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Use of species distribution models to study habitat suitability for sustainable management and conservation in the Indian subcontinent: A decade's retrospective

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Loss of native habitat has been identified as one of the crucial drivers of the growing biodiversity crisis, acting toward the deleterious effects on individual fitness, functional diversity, changes in species richness and community structure. The objective of the study was to review the species distribution modeling works done in the Indian subcontinent throughout the last decade (2012–2021) to highlight the urgent issues of biodiversity conservation and sustainable management. Species distribution model (SDM), ecological niche model (ENM), and habitat suitability model (HSM) are, in general, used to predict the niche of a species. The Scopus search engine result was used for conducting the literature search of peer-reviewed articles. Topics examined included estimation of species' potential distribution area, spread of introduced species, deadly diseases or pests, habitat loss or future range shift of species due to anthropogenic alterations and climate change. The analysis showed that the majority of the works were focused on predicting native species distribution patterns ($n = 119$, 82%) rather than the invasion of alien species in the native ecosystem ($n = 26$, 18%) indicating the further scope of research in these areas. The scientific articles highlighted that the modeling results could be utilized efficiently to design conservation areas if not biased toward charismatic species. A coordinating institute at the inter-ministerial level can help to undertake policy-related planning for sustainable management and execution of decisions.

KEYWORDS

species niche, threats to biodiversity, species extinction, Scopus search, habitat conservation, sustainable management policy

Introduction

The existence of life on Earth has always been determined by the difference between origination and extinction (Jablonski, 2008). The current extinction rates are around 1,000 times higher than the background extinction rates, and in future, this will continue to increase (Pimm et al., 2014). Loss of native habitat has been identified as one of the crucial drivers of the growing biodiversity crisis, acting to the deleterious effects on individual fitness, functional diversity, changes in species richness, and community structure. The alarming implication of habitat loss or degradation is that many species can become regionally or locally extinct with a time lag, even if they do not face further habitat loss. Such extinction debt poses a significant and unnoticed challenge for biodiversity conservation across ecosystems and associated communities. For instance, species having populations near the extinction threshold and long generation times are prone to show extinction debt (Kuussaari et al., 2009). The Red list is said to be heavily biased toward evaluating the birds and mammalian species, but very little part of invertebrate species has been examined against those conservation criteria. If one considers the actual number of invertebrate species extinctions, it can be concluded by the estimation that the sixth mass extinction is underway (Cowie et al., 2022). Hence, understanding about habitat requirement for controlling native biodiversity loss and ecosystem functionality are crucial for applied research initiatives (Boesing et al., 2018).

Globally, the number of species having restricted suitable habitat ranges is quickly increasing, and it is also applicable to familiar taxa. These species are usually geographically restricted and disproportionately threatened or expected to be extinct. It is assumed that many unknown species also share similar patterns of crisis. Unfortunately, widely distributed species dominate the maps for conservation, whereas most species with small ranges are almost invisible (Pimm et al., 2014). South Asia today is one of the main centers of anthropogenic activities. Its complex biogeography creates zonation in regional biotic patterns and threatens species' existence (Hughes, 2017; Chowdhury et al., 2022).

The Indian subcontinent is a physiographical region in the southern part of Asia, consisting of countries namely Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka, and the Maldives (Kumar, 2012; Mann, 2014). There are four global biodiversity hotspots in the Indian subcontinent (Eastern Himalayas, Western Ghats-Sri Lanka, Indo-Burma, Sundaland, and Nicobar Islands) (Mittermeier et al., 1998). For instance, the four countries, namely—Bangladesh, India, Sri Lanka, and the Maldives, harbor a substantial number of mangroves of exceptional biodiversity value, including the world's largest mangrove forest—the Sundarbans. Conservation of these regions becomes more challenging as the taxonomic uncertainty is highly and significantly associated with many taxa that is greater than any other parts of the world (Hughes, 2017). Agriculture dependent economy of this region accelerated extreme competition for acquiring land that has eventually resulted in a fast habitat clearance as well as native resource exploitation (Chowdhury et al., 2022). Along with that, changing climate and invasive alien species (IAS) are two other significant contributors to biodiversity loss.

Distribution modeling aims to understand and visualize species spatial distribution under the future, present, or past climatic scenarios by relating its occurrence to the predictor variables (Guisan and Zimmermann, 2000). Species distribution model (SDM), ecological niche model (ENM), and habitat suitability model (HSM) are usually used for predicting suitable habitats, environmental tolerances, and species responses toward climate change (Guisan and Thuiller, 2005; Iverson et al., 2008; Sunday et al., 2012; Morán-Ordóñez et al., 2017; Bryn et al., 2021). Although SDM is used to predict the actual geographic ranges where a species may be found, ENM estimates the Grinnellian niche of the species. Predictions from the models can be applied to make inferences about community assemblages, evolution, and dynamics that would otherwise not be available to researchers working with local field data only (Murphy and Smith, 2021). The sustainable management of Indian subcontinental flora and fauna is an essential issue of global concern for its richness and presence of several endemic species. Thus, the objective of the study was to review the species distribution modeling works done in the Indian subcontinent throughout the last decade (2012–2021) to estimate the effects of climate change and anthropogenic alterations on native species, and determine the chance of invasive alien species, or disease infestation.

Materials and methods

Literature search and paper selection

For collating the literature from the Indian subcontinent, a two-stage process was followed. Firstly, the Scopus search engine was used for conducting scientific literature searches of peer-reviewed journals that focussed on the distribution models (a similar method was followed by Urbina-Cardona et al., 2019; Feldman et al., 2021). The search spanned a period of 10 years in the last decade, considering papers from 2012 until 31st December 2021. The articles were searched using the following combination of keywords: ("species distribution modeling" OR "Habitat suitability modeling" OR "Ecological niche modeling") AND ("Bangladesh" OR "Bhutan" OR "India" OR "Nepal" OR "Pakistan" OR "Sri Lanka") AND ("English"). The initial search gave about 199 articles (on 1st January 2022).

FIGURE 1
Flow chart of search process.
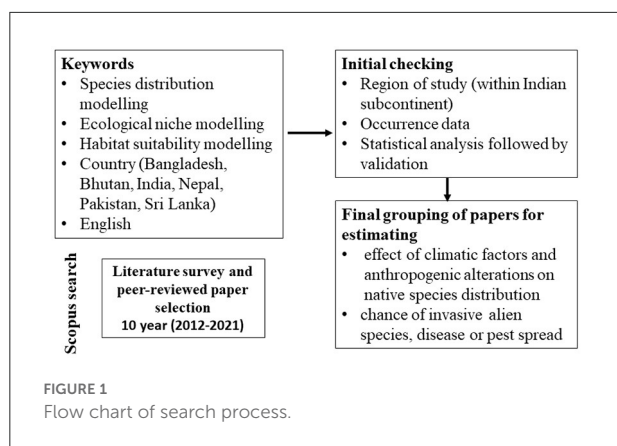
Secondly, the title and the abstract were thoroughly checked for all the articles from the initial list. For considering an appropriate paper for the review, three conditions were followed, (1) the region of the study was situated within the Indian subcontinent, (2) the occurrence data were the presence or abundance points of the selected species, and (3) relationship between species occurrence points with environmental data was estimated by any statistical method followed by a proper validation method. In this way, repeated or same literature and overwhelmingly non-relevant works were eliminated.

