global circulation models predict range expansion across gas emission scenarios	Banerjee *et al*. 2020	-	Ensemble approach
Ageratum conyzoides, Praxelis clematidea, Solidago canadensis, Anredera cordifolia, Conyza sumatrensis, Chenopodium ambrosioides, Avena fatua, Pharbitis purpurea, Aster subulatus	China	Species expansion northward	Guan *et al.* 2020	RCPs 2.6 and 8.5 for the year 2050	Ensemble approach
Lonicera japonica	Forests of the Cumberland Plateau and Mountain Region in the southeast of USA	Expansion in new areas	Lemke *et al*. 2011	-	Ensemble approach
Chromolaena odorata	World	Expansion in new areas	Kriticos *et al.* 2004	-	CLIMEX
	India	Higher suitability for species in northeastern states, the central Himalayan provinces and the Western Ghats and Eastern Ghats	Barik and Adhikari 2012	2020 A2 & B2 and 2080 A2 & B2	MaxEnt
Amaranthus retroflexus, Amaranthus spinosus, Amaranthus viridis, Bidens pilosa, Conyza bonariensis, Conyza Canadensis, Galinsoga parviflora, Physalis angulata	China	Expansion	Wan *et al*. 2017	RCP 4.5 and 8.5	MaxEnt
Chromolaena odorata and Tridax procumbens	India	Both are likely to reduce their potential distribution areas	Panda and Behera 2019	A1B and A2 scenarios for the years 2050 and 2100	MaxEnt
Ageratina adenophora L., *Ageratum conyzoides* L., *Ageratum houstonianum* Mill., *Amaranthus spinosus* L., *Bidens pilosa* L., *Erigeron karvinskianus* DC., *Lantana camara* L., *Parthenium hysterophorus* L., *Senna occidentalis* (L.) Link., *Senna tora* (L.) Roxb., *Xanthium strumarium* L.	Western Himalaya, India	Most of these invasive plants are expected to expand under future climatic scenarios	Thapa *et al*. 2018	RCP 2.6 and RCP 8.5 for the year 2050 and 2070	MaxEnt
Cassia tora and *Lantana camara*	India	Distribution ranges of both species could shift in the northern and north-eastern directions in India	Panda *et al*. 2018	A1B and A2 scenarios for the years 2050 and 2100	MaxEnt, GLM and GAM

MaxEnt- Maximum entropy

Table 2. Studies on species distribution modelling and prediction of aquatic weed invasion under future climate scenarios

Weeds	Region	Prediction about Contraction/expansion in areas	Reference	Future scenario(s) used	Model used
Alternanthera philoxeroides, Ceratophyllum demersum, Crassula helmsii, Elodea canadensis, Hydrilla verticillata, Ludwigia peruviana, Najas minor, Pistia stratiotes, Potamogeton crispus, Sagittaria platyphylla	World	Climatic suitability was significantly higher for temperate coastal rivers and temperate floodplain rivers	Wanga *et al*. 2017	-	MaxEnt
Myriophyllum aquaticum, Pistia stratiotes, Azolla filiculoides, Eichhornia crassipes, Salvinia molesta	South Africa	*Myriophyllum aquaticum* and Pistia will contract and rest three will increase their areas	Hoveka *et al*. 2016	2080	MaxEnt
Nitellopsis obtusa	United States	Decrease in the species' suitable range	Romero-Alvarez *et al*. 2017	RCP 2.6, 4.5, 6, and 8.5	MaxEnt

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