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Assessing harmony in distribution patterns of plant invasions: a case study of two invasive alien species in India

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Abstract

Climate change enhances invasive species distribution by altering species composition in native ecosystems. Here we assessed harmony in plant invasions of two perennial exotic species of similar origin and naturalised in India, i.e., *Chromolaena odorata* and *Tridax procumbens*. Predictions made for the current condition was subsequently projected for the years 2050 and 2100 for both moderate and extreme climate change scenarios. Maximum Entropy (Maxent) was applied to assess their habitat suitability, risk area identification and shifts in range sizes. The distribution of *C. odorata* could mostly depend on temperature and moisture availability; and invade the biodiversity-rich regions of India viz., the Eastern Ghats, the Western Ghats, the Eastern Himalaya and the north-eastern regions. The prevalence of *T. procumbens* in central regions of India could demonstrate its greater dependencies on precipitation seasonality and radiation than that on temperature. These discrepancies in climatic dependencies allowed both for a harmonious distribution, i.e., inhabiting in regions not utilised by other. Both are likely to reduce their potential distribution areas in the future climate, where moisture availability is a key factor for their range expansion. The capacity to tolerate a wide range of temperature and solar radiation allowed *T. procumbens* to manage climate change impacts more efficiently, compared with *C. odorata*. The present study reveals harmony in their distributions and suggests distinct conservation protocols for each of them to control their invasion risks.

Keywords *Chromolaena odorata* · Climate change · Invasion risk · Habitat suitability · Maximum entropy · *Tridax procumbens*

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Introduction

Invasive species use resources efficiently owing to their superior growth potential, efficient dispersal mechanisms and stress tolerant capacities. They invade native ecosystems through natural seed dispersal or anthropogenic interventions and alter their species compositions (Vitousek 1986). More interestingly, invasive species avoid competition among them; and live harmoniously without occupying each other's niche. Even their niche overlap, they can invade native ecosystems in time and space without competition. The availability of vast potential niche space, which is likely to be created by deforestation, land use changes and human disturbances, has every chance of harmonising their distributions. Here we illustrate these relationships between two exotic invasive species, naturalised in India, i.e., *Chromolaena odorata* and *Tridax procumbens*, greatly useful for biodiversity maintenance and planning. As climate change enhances their distributions studying their interactions with the future environment is crucial for biosecurity (Vaclavik and Meentemeyer 2009; Kriticos and Leriche 2010) and conservation prioritisation (Thuiller et al. 2004). Assessing their invasion risks and mapping habitat suitability are essential for faster management to reduce further spread and menace of plant invasions.

Chromolaena odorata and *Tridax procumbens* have high economic values and ecological significance. Both are exotic, naturalised in India (Khuroo et al. 2012; USGS 2018). *C. odorata* (Siam weed), a perennial herb, and native to Central and South America, is listed among the 100 worst invasive species in the world (ISSG 2004). Its economic and ecological implications have been widely addressed worldwide including India (Akpagana et al. 1993; McFadyen and Skarratt 1996; McWilliam 2000; Koutika and Rainey 2008; Codilla and Metillo, 2011; Barik and Adhikari 2012). Introduced in mid-nineties as an ornamental plant in India (Voigt 1945), this species is now distributed in most of the parts of this country and poses serious threats to its agriculture and natural ecosystems (Koutika and Rainey 2008). *C. odorata* can reproduce both by sexual and vegetative means, and apomictic, i.e., capable of producing fertile seeds without pollination (Coleman 1989; Rambuda and Johnson 2004). *C. odorata* has rapid seed growth, i.e. 20 mm per day (Hills and Ostermeyer 2000), and light intensity has a positive influence on its seed germination (Witkowski and Wilson 2001). It proliferates to the nearby places within a short period (Holm et al. 1977), and very well supported by its multiple modes of dispersal (wind, animals and human beings). *C. odorata* occurs in the areas between 30N and 30S latitudes, i.e., at places high annual average rainfall of about 2000 mm (Muniappan et al. 2005), and at places of low rainfall (≥ 200 mm and < 1000 mm), with a moderate to low soil water regimes (Zhang and Wen 2009). Dry season, the short day lengths and prolonged rain days favour the distribution of *C. odorata* (McFadyen and Skarratt 1996; Zachariades et al. 2009). The species grows in places of a mean annual soil temperature > 22 °C, and air temperature between 20 and 37 °C (Timbilla and Braimah 2002). *C. odorata* can endure fire and acidic soil, but low temperatures inhibit its growth (Goodall and Erasmus 1996; Yadav and Tripathi 1981).