After an initial scan, 41 articles were eliminated before the following analysis. The complete reading of these articles showed that they were outside the selection criteria, or the full text was not accessible online. One hundred fifty-eight papers formed the basis of this analysis, and the extracted information included in our review is listed in Appendix 1. The search process is shown in Figure 1. From each paper, the following details were gathered: (1) name of the journal, (2) year of publication, (3) name of the focal taxa, (4) taxonomic details of the taxa, (5) region, (6) country, (7) scope or central objective of the study (e.g., keywords) (8) type of data used (species abundance, presence, or presence-absence), (9) statistical method, (10) the method of collection of occurrence coordinates (e.g., primary or other sources), (11) validation technique, (12) environmental layers used, and (13) name of the packages and software used. Based on that, the papers were grouped into three main categories. They were—(1) speciation or ancestral distribution estimation, (2) estimation of climate change effect and anthropogenic alterations on native species, and (3) determining the chance of invasive alien species, disease, or pest spread (Table 1). As the research objective of this study was to review the articles with an intention for the conservation-related recommendations and their applications in the Indian subcontinent, only the last two topics were elaborately discussed through case studies from the countries. For that, before analysis, two papers contributing

to understanding species' evolutionary aspects were eliminated from counting.

Generalized linear model, generalized boosted models, classification tree analysis, artificial neural networks, surface response envelope, flexible discriminant analysis, multivariate adaptive regression splines, random forest, and maximum entropy—were used as statistical algorithms in most of the articles. Occurrence data points were collected by field survey (e.g., observation, quadrat sampling, camera trapping etc.), followed by online data sources (e.g., iNaturalist, India biodiversity portal, Fish Base, literature, and herbarium survey etc.). In most cases, true skill statistic, Cohen's kappa, and area under the curve were used as the validation techniques. R (packages: Biomod2, Dismo, ENMeval, HMSC, mgcv, virtualspecies, ENMEval, spThin, usdm, BiodiversityR, AdehabitatHS etc.), DIVA-GIS, QGIS, and ArcGIS software were used for analysis.

Data analysis

Among 156 research papers, some described the species distribution patterns in the entire world, including the Indian subcontinent ($n = 11$) (Ranjitkar et al., 2014; Ashraf et al., 2018). Apart from that, most of the research works were from India, followed by Nepal, Sri Lanka, Pakistan, Bangladesh, Bhutan, and Myanmar (Figure 2). The majority of the works were focused on predicting the potential distribution of species, habitat loss in future climatic scenarios, estimating future range shifts, and providing valuable suggestions for monitoring species conservation ($n = 119$, 82%). The research papers predicting the invasion of alien species in the native ecosystem and disease spread together were 26 in no (18%) (Figure 3).

Studies on plant species distribution patterns

Among the 156 research papers, the works on plant species distribution were 84 in number, among which research on native plants species distribution was higher (e.g., sal, Himalayan alder, Himalayan rhubarb, Himalayan birch, chir pine, garjan, teak, olive, sandalwood, kamala tree, coffee, rubber, wild strawberry, potato, wheat, maize, wild rice, wild banana, kalmegh etc.; $n = 67$) than the invasive alien plants (e.g., sage, mesquite, common water hyacinth, kariba weed, billygoat weed, bitter vine etc.; $n = 17$). Investigations were also done for understanding fungi (e.g., Chinese caterpillar fungus; $n = 2$), lichen ($n = 1$), phytoplankton ($n = 1$), and macrofungi ($n = 1$) distribution pattern.

TABLE 1 Classification of study topics, including sample references from each country (if available).

Study topic	Description	Example references used for case studies	
Effect of climatic factors and anthropogenic alterations on native species	Potential distribution, habitat loss or future range shift, species conservation, inputs for monitoring the future spatio-temporal changes	Bangladesh	Islam et al., 2020
		India	Adhikari et al., 2018; Chatterjee et al., 2020; Ganesh et al., 2020; Ramachandran et al., 2020; Jha and Jha, 2021; Roy et al., 2021b; Srinivasulu et al., 2021
		Myanmar	Meetei et al., 2018
		Nepal	Rana et al., 2018; An et al., 2021
		Pakistan	Khanum et al., 2013; Escobar et al., 2015
		Sri Lanka	Ratnayake et al., 2019; Rupasinghe et al., 2021
Invasive alien species and spread of disease	Spread of invasive species and alteration of natural ecosystem, spread of deadly diseases and pests (e.g., nipah virus, dengue)	Bangladesh	Hahn et al., 2014
		Bhutan	Thiney et al., 2019
		India	Panda et al., 2018; Choudhary et al., 2019
		Nepal	Shrestha and Shrestha, 2019; Adhikari et al., 2020
		Pakistan	Ahmad et al., 2020

These categories emerged from the 158 publications located during the Scopus literature review.

FIGURE 2
Indian subcontinental countries that contributed research articles on distribution modeling (2012−2021 in Scopus) are highlighted on the world map.
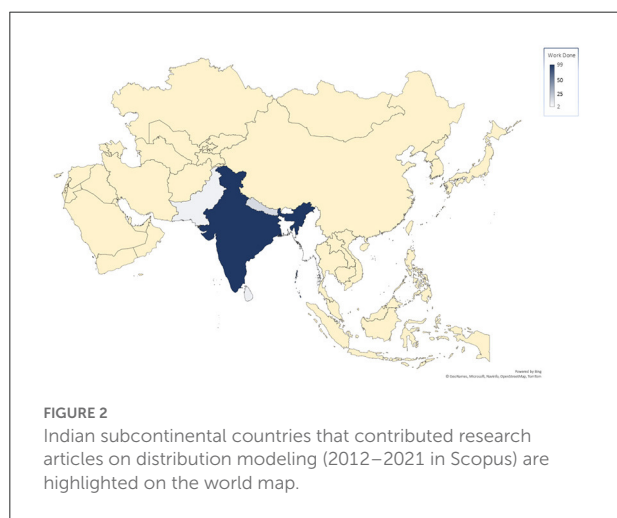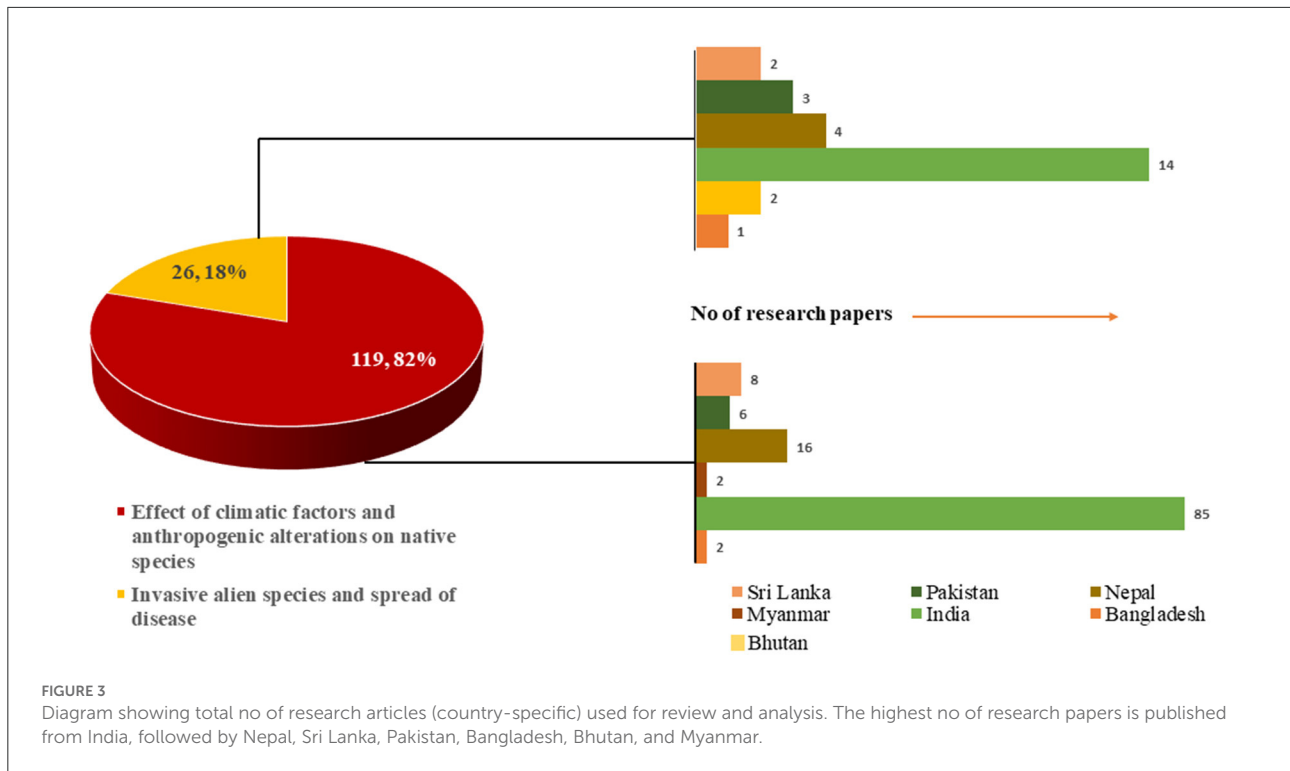
Studies on animal species distribution patterns

Research works describing the patterns of aniaml distribution was total 67 in number, among which research on mammal was highest in no (e.g., Bengal tigers, greater one-horned rhinoceros, Asiatic black bear, red panda, bat, sangai, Himalayan brown bear, Asiatic wildcat, jungle cat, Indian fox, golden-jackal, leopard, Malayan giant squirrel, brown mongoose, Himalayan Langur, desert hamster, Royle's

pika, Asian elephants, Assamese macaque, Asiatic black bear, Kashmir musk deer, and Gaur; $n = 28$), followed by birds (e.g., frogmouth, Nilgiri flycatcher, tree-nesting colonial waterbirds, wooly-necked stork, vulture, cotton pygmy goose, red-crested pochard, Indian peafowl, Western tragopan, great Indian bustard, forest owlet etc.; $n = 13$), insects (e.g., screwworm, desert locust, *Aedes* mosquito, guava fruit fly etc.; $n = 8$), reptiles (e.g., Himalayan pit viper, mountain pit viper, king cobra, monocled cobra, short-tailed ground agama, Indian skink etc.; $n = 6$), amphibia (e.g., Sri Lankan torrent toads, rock toad, Kirtisinghe's rock frog, and Gannoruwa shrub frog; $n = 4$), fish (e.g., snow trout, mola, and copper mahseer; $n = 3$), mollusca (e.g., giant African land snail etc.; $n = 3$), nematoda ($n = 1$), and benthic invertebrates ($n = 1$).

Case studies on the effect of climatic factors and anthropogenic alterations on native species

Some important studies were described as case studies to discuss species conservation status, future needs for protection and sustainable management in their native countries. The case studies, if available, were selected from each country and divided into two sections—one explaining the native plant species distribution and the other one about native animal species distribution. As India has contributed a significant number of research articles ($n = 85$) on the study topics, examples

FIGURE 3
Diagram showing total no of research articles (country-specific) used for review and analysis. The highest no of research papers is published from India, followed by Nepal, Sri Lanka, Pakistan, Bangladesh, Bhutan, and Myanmar.

were carefully selected from available documents based on the scientific importance of the focal taxa and modeling technique. For plant species distribution, one example was from Northeast India, the Himalayas, and Jammu and Kashmir region, and another was from the Eastern Ghats region. For animal species, one example from each vertebrate taxa (e.g., fish, amphibia, reptilia, bird, mammal) was selected.

Plant species distribution

Country—Bangladesh

(I) Species: Garjan, *Dipterocarpus turbinatus*.

Study predicting species range shift in changing climate.

Bangladesh is vulnerable to climate change for its geographic location (MOEF, 2008). Climate change causes changes in the tree phenology, forest cover and spatial distribution. *Dipterocarpus turbinatus*, locally known as Garjan, is one of the evergreen tree species which is globally valuable as well as vulnerable. It is native to the countries like Bangladesh, India, Myanmar, and Sri Lanka. Garjan forests are one of the vital shelters for threatened native wildlife species. Garjan requires a mean annual temperature range of 6–45°C and an annual rainfall range of about 2,000–4,000 mm for proper growth. Although valuable, the population seemed to have a declining trend due to land cover land-use change, forest fragmentation, illegal felling, improper management, and species invasion (Islam et al., 2001; Biswas and Misbahuzzaman, 2008; Ashton and Kettle, 2012). Islam et al. (2020) conducted SDM to

predict species' future range shifts in Bangladesh. The prediction indicated that the habitat would shift toward the south-eastern corner of the country, which has a comparatively high altitude. The annual temperature range would be the most significant bioclimatic variable. *D. turbinatus* might become extinct in the north-eastern parts of the country due to increased stress in future.

Country—India

(II) Species: native tree, herb, and pteridophyte species in Northeast India, Western and Eastern Himalaya, and Jammu and Kashmir.

Study for improving threat assessment and categorization process.

The pre-requisite for conservation planning is prioritizing species conservation through threat assessment. Adhikari et al. (2018) assessed the conservation status of five trees, eight herbs, and one pteridophyte (e.g., *Acer hookeri, Angelica glauca, Angiopteris evecta, Aquilegia nivalis, Bhesa robusta, Begonia satrapis, Corydalis cashmeriana, Gynocardia odorata, Ilex venulose, Lagerstroemia minuticarpa, Rheum austral* etc.) species in Northeast India, Western and Eastern Himalaya, and Jammu and Kashmir. They utilized the potential distribution prediction maps of ENM as a tool to guide surveys responsible for the discovery of new populations of threatened species. It was further used to improve threat assessment and for categorization. The species status based on this study showed that all species fell under the critically endangered and

endangered category. For example, *B. robusta,* earlier, was classified as least concerned, fell into the critically endangered conservation category.

(III) Species: rare, endangered, and threatened plant species (RET) and endemic species of conservation value in the Eastern Ghats.

Study predicting the future of range-restricted species.

Intense deforestation in the Eastern Ghats over decades has affected its rich and unique species diversity (Balaguru et al., 2006; Ramachandran et al., 2018). Its "broken-chain topography" further enhances the chance for this region to be overexploited and degraded. Although, very few studies are available for the region that analyse the climate and land use land cover (LULC) change aspects (Remya et al., 2015). Ramachandran et al. (2020) studied that aspect by using SDM. The suitable habitats for a group of endemics (28 in no) and RET (22 in no) species were stimulated for 2050 and 2070 in the Eastern Ghats region. From the model result, the bioclimatic variables like the mean temperature of wettest quarter, isothermality, precipitation of wettest, coldest and warmest quarter, and annual precipitation were found to have a significant percentage of influence on endemic species distribution. Similarly, RET species were mainly dependent on climatic factors like rainfall and LULC and geographic factors like slope. Most suitable habitats for the future occurrence of the endemic and RET species would be available in the core forest areas and high-elevation areas of less disturbance. However, the restricted distribution of these species' groups might increase their chances of future extinction.