T. procumbens is a perennial herb, native to northern and southern America (USGS 2018). It is widely distributed throughout India (Mundada and Shivhare 2010) and is one of 126 world weeds (Holm et al. 1997). It has several therapeutic potentials and immense medicinal values, with anti-trypanosomal activities (Abubakar et al. 2012). *T. procumbens* is frequent along open lands, roadsides and disturbed habitats, mostly in places of sufficient sunlight in a hot and humid environment. Its seed dormancy is more than 2 years, and its seed germination enhances > 30 °C (Lutzeyer and Koch 1992; CABI 2015). Its pappus increases the efficiency of soil water use (Pemadasa and Kangatharalingam 1977).

Unlike *C. odorata*, *T. procumbens* cannot have a vegetative reproduction. It can have wind-mediated dispersal only. Although this species has great ecological significance in India, no study focuses on its invasion potential and impacts of climate change on its distribution essential for better management practices.

Here we predicted distributions of *C. odorata* and *T. procumbens* for the current condition and subsequently, projected for the years 2050 and 2100. We assessed their distributions for both moderate (A1B) and extreme (A2) climate change scenarios. The areas of invasion suitability and range shift of both were mapped and compared in the changing climate. The harmony in their distributions in changing environments was quantified using the Maximum Entropy model.

Methods

Study area

The present study considers two invasive exotic species of India, which lies between 6°45′–37°6′N latitudes and 68°7′–97°25′E longitudes with a spread over an area of 3, 166, 414 km^2. It is bounded by the Indian Ocean and the Arabian Sea in the south-west, the Bay of Bengal in the south-east, the Great Himalayan Range on its northern frontiers. The trade-offs between the Himalayas and the Thar Desert influence the climatic regime from the tropical south to the temperate and alpine north (Chang 1967). The mean annual temperature ranges between −45 °C and > 50 °C, and precipitation ranges between < 500 mm and > 2000 mm, respectively.

Data preparation

Floral information for *C. odorata* and *T. procumbens*, gathered during the execution of a national-level biodiversity characterisation project (http://bis.iirs.gov.in), for 1307 and 1144 location points, respectively (Roy et al. 2012). A standard size of 1 m^2 was used to sample herbs. We procured 35 climatic variables at 10′ (ca. 18 km) resolution from Cli-Mond dataset (Version 1.2) for the current condition and two forecasted scenarios (A1B and A2) of the years 2050 and 2100 (Kriticos et al. 2012; Supplementary Table 1). The present study highlights two climate change scenarios of moderate and extreme conditions in the future climate, assuming their logical implications in driving species distributions. The A1B scenario is associated with high economic growth, efficient technological innovations, with a balanced use of energy resources. It assumes population peaks at mid-century that declines afterwards. The A2 scenario is considered an extreme scenario, which assumes growth both at local and regional scales, with slow economic development and technological changes, and population growth continues at the current rate (Solomon et al. 2007). We considered two climate change scenarios to assess impacts of raised temperature on potential distributions. ASCII grids of each climate layer masked to India's territorial boundary were projected to WGS84 equal-area projection using ArcGIS 10.

The multicollinearity among environmental variables produces inconsistent model outputs. Therefore, we considered the least correlated ecologically significant variables for the study analysis (Panda et al. 2017). The variance inflation factor (VIF) is a widely used tool for diagnosing multicollinearity and selection of least correlated variables (Hair et al. 1995). Several VIF thresholds, i.e., 10 or 5 or 4, are recommended for selection of variables

(Neter et al. 1989; Rogerson 2001). We fixed a VIF threshold of 10 for the present analysis. We used the package 'usdm' to estimate the VIF of variables (Naimi 2015). We did not consider variables > 0.75 correlation (Panda et al. 2017). After dimensionality reduction, we selected eight variables for modelling: mean diurnal temperature range (DTR), mean temperature of warmest quarter (TWmQ), precipitation of driest week (PDrWk), precipitation seasonality (PS), radiation of wettest quarter (RWeQ), radiation of warmest quarter (RWmQ), radiation of coldest quarter (RCQ) and moisture index (MI).