Country—Nepal

(IV) Species: Himalayan alder, *Alnus nepalensis* and *Alnus nitida.*

Study for recommending conservation area for an alder tree-based agroforestry system development.

Himalayan alder species are ecologically important nitrogen-fixing trees helpful both in traditional or contemporary agroforestry practice and sloping land restoration (Sharma et al., 2007). Therefore, understanding their distribution and potential plantation zones could be helpful for the agroforestry sector. Rana et al. (2018) modeled habitat suitability for identifying the climatic zones of *Alnus nepalensis* and *Alnus nitida.* The model result indicated that the most favorable condition for *A. nepalensis* persistence was in the moist northwest-facing slope of central Nepal, whereas for *A. nitida,* it was in western Nepal. The major environmental factors contributing to *Alnus* distribution were precipitation of the warmest quarter (*A. nepalensis)* and precipitation of the driest quarter (*A. nitida).*

Further, future climatic forecast indicated significant changes in the potential distribution of both species by 2050; there would be expansions and reductions in suitability. *A. nepalensis* population would decline, whereas *A. nitida* population would secure suitability toward the northeast. In addition to climate, mountains and increasing elevation

in northern aspect of the country create an obstacle for *A. nepalensis* seed dispersal and their establishment (Salick et al., 2009). In such cases, *A. nitida* could be an alternative. It would be advantageous in the future first to check the compatibility between cardamom or tea plantation and *Alnus* and then establish this nitrogen-fixing, rare shade tree for the agroforestry systems in a stable area. The potentially suitable area predicted by the model could finally be designated as the conservation area for recommending an alder tree-oriented agroforestry system.

Country—Pakistan

(V) Species: Asclepiads.

Study predicting the range shrinks of medicinally important Asclepiads distribution.

Khanum et al. (2013) modeled the distribution of three medicinally important Asclepiads, namely *Tylophora hirsuta, Pentatropis spiralis,* and *Vincetoxicum arnottianum,* in future climate change scenarios. The Indian subcontinent, especially India and Pakistan, is a secondary center for Asclepiad's diversity. Asclepiads are highly dependent on the local climate. Model prediction showed that the precipitation variables mainly affected the current distributions of *P. spiralis* and *V. arnottianum,* whereas temperature regulated *T. hirsuta* distribution. Overall modeling results suggested that the future distribution of medicinal plants might decrease under future climate change scenarios, resulting in local extinction. Habitat loss risk would be greatest for *T. hirsuta,* followed by *P. spiralis* and *V. arnottianum.* Range expansions in the case of *V. arnottianum* and *T. hirsute* could be seen toward the comparatively higher peak of the country, which might be accelerated through adaptations.

Country—Sri Lanka

(VI) Species: Neglected and Underutilized Fruit Species (NUFS).

Study for understanding the future challenges of global food security.

More than 60 varieties of NUFS grow in Sri Lanka (Haq, 2002). NUFS are a vital source of local food which contributes to nutrition security, traditional medicine, and the country's economy. Ratnayake et al. (2019) modeled the potential areas for four popular NUFS, namely *Aegle marmelos, Annona muricata, Tamarindus indica,* and *Limonia acidissima* occurrence under future and current climatic scenarios. Understanding their spatial distribution is required to deal with the cultivation success and future global food security challenges (Delêtre et al., 2012). Results suggested that soil contributed most significantly to *A. muricata* and *L. acidissima* distributions, whereas the minimum temperature of the coldest month and precipitation of the driest month for *T. indica* and *A. marmelos* distribution, respectively. The suitable area laid mainly around Kandy, Kalutara, Kurunegala, Gampaha, and Kegalle districts. Overall, all four NUFS were expected to decrease by more than 40% in future and would confine to wet zone regions, thus suggesting the requirement of immediate management concerns.

Animal species distribution

Country—India

(I) Species: least concerned small indigenous freshwater fish *Amblypharyngodon mola.*

Study for identifying indicator variables regulating indigenous fish distribution.

Amblypharyngodon mola is one of the important members of small indigenous freshwater fish species (SIF) and belongs to the family Cyprinidae (Dubey et al., 2014; Ahamed et al., 2017). Although their current IUCN status is least concerned, they are facing today risk of extinction due to negligence. They often remain unnoticed under the species of high economic value. The potential suitability areas of *A. mola* were predicted in the current climatic situation by Roy et al. (2021b). Variations of annual upstream precipitation, mean upstream temperature of the driest quarter and soil pH in water across elevational gradients determine fish distribution patterns. Clear zonation was found to be present between highly suitable and other categories. Assam, Bangladesh, Kerala, Tripura, West Bengal, and eastern coastal parts of Orissa were predicted to have optimal conditions. Despite high freshwater fish species richness, the Ganges delta and plain ecoregion are most vulnerable in the World. The delta is facing extensive threats due to the high converted land percentage, sea-level rise, human footprint, large cities and megacities, lesser urban land cover, surface water consumption, irrigation together with issues of climatic disasters (Abell et al., 2008).

(II) Species: endemic rock toad *Duttaphrynus hololius.*

Study for covering lacunae of data deficient species distribution.

The rock toad (Günther, 1876)[1] is a data-deficient and uncommon species endemic to the Deccan plateau. The new modeling and analyses by Ganesh et al. (2020) produced a better and more clarified picture of its distribution. The map showed higher probabilities of occurrence (about 77–92%), notably in the Mysore plateau, which is further surrounded by low probability zones (about 23–31%) of south Cauvery and north Penner Rivers. Despite being hilly, the Western Ghats region was projected to be a totally unsuitable zone. Altogether, the new information on the occurrence and range projections covered some lacunae on the only probable amphibian endemic to the Indian peninsula's dry zone.

(III) Species: endemic threatened squamates.

Study for investigating the future distribution and recommending conservation area network.

Squamates are one of the most environmentally sensitive species. Srinivasulu et al. (2021) have modeled 22 threatened and endemic squamates distribution in the Western Ghat hotspot. For the study, the nine terrestrial ecoregions of the Western Ghats were considered—the Deccan thorn scrub forests, Malabar coast moist forests, Khathiar-Gir dry deciduous forests,

Narmada Valley dry deciduous forests, North Western Ghats montane rainforests, North Western Ghats moist deciduous forests, South Western Ghats moist deciduous forests, South Western Ghats montane rainforests, and South Deccan Plateau dry deciduous forests (Olson et al., 2001).

A decrease in climatically suitable areas in future for the majority of the studied species was observed. The greatest declines were predicted for *Eurylepis poonaensis* (97.9%), followed by *Cnemaspis indica* (85.92%). There was no significant relationship between trends in suitable climatically areas and taxonomic groups. Temperature seasonality had the maximum contribution across all species. The South Western Ghats montane forest and the Malabar coast moist forest had optimal conditions for becoming diversity hotspots. In changing climatic scenarios, hotspots of species diversity were predicted to be condensed in the southern and north-central Western Ghats. The final recommendation of the analysis was to develop a conservation area network which has 97 clusters (for 10% target species representation) with an area of ∼21,442 sq km.

(IV) Species: extinction-prone vulture population.

Study on the future distribution of the resident and migratory population.