Species distribution modelling

Several species distribution models (SDM) quantify species-environment relationships, impacts of climate change and the geographic distribution of invasive species (Thuiller et al. 2005; Hijmans and Graham 2006; Elith et al. 2011; Petitpierre et al. 2012). In the present study, we considered Maximum Entropy (Maxent), a robust nonlinear machine learning technique in biological systems (Phillips et al. 2006). Maxent works on the principle of metastable equilibrium using the present occurrences only. The pseudo-absences data are simulated from the background (Phillips et al. 2006). It has advantages of clamping and regularisation, with abilities to examine whether projections lie within environmental space or geographic space (Murray 2010).

Data processing

We placed the 'csv' file of species with GPS location points and 'asc' files of climate variables in the folder of the package 'dismo' (Hijmans et al. 2015). We put the 'jar' file of Maxent software (Version 3.3.1) in 'java' folder of this package. To cross-validate, we randomly partitioned species data into two independent datasets, i.e., 75% for training and 25% for testing. We applied a pair-wise distance sampling method to correct sample bias that may persist even in planned sampling (Fourcade et al. 2014). A threshold distance of 0.33 between the present occurrences, and test- and -background points was set and equal weights were allocated to each point locations (Hijmans 2012). We set sample sorting bias (SSB) equals 1 or close to 1 for background point selection and did not allow repetitions in testing absence site selection for both models (Hijmans and Elith 2015). The background points were selected randomly between 1000 and 10,000, with an increment of 1000 for each model run. We consider background points for the present run when the differences between testing-presence site and testing-absence site to training presence yield SSB equals 1 or close to 1 after several repetitions. For Maxent, we considered 10,000 background points robust to correlative environmental variables, and applied 'clamping' to project within environmental space and set other default parameters tuned for a wide range of datasets for plants and animal studies (Phillips and Dudík 2008).

Model validation

The model validation was done with the 25% test data. The receiver-operator curve (AUC), a threshold independent accuracy measure, was preferred for its applications in large-scale biological applications. The AUC values of each model were compared with the null model for both calibrated and un-calibrated conditions, i.e., with/without bias. We derived the niche equivalency and niche similarity of both species for the robust model using the

'phyloclim' package (Heibl and Calenge 2013). The D and I values were computed after 100 times randomisations, which was considered sufficient to reject predictions of the null model with a high confidence level (Warren et al. 2008). Also, we compared the similarities and differences of both in their environmental niche space. All statistical analyses were done using R version 3.3.0 (R Core Team 2016).

Map preparation

Maxent-derived habitat suitability maps were prepared by using 10-percentile training presence logistic threshold, which excludes 10% of the data used for the model building (Phillips and Dudík 2008; Young et al. 2011). This threshold is most common for its conservative estimate of a species' tolerance to each predictor variable, accounting environmental complexities, and yielding ecologically significant outputs (Brito et al. 2008; Lobo 2008). The maps conformed to equal area WGS84 projection were resampled to four habitat suitability classes: very low (0–0.25), low (0.25–0.5), high (0.5–0.75) and very high (0.75–1). We also prepared binary maps to demarcate areas of habitat suitability and unsuitability. We subtracted the binary maps for the current conditions from the projected maps of 2050 and 2100 to quantify range size changes impacts of climate change. Mapping was done using ArcGIS 10.3.

Results

VIF values for selected variables were < 4 except for the year 2100, where VIF values were 4.6 and 5.7 in the A1B and A2 scenarios, respectively. The niche equivalency test showed both species have identical niches. The D values (0.20–0.24) and I (0.40–0.47) values derived by niche similarity test were within 95% confidence intervals of the null model (p < 0.001). The mean DTR value could vary between 9.3 °C and 10.1 °C in the distributional range of *C. odorata*. It showed a marginal rise in its maximum value (12–12.06 °C), but a significant rise in the minimum value (5–6 °C) in the future climate. The mean TWmQ value could rise > 7 °C, with a rise in both the maximum (28–35 °C) and minimum (16–22.6 °C) values. PDrWk could rise marginally from the present condition (0.67 mm) to climate change scenarios of 2050 (1.1–1.14 mm). But this variable showed a marginal drop in precipitation for the year 2100 (0.6–0.62 mm). The mean PS could vary marginally between 0.97 and 1.14 showing significant changes between the present and future climates (0.53–0.64). However, the variations in PS values were less significant in the distributional ranges of *C. odorata*. On the other hand, the mean RWeQ value could rise marginally (159.2–162.4 W m^{-2}) in the places of *C. odorata*. Its minimum values (115–123.8 W m^{-2}) showed a substantial rise, but its maximum values dropped marginally (211–203 W m^{-2}). Similarly, the mean RWmQ value increased from the current condition (203.5 W m^{-2}) to the future (222.2 W m^{-2}) owing to significant rises in minimum values (121–160.7 W m^{-2}) *vis-à-vis* marginal rise in maximum values (248–254.8 W m^{-2}). The mean RCQ showed negligible changes (171.2–173.3 W m^{-2}) because of the proportionate drop in minimum values (140–128 W m^{-2}) concerning the rise in maximum values (203–244 W m^{-2}). The mean MI could increase from 0.34 to 0.79 in the future climate change scenarios (Table 1).

The mean DTR value could vary between 12 and 12.3 °C in the distributional ranges of *T. procumbens*. Its maximum values could drop marginally (14.6–15.1 °C) with

Table 1 Descriptive statistics of variables for the current condition and climate change scenarios (A1B and A2) of the years 2050 and 2100

	Current			2050A1B			2050A2		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Chromolaena odorata									
DTR	5	12	9.30	5.85	12.01	9.93	5.84	12.02	9.92
TWmQ	16	33	27.99	19.21	36.61	31.14	19.04	36.38	30.93
PDrWk	0	6	0.67	0	7.34	1.10	0	7.34	1.14
PS	0.53	1.40	0.97	0.64	1.37	1.03	0.63	1.37	1.02
RWeQ	115	211	159.24	119.66	207.86	162.02	119.35	207.62	161.96
RWmQ	121	248	203.49	147.22	249.88	211.67	146.77	249.67	210.96
RCQ	140	203	173.34	135.94	226.87	173.04	136.32	221.04	173.09
MI	0	1	0.34	0.39	1.61	0.83	0.39	1.61	0.84
Tridax procumbens									
DTR	7	15	11.95	7.68	15.11	12.32	7.67	15.14	12.33
TWmQ	19	34	30.92	21.60	37.18	34.26	21.42	36.97	34.04
PDrWk	0	6	0.21	0.00	4.82	0.45	0.00	5.28	0.47
PS	0	2	1.22	0.60	1.70	1.25	0.59	1.69	1.25
RWeQ	155	234	175.53	155.56	242.52	176.69	155.56	242.51	176.68
RWmQ	195	268	239.03	196.46	271.57	241.06	195.99	271.38	240.94
RCQ	118	200	177.78	115.25	198.68	175.52	115.49	198.77	175.70
MI	0	1	0.003	0.15	1.02	0.51	0.15	1.03	0.51

	2100A1B			2100A2		
	Min	Max	Mean	Min	Max	Mean
Chromolaena odorata						
DTR	5.91	12.03	10.04	5.93	12.06	10.10
TWmQ	21.42	39.46	33.71	22.63	41.08	35.13
PDrWk	0	6.43	0.62	0	6.42	0.60
PS	0.63	1.41	1.10	0.63	1.49	1.14
RWeQ	122.42	203.17	162.61	123.84	203.13	162.42
RWmQ	154.85	254.75	218.34	160.71	261.17	222.22
RCQ	131.27	244.16	172.07	128.72	256.56	171.21
MI	0.35	1.62	0.79	0.33	1.62	0.77
Tridax procumbens						
DTR	7.80	14.77	12.18	7.87	14.59	12.11
TWmQ	23.81	39.84	36.97	25.01	41.66	38.47
PDrWk	0.00	1.64	0.20	0.00	1.64	0.16
PS	0.74	1.75	1.31	0.81	1.80	1.34
RWeQ	152.79	247.75	176.52	149.54	248.04	176.16
RWmQ	200.91	273.91	242.84	204.00	275.14	244.05
RCQ	111.16	201.74	173.62	109.51	203.44	172.47
MI	0.15	1.00	0.49	0.15	1.01	0.48