Vultures are obligate scavengers and one of the most extinction-prone bird groups in the world (Sekercioglu et al., 2004; Straub et al., 2015; Phipps et al., 2017; Anoop et al., 2020). In India, there are nine old world vultures; most belong to the critically endangered and endangered category. The Gangetic-Thar-Deccan region (GTDR, administrative units are Uttar Pradesh, Rajasthan, and Madhya Pradesh) in India supports the bulk of the migratory and resident populations (Jha, 2018).

Jha and Jha (2021) have done species distribution modeling to estimate the current range of their habitat, predict potential future habitat, identify the vulnerable areas and finally find out a variation in global and local scale modeling results. First, the vulture occurrences were grouped according to the Forest Department's management strategy. Global and local species distribution models were generated to compare and analyse the difference in habitat suitability. The local models were developed separately for each individual region. Bioclimatic (temperature and precipitation variables) and bioenvironmental (climatic, LULC, human Footprint, normalized differential vegetation index, aspect, and elevation variables) models were generated globally as well as locally. The significant bioclimatic environmental variables were the mean diurnal range of temperature (6.55–18.50°C), temperature seasonality (361.67–818.56°C), isothermality (36.16–54.29°C), annual precipitation (104–2,124 mm), precipitation of the driest month (0–12 mm) and the precipitation seasonality (103.61–175.05 mm).

For the future, the top climatic factors that contributed significantly to the distribution of all vultures were isothermality, temperature seasonality, annual precipitation, precipitation seasonality, precipitation of driest month, and warmest quarter. For the resident vultures, these were isothermality,

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1 https://indiabiodiversity.org/observation/show/358366

precipitation and temperature seasonality, annual precipitation, precipitation of driest month, and warmest quarter. Lastly, for the migrants, these variables were annual precipitation, isothermality, precipitation of the warmest quarter, mean diurnal range temperature, and precipitation seasonality. The unsuitable area of all vultures would increase in future for a moderate emission scenario.

(V) Species: near-threatened Malayan giant squirrel, *Ratufa bicolor*.

Study predicting the future habitat loss.

Malayan giant squirrel *Ratufa bicolor* is an arboreal, diurnal, herbivorous, and near-threatened rodent species found mainly in the semi-evergreen and evergreen forest areas of north-eastern India. They are known as the indicator species for forest health and habitat quality (Koprowski and Nandini, 2008; Bahuguna and Singh, 2013). Along with climatic and anthropogenic factors, the long generation length (between 8 and 9 years) has put the species in more vulnerable conditions. Chatterjee et al. (2020) have studied the factors governing their distribution within India and modeled the suitable existing areas for occurrence and vulnerability.

Precipitation of wettest month was found to have the highest power for predicting the distribution at the current time, along with elevation, LULC, and vegetation pattern. Among different LULC and vegetation patterns, most of the species' occurrences were found in the tropical semi-evergreen, tropical moist deciduous, and subtropical evergreen forests. More than 33% of occurrences were between 1,001 to 1,500 m elevation. In future, precipitation of wettest month would contribute to maximum species distribution, followed by the mean temperature of warmest quarter and the precipitation seasonality. With changing climate by 2050, it was predicted that only 2.94% area of its distribution range would remain stable, and the other 97.1% would become unfavorable. By this way, species' suitable habitat would vanish by more than 90%.

Country—Myanmar

(VI) Species: *Ptyas doriae*.

Study on species potential distribution.

Meetei et al. (2018) analyzed *Ptyas doriae* distribution to determine the Grinnellian niche. The result predicted a larger section in Southeast Asia, including parts of north-eastern India, China, northern Myanmar, Laos, Thailand, and Vietnam, had an optimal suitable climate for this species persistence. The variable contributing the highest influence in determining their distribution was the precipitation of the warmest quarter. The summer months might be essential for the maintenance of forest covers, which could act as an important determinant of distribution.

Country—Nepal

(VII) Species: Bengal tiger, *Panthera tigris*.

Study on sex-specific distribution models for more informative trail maps.

Tigers are one of the iconic species among the 31 largest and globally important mammalian carnivores. They are sparsely distributed across the Asia (Ripple et al., 2016). Despite that, fewer than 4,000 animals are living in the wild, and inhabiting <7% of their past geographic range (WWF, 2016). Range restrictions of the species are primarily because of human activities and development, prey depletion, hunting, and illegal killing. An et al. (2021) generated sex-specific distribution models for Bengal tigers using two analytical frameworks for more informative and detailed maps based on camera trapping data within Chitwan National Park in Nepal and its surrounding zones.

Results of MaxEnt analysis suggested that about 8% area fell under the least suitable category and about 85% for moderately suitable habitats. The suitable and highly suitable classes accounted for about 7%. Lowland floodplains had the highest suitable area, while most of the regions of Churia hills had moderately suitable areas. For female tigers, prey abundance and sal forest cover percentage were most influential, contributing 35 and 31%, respectively. Female tigers had a more restricted range of suitable habitats. Results also indicated differences between male and female tigers with respect to the proximity to human settlements. Male tigers were found less averse to human settlements suggesting probable concerns for tiger conservation at the social and ecological intersection.

Country—Pakistan

(VIII) Species: Asian black bear, *Ursus thibetanus*.

Study on the species distribution with night time satellite imagery.

The Asian black bear is a red-listed species of broad geographic range, preferring highland areas of low temperature and high precipitation, which has been fragmented today drastically by land use change (Servheen, 1990; Garshelis and Steinmetz, 2008). Despite several protection plans at the international and national level, their population are declining rapidly, mainly due to competition for resources and human-bear conflicts. According to the IUCN (2014) map, *U. thibetanus* occurs in restricted areas of Pakistan, northern parts of Nepal, and India (e.g., Himachal Pradesh, Uttarakhand, Assam, Manipur, and Mizoram). Escobar et al. (2015) integrated ENM with night time satellite imagery for better and more reliable prediction. The night time light reflectance values were determined. The highest value attached to the bear occurrence tracks was the criterion to indicate the threshold, above which the species avoid artificial light. Based on overall results, the species was considered as a habitat generalist. Thus, threats to the conservation of *U. thibetanus* should be managed at fine geographic scales, e.g., in areas of low human disturbance and ideal environmental conditions.

Country—Sri Lanka

(IX) Species: endemic and endangered frog, *Pseudophilautus zorro*.

Study on the range-restricted distribution of the species.

The shrub frog *Pseudophilautus zorro* is an endemic, endangered, and range-restricted species which is found in Sri Lanka's central highlands. There is vast knowledge gap about the basic ecology of the species, which is critical for proposing conservation strategies. Rupasinghe et al. (2021) assessed the niche of the species to identify potential areas of occupancy and, after that, calculated the area of occupancy and the extent of occurrence. Kandy, Kegalle, and Matale districts in the Sabaragamuwa and Central zones had highly suitable regions. Mean diurnal range had the maximum contribution, followed by precipitation of the driest month and temperature seasonality. The reproduction and survival of *P. zorro* depend on leaf litter moisture. High environmental temperature thus increases evaporation from litter (Kreye et al., 2018), reducing species survival.

Case studies on invasive alien species and the spread of disease

Plant species distribution

Country—Bhutan

(I) Species: *Ageratum conyzoides, Aegratina adenophora, Chromolaena odorata, Mikania micrantha, Lantana camara,* and *Parthenium hysterophorus.*

Study on alien invasive weeds distribution.