DTR mean diurnal temperature range (°C), *TWmQ* mean temperature of warmest quarter (°C), *PDrWk* precipitation of driest week (mm), *PS* precipitation seasonality (CV), *RWeQ* radiation of wettest quarter (W m^{-2}), *RWmQ* radiation of warmest quarter (W m^{-2}), *RCQ* radiation of coldest quarter (W m^{-2}), *MI* annual mean moisture index
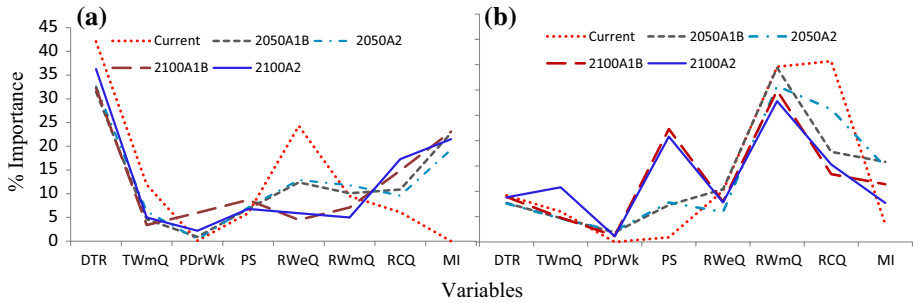
Fig. 1 Importance of significant variables in distributions of **a** *Chromolaena odorata* and **b** *Tridax procumbens* using Maxent (Phillips et al. 2006). *TR* diurnal temperature range, *TWmQ* temperature of warmest quarter, *PS* precipitation seasonality, *RCQ* radiation of coldest quarter, *RWeQ* radiation of wettest quarter, *RWmQ* radiation of warmest quarter, *MI* annual moisture index

marginal rises in minimum values (7–7.8 °C). The mean TWmQ value could rise in an equivalent proportion like that of *C. odorata*, i.e., > 7.4 °C as a result of the rise in both maximum (34–41.7 °C) and minimum (19–25 °C) values. The mean PDrWk could exhibit a marginal fall from the present condition (0.21 mm) to the future climate (0.16 mm). Instead, the mean PS could show a marginal rise (1.22–1.31), with marginal rises in minimum values (0–0.8) and drops in maximum values (0.64–2). The mean RWeQ value could show a small increment in the future climate (175.5–176.5 W m^{-2}). However, minimum RWeQ values could increase marginally from the present to the future climate change scenarios of 2050. On the contrary, its value could drop by 3–6 W m^{-2} in 2100. Similarly, the mean RWmQ value could increase (239–244 W m^{-2}) in the distributional ranges of *T. procumbens* in the new climate owing to rises in both minimum values (195–204 W m^{-2}) and maximum values (268–275 W m^{-2}). In contrast, the mean RCQ could decrease (177.8–172 W m^{-2}). The maximum (200–203.4 W m^{-2}) and minimum (118–109.5 W m^{-2}) values could show small variations. The mean MI values could drop from 0.51 to 0.48 in the new climate (Table 1).

Temperature could influence the distribution of *C. odorata* (33.7–54%) more prominently compared with the distribution of *T. procumbens* (12.2–20.1%). Its influence could decrease from the current condition to the future climate of 2100 through 2050. Similarly, the mean DTR could exhibit significant influences in the distribution of *C. odorata* compared with *T. procumbens*. On the contrary, TWmQ, PDrWk and PS could show a greater impact in the distribution of *T. procumbens* than that of *C. odorata*. RWeQ could show a significant influence in the distributional ranges of *C. odorata*, whereas RWmQ and RCQ could exhibit significant impacts in the distributional ranges of *T. procumbens*. Moisture availability could increase its influence in the distributional range of *C. odorata*, more in scenario A1B than in scenario A2. On the contrary, moisture availability could influence the distributional ranges of *T. procumbens* was higher in scenario A2 than in scenario A1B (Fig. 1).

Chromolaena odorata could invade the Indian peninsula (except in south-eastern region), parts of the Western Ghats, the north-eastern parts of India including the eastern Himalaya, and the Eastern Ghats. *T. procumbens* could be predicted to occupy the central and west-central plains of India (Fig. 2a–e). Interestingly, the high priority areas of *T. procumbens* did not overlap with that of *C. odorata*. Rather these places were predicted unsuitable for the distribution of *C. odorata*, e.g., north-east India predicted suitable for
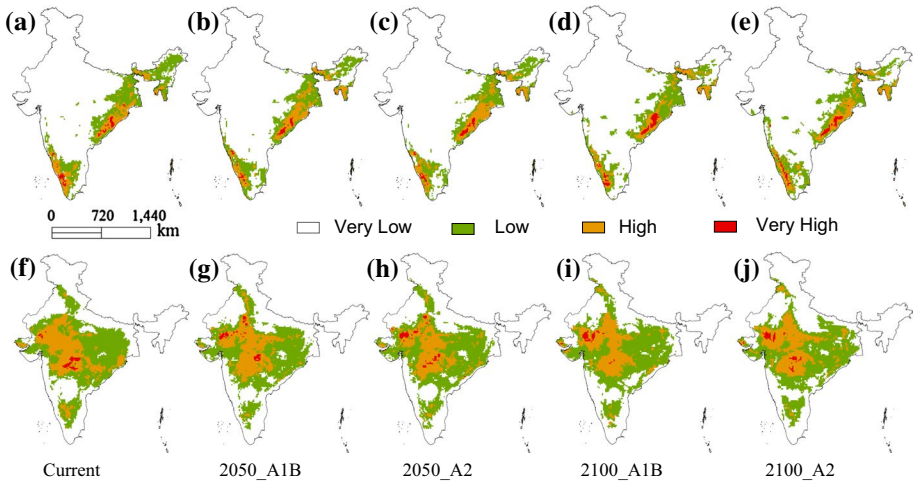
Fig. 2 Habitat suitability maps of *Chromolaena odorata* (**a–e**) and *Tridax procumbens* (**f–j**) derived using Maxent (Phillips et al. 2006); Predictions made for the current condition are projected for A1B and A2 scenarios of the years 2050 and 2100

the distribution of *C. odorata* was unsuitable for the distribution of *T. procumbens*. Both could show niche overlap in some low priority areas along eastern frontiers (Fig. 2f–j). The changes in range size showed temporal shifts with no notable changes in distributions between climate change scenarios of a particular year. The spatial–temporal changes in range size were random without any specific pattern with an overall reduction in climate change (Fig. 3a–d). The significant reduction in range size in *C. odorata* was along the northeast and in *T. procumbens* along the Gangetic plains. *T. procumbens* was found to invade south, west, north-west and eastern plains, and the peninsular region was predicted unsuitable for the distribution of this species (Fig. 3e–h). Comparisons of an overall reduction in habitat suitability in different climate scenarios of the years 2050 and 2100 using two modelling techniques are represented (Fig. 4).

Under un-calibrated conditions, AUC values for *C. odorata* were found to be higher than that of *T. procumbens*. AUC values ranged between 0.917 and 0.939 and 0.821 and 0.858 for *C. odorata* and *T. procumbens*, respectively. AUC values were predicted to be lower in the calibrated conditions than that of the uncalibrated models. The model accuracies for calibrated models were between and in *C. odorata* and *T. procumbens* between 0.542 and 0.586 and 0.506 and 0.582, respectively. Overall AUC values under un-calibrated and calibrated null model conditions were close to 95 and 50%, respectively (Table 2).