Thiney et al. (2019) studied the distributions of six globally noxious alien species in Bhutan. The study proved that even the mountain environment, despite its barriers of sharp slopes, limited niches, and harsh climate, was threatened by invasion in the changing environmental conditions. The study tested the hypothesis that the invasive species were highly resilient to various environmental conditions, e.g., a topographically variable landscape or highly heterogeneous ecoregions. Results suggested that there would be a significant increase in invasion regions during future climate scenarios, except for *P. hysterophorus*. It would experience a northerly shift and decrease in extent. Among the six studied species, *C. odorata* might become widespread over time. Despite that, most species would have restricted expansion to the country's southern region.

Country—India

(II) Species: *Cassia tora* and *Lantana camara.*

Study on the distribution of invasive annual and perennial species.

The species-specific invasive potentials of *Cassia tora* (Fabaceae) and *Lantana camara* (Verbenaceae) in climate-changing scenarios were studied by Panda et al. (2018). These two species have different patterns of the life cycle (annual and perennial, respectively), but the similar origin and life forms. *C. tora* is native to eastwards Polynesia (Singh, 1968), and *L. camara* is native to South and Central America (Day et al., 2003). They are familiar weeds in the jhum fallows and dry forests in India (Sharma et al., 2005). These alien species together increase

native ecosystem vulnerability to climatic stressors (Vitousek, 1986; Burgiel and Muir, 2010).

Species with different phenological cycles (e.g., perennial or annual) use resources differently. Perennials need resources throughout the year, whereas annuals are during each growing season (Leffler and Ryel, 2012). The modeling result indicated that distributions of both species were significantly related to solar radiation of the warmest and wettest quarter. Radiation of the wettest quarter and the mean diurnal temperature range were highly correlated to *L. camara* distribution, compared with *C. tora*. Irradiative surfaces, open spaces, deforestation, fire, and agriculture could further help to establish invasive species (O'Donnell and Ignizio, 2012).

In future, precipitation seasonality would significantly contribute to *C. tora* distribution. Precipitation variations had negative effect on *L. camara* but positive impact on *C. tora.* There are chances that Central India might be most suitable for *C. tora* occurrence in changing climate scenarios. On the contrary, *L. camara* was found to have comparatively more colonizing capacity due to its higher seed dormancy and yielding capability. For that, the potential of *L. camara* invasion of the Western Himalayas and the Western Ghats would be higher.

Country—Nepal

(III) Species: 24 invasive alien plants.

Study for highlighting geographic hotspots of invasion.

Shrestha and Shrestha (2019) conducted ensemble species distribution models to predict the potential regions suitable for the 24 selected invasive alien species (IAPs) in future (2050 for RCP 6) and current climate change scenarios. The geographic hotspots of invasion were highlighted after considering climatic zones, physiography, land cover, and federal states. A much higher degree of overlapping area would be between invasion hotspots and agricultural lands/forests. The maximum invasion hotspots were predicted in the Terai-Duar savanna and grasslands' tropical zone (situated below 1,000 m). In the current climatic situation, no potential invasion hotspots were predicted in the subalpine region (3,000–4,000 m). But the hotspots could expand toward higher elevations areas of temperate and subalpine zones in the future. The analysis result thus highlighted the need to integrate biological invasions into subtropical climatic country Nepal's climate change policies, especially in the case of the Himalayas.

Animal species distribution

Country—Bangladesh

(I) Species: threatened bat *Pteropus giganteus.*

Study on the relationship between *Pteropus giganteus* roosts and human Nipah virus spread.

Hahn et al. (2014) analyzed threatened bat *Pteropus giganteus* roosts characteristics and developed an ecological niche model for identifying suitable habitat in Bangladesh and their association with human Nipah virus cases. Bat habitat range is primarily disturbed due to habitat loss, hunting and

deforestation in Bangladesh. Additionally, the misconception about *P. giganteus* that it is a pest and animal reservoir of the deadly Nipah virus creates a clash between its conservation initiative and public health. Results indicated that human population and road density were significant predictors in the ENM. It was identified by modeling that 2–17% of the land area was suitable for roosting. The species' habitat preference is dependent upon the characteristics of trees, percentage of forest fragmentation, level of human disturbance (e.g., human population density, distance to roads), annual precipitation and elevation. It was concluded that the primary agricultural practices facilitated the deleterious effects. To prevent the spread of zoonotic diseases, one must improve basic knowledge about the *Pteropus* species' life history and resource utilization patterns.

Country—India

(II) Species: guava fruit fly, *Bactrocera correcta.*

Study on the infestation by the polyphagous pest.

Bactrocera correcta is a polyphagous fruit fly of the Tephritidae family, predominant in tropical and subtropical areas. Choudhary et al. (2019) predicted the habitat suitability of the species in future climate change scenarios (2050 and 2070) in India. The significant variables for the species distribution were precipitation of driest month, temperature seasonality and annual precipitation. Under future and present climate change conditions, a highly suitable area would be in the coastal parts of Gujarat, Karnataka, Kerala, Tamilnadu, and Maharashtra (>0.6). In contrast, the majority of the area of central India (Madhya Pradesh, Odisha, Chhattisgarh, and Rajasthan) would be with low to mild infestation. Overall, the model projected a shift in species distribution and suitability by the end of this century.

Country—Nepal

(III) Species: giant African land snail (GALS), *Achatina fulica.*

Study on distribution patterns of the world's worst alien invasive species.

GALS is one of the world's worst alien invasive species (Lowe et al., 2000), posing threats to native biodiversity and humans by causing economic loss (Budha, 2015). Their increased colonization and associated risks are primarily accelerating due to anthropogenic disturbances, including the extension and expansion of roads (Pimentel et al., 2001). The transporting materials of the vehicles have caused the introduction of this alien species in new areas. Adhikari et al. (2020) modeled the distribution of GALS and identified that the distance to the nearest road (35%) had the greatest percentage contribution, followed by mean temperature of driest quarter (33%), and annual precipitation (10%). The probability of GALS' presence was higher near the road, within about 900 m of roads. The result indicated potential risks of GALS on agricultural production in the lowlands, which serve as the rice bowl of Nepal.

Country—Pakistan

(IV) Species: *Aedes albopictus* and *Aedes aegypti.*

Study on mosquito distribution and dengue prevalence by geostatistical model.

Aedes albopictus and *Aedes aegpti* are two known mosquito species and dengue vectors (Akiner et al., 2016). There are numerous efforts made by the government and healthcare bodies, but it is still challenging to control the epidemic (Kannan et al., 2019). Determining the effects of climate change on future distributions of the mosquitoes can provide a visual insight into their distribution which would be helpful in understanding and controlling the epidemic (Campbell et al., 2015). Ahmad et al. (2020) performed a geostatistical analysis of the dengue fever risk in Khyber Pakhtunkhwa and estimated the maps after incorporating associated uncertainty. Geostatistical models can quantify the prediction probabilities and uncertainties in rate evaluations without any higher computational load and reduce the noise of the dataset (Hampton et al., 2011). One of the methods used in the study was the binomial Kriging method. The Maxent analysis showed that human density and distance to roads were the most critical factors for dengue infections.