Discussion

The distribution of *C. odorata* is highly probable along the Western Ghats, the eastern Himalaya, the Eastern Ghats and the north-east parts of India. It corroborates with the findings of Barik and Adhikari (2012) who advocated the suitability of these regions. They predicted the potential distribution of *C. odorata* under A2 and B2 scenarios for the years 2030 and 2080. Several studies also reported its presence in the Western Ghats (McFadyen
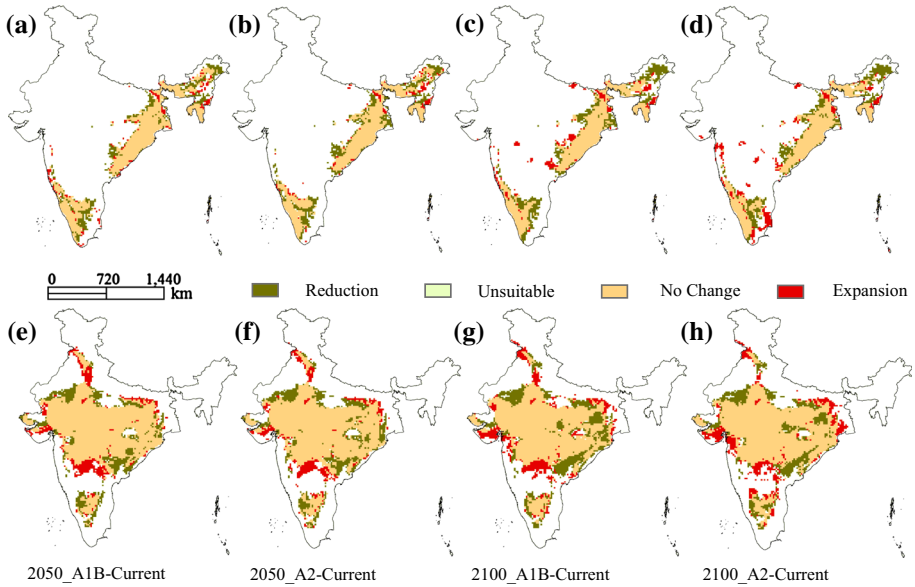
Fig. 3 Range shift maps of *Chromolaena odorata* (**a–d**) and *Tridax procumbens* (**e–h**) derived using Maxent (Phillips et al. 2006). The current distribution maps are subtracted from the predicted maps of the A1B scenario and the A2 scenario for the years 2050 (**a** and **b**; **e** and **f**) and 2100 (**c** and **d**; **g** and **h**)
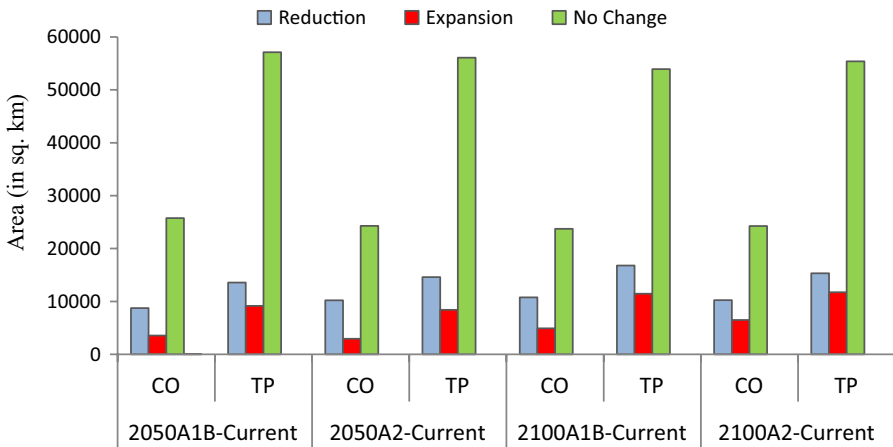

Fig. 4 Changes in distributional ranges (km^2) of **a** *Chromolaena odorata* (CO) and **b** *Tridax procumbens* (PT) under moderate (A1B) and extreme (A2) climate change scenarios for the years 2050 and 2100. Predictions made using Maxent (Phillips et al. 2006)

2003; Kriticos et al. 2005; Muniappan et al. 2005). Its absence in the semi-arid regions indicates negative influences of low- and high- temperature extremes and soil moisture availability determine its invasion success. It corroborates with the earlier findings that the low temperature inhibits its growth (Goodall and Erasmus 1996; Yadav and Tripathi 1981). It is unable to invade places of low moisture availability, i.e., the Mediterranean, semi-arid

Table 2 Maxent model evaluations for on-calibrated (uc_AUC) and calibrated (cAUC) conditions in the current condition and future climate change scenarios (A1B and A2) of the years 2050 and 2100

Year/scenario	Current	2050_A1B	2050_A2	2100_A1B	2100_A2
Chromolaeana odorata					
uc_AUC	0.917	0.939	0.936	0.934	0.935
cAUC	0.542	0.558	0.579	0.586	0.547
null_AUC	0.971	0.986	0.977	0.972	0.977
null_cAUC	0.516	0.519	0.511	0.513	0.510
Tridax procumbens					
uc_AUC	0.821	0.850	0.849	0.836	0.858
cAUC	0.506	0.582	0.565	0.506	0.564
null_AUC	0.945	0.942	0.946	0.946	0.951
null_cAUC	0.503	0.503	0.502	0.501	0.504

The model performances with the null model showed Area under Receiver-Operator Curve (AUC) has better precision in un-calibrated models compared with calibrated models

and temperate climates (Kriticos et al. 2005). McFadyen (2002) reported the western and northern regions of India are unsuitable for *C. odorata*. The temperature is an important factor indicating the significance of energy dynamics in its distribution (Turner et al. 1988). Its presence of in places of low DTR substantiates its dependence on temperature.