Discussion

The highlighted case studies described the urgent need for species conservation in each country. Asia's remarkable economic growth brought many benefits through income and employment but fuelled threats to its biodiversity and ecosystems through habitat degradation (Squires, 2013). Economic interests are preferred over environmental concerns in Asia. That is obvious from the rising social-cost bill or stated in the "Asia and the Pacific SDG Progress Report 2020" (Yorifuji et al., 2015; United Nations Economic Social Commission for Asia and the Pacific, 2020). The variables, e. g., non-renewable energy usage, per capita income, fertility rate, urbanization, and population density, are some crucial drivers that affected the ecological footprint in the eight Asian developing countries from 1990 to 2015 (Sharma et al., 2020). The re-evaluation of the existing policies on the environment and economy is necessary for Asian countries as they struggle to achieve sustainable development goals.

Need for re-evaluation of existing policies and barriers to implementation

For developing proper climate change mitigation and adaptation, the conversion of suitable land for agricultural purposes must be estimated at the country level (Zabel et al., 2014). The fast-growing research on the farming domain in Asian countries has mainly concentrated on expanding agricultural lands by converting natural areas (Laurance et al., 2014; Chaplin-Kramer et al., 2015). Expansion poses

a substantial question of balance between food security and conservation of wildlife for governments (Horgan and Kudavidanage, 2020). Some Asian countries have introduced national agroforestry policies in recent years (India in 2014, followed by Nepal in 2019) (Chavan et al., 2015; Atreya et al., 2021). Agroforestry is generally associated together with the concepts of multifunctionality at the tree, field, landscape, and farm levels. Agroforests are an essential category of planted forests on crops or pastureland, which have the potential for providing a wide range of forest-related sustainable ecosystem services to human society (Noordwijk et al., 2003). The system can potentially enhance the resilience of smallholder farmers in the future (Lasco et al., 2014; Bettles et al., 2021).

Climate change can negatively impact agriculture and leads to circumstances of food insecurity at a global and regional level. For example, the agriculture sector of Pakistan accounts for about 19.5% of gross domestic product, where it employs about 42.3% of the labor force (Finance Division, 2018). Although, in the Global Food Security Index, the country ranks 77th (Khanum et al., 2013; World Bank, 2017; Ministry of National Food Security and Research, 2018). Agroforestry-based products have a significant potential for providing employment opportunities, improvements in soil, air and water quality, carbon storage, building materials, medicines as well as biodiversity benefits (Dhyani et al., 2005, 2007; Barrios et al., 2012; Duguma et al., 2019; Chapman et al., 2020; Bettles et al., 2021). It is an important topic now in global and national agendas considering sustainable development. It is internationally recognized as a climate-smart agricultural system by the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC) (Park et al., 2022).
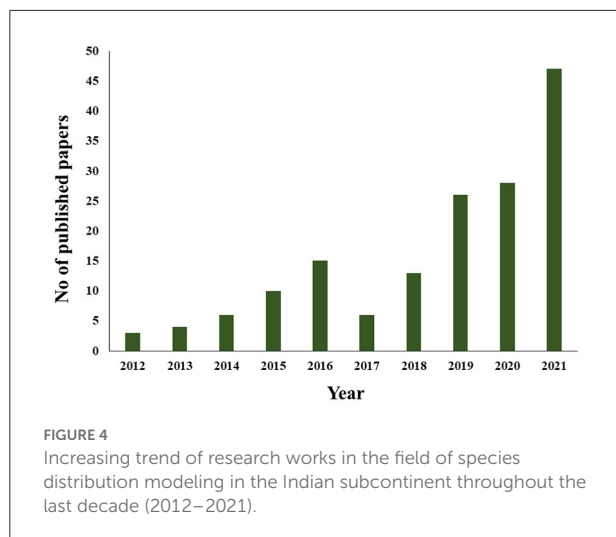
Although agroforests are less diverse than native forests, they contain numerous animal and plant species (Murdiyarso et al., 2002). They provide ecological resilience, relieve pressure on harvesting native forests and maintain beneficial ecological functions (Angelsen and Kaimowitz, 2001; Noordwijk et al., 2003). Rahman et al. (2021) assessed the effects of tree cover and its diversity on carbon storage in Bangladesh. Analysis indicated that tree diversity increased total carbon storage in home gardens representing a potential nature-based solution. Generally, the preferred species are namely Acacia, Ailanthus, Albizia, Bamboo, Casuarina, Eucalyptus, Gmelina, Kadam, Melia, Populus, Shisham, and Teak (Singh and Dhyani, 2014).

Agroforestry growth and development are influenced directly or indirectly by economic policies, e.g., credit, power, taxation, trade, transport etc. Despite all the benefits, there are constraints in implementing agroforestry system climate goals. There is a need for better coordination between the Center-State agriculture departments, agriculture and forest departments, research organizations, financial institutions, panchayats, NGOs, the corporate sectors, and farmers. A coordinating institute for support at the inter-ministerial level can help to undertake policy-related planning and execution decisions. The system is also limited due to the lack of technical and functional knowledge, lack of participation of people, absence of separate policy, and market development about the process. For instance, in India, after agriculture, the second largest land use sector is represented by forestry, although it contributes only about 1% of GDP, reflecting the inert potential of the industry (Singh and Dhyani, 2014; Park et al., 2022).

The re-evaluation of existing policies for diminishing the risks of invasive species is also crucial in this regard. The "Integrated Forest Management (IFM)" (2009) scheme, initiated by the Ministry of Environment, Forest, and Climate Change (MoEFCC) in India for eradicating and controlling the pest species in forested areas, failed primarily because of a lack of proper sustainable management (Kannan et al., 2013). Identification and implementation of the invasion pathways and the biosecurity measures are essential for policy formulation (Nuñez et al., 2020). Although stern trading policies frequently face strong objections due to their economic benefits. Additionally, the increasing tendency of invasive species denialism, absences from the quarantine lists and the unresolved conflict of interest among stakeholders become significant roadblocks in the decision-making process (Russell and Blackburn, 2017; Banerjee et al., 2021). The small farmers face high risk for species invasion and effects of climate change on horticulture and agriculture. So, there is an urgent need to study and estimate the invasion cost.

Climatic change, economic development, population growth, and related land use changes all together impact directly on another resource, the freshwater ecosystem (Immerzeel and Bierkens, 2012), which raises concerns for freshwater biodiversity. Worldwide lack of monitoring stations and water quality data, poor integration of existing remote sensing data into inland water sciences led toward decreased allocation of resources, weak management, and lack of coordination for conservation (Dube et al., 2015; Ross et al., 2019). Water security is hindered due to the lack of an integrated management plan among countries sharing river basins. There is also a need for range-wide environmental data of freshwater realms to quantify the correlation between occurrence and abiotic environment. Freshwater-specific datasets are often restricted to individual watersheds or a country. Additionally, the terrestrial environmental variables cannot well explain the directional flows of freshwater (Domisch et al., 2015). The spatial detail is thus crucial for determining the variability of physical and socio-economic phenomena at a finer scale and planning the hot spot areas for developments (Giupponi and Gain, 2016).

FIGURE 4
Increasing trend of research works in the field of species distribution modeling in the Indian subcontinent throughout the last decade (2012−2021).

Species distribution models as a cost-effective and sound tool for biodiversity conservation and sustainable management

SDM can be utilized as a sound and cost-efficient planning tool to critically assess biodiversity for sustainable development (Edenius and Mikusiński, 2006). SDM quantify species' functional niche at different spatial scales. Analysis and results can act as the spatial templates used to address population viability, the distribution range or habitat contraction of a species, and natural habitats for (re)introduction in climate change scenarios. The recent increasing trends in species distribution modeling works in ecology have supported this statement (Figure 4). Moderate to high suitability stable areas should be prioritized for conservation (Vaidyanathan, 2018). Prediction results can also be used as an easy warning system that identifies potential invasion areas, hence giving the early opportunity to prioritize the vulnerable region (Sarma et al., 2015). For instance, the dense forest canopy cover can be maintained, and continued plantation can be done to check the invasion of shadow-phobic species. Continuous uprooting of some weeds involving local people may help control their colonization (Panda et al., 2018). "A weed risk assessment protocol" could be included in the national policy framework to identify species' invasiveness and adaptability to climate change. Formulating legal provisions can engage landowners in ecosystem management actions. Shifting focus from alien to exclusively native species should be encouraged by promoting the businesses (Banerjee et al., 2021).

The niche models are species-specific and dynamic. So, there is need for updating the occurrence dataset after every field visit (Adhikari et al., 2018). This intensive field validation has to be continuously followed to offer the scope to improve the model prediction. Long-term conservation of biodiversity requires community-based management programs. The decision-makers and non-government organizations worldwide are using today's citizens to volunteer and enhance modeling ability and investigate the depleting natural resources, identify endangered species, and conserve protected areas (Conrad and Hilchey, 2011). Formulating sustainable plans and policies for future management would be good if focused beyond 50 years after identifying global and regional trends of conservation approach (Vaidyanathan, 2018).

Endemic, range-restricted, non-charismatic, and neglected species can be conserved through a protected area network (Abraham and Kelkar, 2012). These potential new conservation areas should be designated aiming toward higher species representation targets as an alternative to a flagship or umbrella species-based approach (Ratnayake et al., 2019; Roy et al., 2021a; Srinivasulu et al., 2021). A protected area can be defined as—"An area of land and/or sea especially dedicated to the protection and maintenance of biological diversity, and of natural and associated cultural resources, and managed through legal or other effective means" (IUCN, 1994)[2]. SDM prediction can provide knowledge about the long-term persistence of a protected species in future climatic scenarios (Roy et al., 2021b).

Combining climate with remote sensing data can further improve the predictive ability of the historical ranges of a species (e. g., models based on environmental plus night time light data). Night time light imagery is an excellent alternative for species' habitat range estimation, corridor and protected area designing, threatened species prioritization, policy implementation, and human-wildlife conflict area determination (Escobar et al., 2015). Further, the time window and the selection of the locations of allowed disruptive activities (i.e., film shooting or tourism) in protected areas need more scientific considerations to minimize the negative impacts of conflict. Like, identifying the difference between male and female carnivores' breeding habitat choices through SDM can provide essential insights into their preference (An et al., 2021).

Some shortcomings of the models and recommendations for improvement

SDMs predict species' geographic ranges with the assumption of the niche conservatism theory that niche changes very slowly across space and time to sustain their populations (Soberón and Nakamura, 2009; Wiens et al., 2010). Several transferred SDMs were generated by transferring the data obtained from one region to other areas or to another time (Jeschke and Strayer, 2008; Werkowska et al., 2017). The results of the studies are widely helpful in forecasting the possibility of distributions under past environmental conditions, disease breakout, and species responses to climate

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2   https://www.iucnredlist.org/ja/species/22824/166528664

change (Nogués-Bravo, 2009; Morán-Ordóñez et al., 2017; Yates et al., 2018). Although several recent studies reported that the range of species' niches changes rapidly when transported to a new geographic region (Broennimann et al., 2007; Pearman et al., 2008; Guisan et al., 2014; Atwater and Barney, 2021). So, understanding how the changed species-environment relationship affects the spatiotemporal transferability of SDMs is crucial for the future application of conservation design and improvement (Pearman et al., 2008; Petitpierre et al., 2017; Atwater and Barney, 2021). It is essential to consider data quality as well as niche change to improve the transferability of SDMs in the case of invasive species to support better conservation management and policy decisions (Liu et al., 2022). There is a need for an additional extended assessment of habitat suitability, especially for the range-shifting species, through an integrated SDM database (iSDMdb) (Frans et al., 2022).

A fundamental limitation of SDM is that they do not consider species interactions like competition or predation. It assumes that a species' existence depends only on abiotic factors (Peres-Neto and Legendre, 2010; Dormann et al., 2012; Wisz et al., 2013). The joint species distribution model (JSDM), a community-level and novel modeling framework, recently emerged as a promising technique to integrate the possibility of species interactions additionally into metacommunity and macroecology studies (Leibold et al., 2021; Pichler and Hartig, 2021). Model predictions can be applied to large-scale and regional metacommunity analyses (Gilbert and Bennett, 2010; Mittelbach and Schemske, 2015; Leibold and Chase, 2017). For instance, Zhang et al. (2020) found that community-level data improved the rare species' distributions to a certain extent.

One of the key assumptions of SDM is that species are at climatic equilibrium in their current distribution range. However, in reality, biotic interactions can prevent that through dispersal limitation or human disturbance, hence underestimating climatic tolerance (Hutchinson, 1957; Richmond et al., 2010). So, the model predictions relying on the climatic tolerance derived from unevenly sampled and biased species distributions have limited utility. One of the probable solutions could be to develop SDMs based on species' physiological tolerance data or growth requirement estimates (e.g., USDA PLANTS database). Considering species occurrences outside the natural range is needed to closely predict species' fundamental niche and range shifts in response to climate change. However, exhaustive field and lab work is essential to measure the tolerance limits (Booth et al., 2015; Curtis and Bradley, 2016).

For the accuracy of predictions and to maximize the performance of SDMs, selecting the most appropriate predictor variable is crucial (Araújo and Guisan, 2006; Braunisch et al., 2013; Barbet-Massin and Jetz, 2014). As expert knowledge is not much available, the choice of predictors remains a crucial question when executing SDMs. Another associated challenge of SDM is to unify multi-scale variables that may contribute to species distribution at different spatial resolutions. Species–environment relationships are strongly scale-dependent, and thus it reduces model accuracy and appropriateness for producing environmental suitability maps (Virkkala et al., 2005). Fournier et al. (2017) showed that after integrating multiple drivers, the modeling result had a smaller potential range of species than predicted using the climatic model alone, suggesting an overestimation.

Conclusion

Most of the works in the Indian subcontinent were focused on predicting native species' potential distribution, habitat loss, or future range shifts in changing climate ($n = 119$, 82%) rather than the invasion of alien species in the native ecosystem ($n = 26$, 18%) indicating the further scope of research in these areas. The scientific articles highlighted that modeling results could be utilized efficiently to design conservation areas like the native tree-based agroforestry system or protected area network for range-restricted, endemic, endangered, or threatened species to cope with the challenges of climate change scenarios. But analysis should not be biased toward charismatic species because that can affect the conservation-related decision-making process. Encouragement should be given to study the data-deficient species from molluscs, fish, amphibia, insects, lichen, fungi, or plankton. Modeling such species can help understand the future challenges of global food security and eradicating zoonotic disease spread. The population status of a species in the wild should be examined at regular intervals against the conservation criteria to understand how much native land is needed to control biodiversity loss and ecosystem functionality. Most importantly, the re-evaluation of existing policies and identification of geographic hotspots of invasion in subcontinental countries will be crucial to eradicate alien species infestation. A coordinating institute at the inter-ministerial level can help to undertake policy-related planning for sustainable management and execution of decisions.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SRo: conceptualization, data analysis, and writing—reviewing original draft. AS: data analysis and reviewing original draft. SRa: conceptualization, supervision, and resources. SS: supervision and resources. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsrma. 2022.1031646/full#supplementary-material

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