On the contrary, *T. procumbens* is found in places of high mean annual temperature, enhancing its seed germination. The earlier studies have similar findings that temperature above 30 °C facilitates seed germination (Lutzeyer and Koch 1992; CABI 2015). The variations in seasonal precipitation are found to be crucial in distributions of *C. odorata* and *T. procumbens*, more significantly in the distribution of *T. procumbens*. It corroborates with the earlier findings that alterations in precipitation regimes have cascading effects on species invasions (Panda et al. 2018). PDrWk showed a weak correlation, but precipitation in the driest period is predicted to influence the distribution of *C. odorata* significantly. It is in congruence with earlier studies that the dry season with short day length and prolonged rainy days favour its invasion (McFadyen and Skarratt 1996; Zachariades et al. 2009).

The distributions of *C. odorata* and *T. procumbens* are highly constrained by solar radiation. RWeQ greatly influences the distribution of *C. odorata*. On the contrary, the distribution of *T. procumbens*, its impact is likely to reduce from the current condition to 2100 through 2050. It shows the synergy between the rising influences of temperature and radiation. Unlike *T. procumbens*, the distribution of *C. odorata* could counter-balance the adversities of excess water by solar radiation of wettest months. The earlier studies reported negative effects of water logging on its growth (Cruttwell 1972; McFadyen and Cruttwell 1991). RWmQ could contribute the maximum in the distribution of *T. procumbens* indicating that warm condition favours its distribution. The significant influence of RCQ in its distribution indicates that light intensity crucial for its seed germination (Witkowski and Wilson 2001). The reducing impact of RWmQ in the future climate indicates synergy between radiation and temperature; and the negative effects of radiation with the rise in temperature. The thermophilic properties of *T. procumbens* are further supported by its availability in places of high DTR and TWmQ.

Overall the influences of moisture availability would increase with the rise in temperature in the future climate. The distribution of *C. odorata* would occur along east–west

coastal plains and the north-east explaining its dependability on the availability of moisture. In contrast, *T. procumbens* showed a consistent decrease in its dependency on the availability of moisture in the future climate. It indicates that the species would be less significantly influenced by the availability of moisture. Its pappus on achene plays important role in increasing water use efficiency and endurance to water stress (Pemadasa and Kangatharalingam 1977). However, seasonal variations in precipitation significantly control its distribution. The unsuitability of areas receiving heavy rainfall describes that places of moderate rainfall favour its colonisation.

In general, the reduction of range size is more than that of its expansion. The significant reduction of range size in *C. odorata* in the future climate indicates the influence of the global rise in temperature on its distribution. Although the range reduces in *C. odorata* owing to rising temperature in the future, the species density in certain areas is greater in 2100 than that in 2050, and thus, describes influences of the local climate on its distribution. The low-temperatures of the northeast parts of India would constrain its growth and propagation. Comparatively, *T. procumbens* is more likely to be controlled by thermal stress and showed proportionate changes in range size. The expansion of its range towards south, west, north-west and eastern plains indicates its preference to warm conditions. It showed less dependency on soil moisture, but the extreme water stress has negative impact on its colonisation. Overall open places with low to medium rainfall are suitable for its distribution. It corroborates with the earlier findings that it is frequent along open lands, roadsides and disturbed habitats, with sufficient sunlight in a hot and humid environment and enhancement of seed germination at > 30 °C (Lutzeyer and Koch 1992; CABI 2015). The prevalence of *T. procumbens* in central regions of India with intensive agriculture also supports its preference to open places. Its capacity to withstand high mean temperature and water stress is greater than that of *C. odorata*. Unlike *C. odorata*, *T. procumbens* cannot have a vegetative reproduction. It dispersal mechanism is less efficient, i.e., wind-mediated only. It might control its invasion to higher altitudinal regions. *T. procumbens* has several therapeutic potentials and immense medicinal values; whereas *C. odorata* has more efficient dispersal ability and seed-yielding capacity. Their competitive advantages could determine their dominances in distributions, and the disparities in climatic dependencies could regulate their invasion successes in a harmonious environment.

Conclusions

Climate change has a significant effect on the distribution and range size of *C. odorata*. The species is more likely to be affected by the rise in temperature and availability of moisture. On the other hand, *T. procumbens* could tolerate a wide range of temperature and solar radiation. These disparities in climate dependencies between two invasive species could shape their harmonious distribution avoiding competition. The exotic invasion could depend on the time of introduction, where species introduced early has a competitive advantage to dominate, but more research is required. Although the current study elucidates the variations in climate change effect on individual species, the inclusion of non-climatic predictors may further improve the precision and interpretability of models. Assessing distributions of more species could provide greater ecological insights in understanding plant invasions.

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