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Advancing research on alien species and biological invasions

Invasive alien plants in South Asia: Impacts and management

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Abstract

South Asia is home to an immense diversity of flora and fauna, which makes it one of the global biodiversity hotspots. Plant invasions are one of several factors that threaten South-Asian biodiversity. This review lists problematic invasive plant species, analyses their negative impacts, and summarises management methods implemented in South Asia using data obtained from research articles and relevant databases (CABI, GISD, GloNAF). The data was used to evaluate the research trends over time, knowledge of the impacts of invasive plants, and management measures aimed at the invasive species. In total, 392 currently invasive vascular plant species were recorded in South Asia. Of these, 41 species are widely distributed in South Asia, occurring in at least three countries, and 20 species that are listed as invasive in South-Asian countries by the book Invasive Plant Species of the World are considered as the most problematic. For a subset of the most problematic species where such information is available, we present management measures that are in place in individual countries. The number of studies on invasive species in South Asia has been increasing, with more than half (53%) represented by local and regional inventories. Among the countries in South Asia, India has the highest number of invasive (145) and naturalized plant species (471). However, the percentage contribution of invasive and naturalized species to the native flora is the highest in the Maldives Islands. Studies on impacts are limited to those on native plants and agriculture; there is a lack of research on impacts on ecosystems and hydrology, as well as on economic costs and human health. Moreover, impacts have been quantified for very few species. Currently, the management of invasive plants is mostly done by physical or mechanical methods; research into opportunities for biological control is inadequate. Our review highlights the urgent need to quantify the impacts of all prevalent and problematic invasive species in South Asia as a crucial step in allocating resources for their management and addressing the knowledge gap in this region.

Keywords
Biodiversity, biological control, invasions, inventories, naturalized species

Introduction

A species that is introduced outside of its native range due to intentional and unintentional human activity is considered an alien species (Richardson et al. 2000; Pyšek et al. 2004). Alien species creating self-sustaining populations in the invaded region are termed naturalized species, and a subset of naturalized species that rapidly spread in the invaded region from the site of its original introduction are considered invasive (Richardson et al. 2000; Pyšek et al. 2004; Blackburn et al. 2011). Some definitions consider only those alien species as invasive that have negative impacts on the environment (IUCN 2000). Invasive species grow fast, become widespread, form self-sustaining populations, produce large numbers of reproductive offspring, and can grow in a range of habitats, such as agricultural land, grassland, wasteland and other ruderal habitats, dry land, and riparian habitats (Chytrý et al. 2008, 2009; Patzelt et al. 2022; Pyšek et al. 2022).

Biological invasions are considered the fifth most important driver of global environmental change (IPBES 2019). Of the global plant species pool, ~14,000 taxa are known to have naturalized, i.e. ~4% of the world flora (van Kleunen et al. 2015, 2019), and ~2500 species are considered invasive (Pagad et al. 2018), with the Asteraceae family contributing the highest number of naturalized taxa (Pyšek et al. 2017). The number of invasive species has increased globally due to escalating international trade (Seebens et al. 2015). The highest numbers of invasive plant species are reported from California (USA), Cuba, Florida (USA), India, Japan, South Africa, and Queensland (Australia) (Pyšek et al. 2017). Many countries have databases of invasive alien plants, but still, there is a lack of comprehensive information, which hampers efforts to develop and implement the policies for effective management (van Kleunen et al. 2015).

The impacts of invasive species on ecosystems and the environment are well documented in Europe (Kumschick et al. 2015; Nentwig et al. 2018; Langmaier and Lapin 2020) and North America (Duenas et al. 2018) in the Northern hemisphere, and South Africa (van Wilgen et al. 2020; McGaw et al. 2022; Richardson et al. 2022), New Zealand (Brandt et al. 2021) and Australia in the Southern Hemisphere. In addition to this, several databases such as GISD (Global Invasive Species Database; www.iucngisd.org), GRIIS (Global Register of Introduced and Invasive Alien Species; www.griis.org; Pagad et al. 2018), CABI (Invasive Species Compendium; https://www.cabi.org/ISC), GloNAF (Global Naturalized Alien Flora; van Kleunen et al. 2015, 2019; Pyšek et al. 2017), and DAISIE (Delivering Alien Species Inventories for Europe) (DAISIE 2009; Hulme et al. 2010) provide data for particular regions, which could help with prioritization of problematic species in particular countries. However, there are geographical and taxonomical biases in invasion ecology (Pyšek et al. 2008, 2017).

South Asia includes eight countries: Afghanistan, Bangladesh, Bhutan, India, Pakistan, Maldives, Nepal, and Sri Lanka. It is surrounded by the Himalayas in the north and the Indian Ocean in the south. South Asia covers about 5.2 million km^2, which is about 11.7% of the Asian continent and 3.5% of the world's land surface area. The climate varies, ranging from tropical monsoon in the south to a temperate climate in the north. South Asia overlaps with three biodiversity hotspots (Himalaya, Indo-Burma, and Western Ghats – Sri Lanka), harbouring 15.5% of global floral diversity (http://www.sacep.org). Invasive plants threaten Himalayan biodiversity, which is exceptionally rich in terms of diversity and endemism (Kumar and Scheiter 2019; Gupta et al. 2021). Climate change and anthropogenic pressure increase the problems caused by invasive species in these pristine regions (Mungi et al. 2018). With increasing trade, travel, and tourism, this trend is unlikely to stop in the near future (Early et al. 2016), so monitoring biodiversity-rich areas is important to identify the status of invasive species and implement proper management.

The socioeconomic problems caused by plant invasions are escalating on all continents. The direct cost from damage by invasive species is thirteen times higher than that incurred by management (Diagne et al. 2021). An analysis between 1970 and 2017 showed that the minimum estimated cost of biological invasion worldwide to human societies was US$ 1.288 trillion (Diagne et al. 2021, but see Novoa et al. 2021). Economic costs due to biological invasions are comparably high in South Asia (US$ 185.8 billion; Liu et al. 2021), and agriculture is the most affected sector. These costs have increased markedly in the past decades and do not show any sign of slowing down. In India alone, the estimated economic cost is US$ 176.7 billion; for Bhutan, Maldives, Pakistan, and Sri Lanka, the cost is estimated to be less than US$ 15 billion. However, no cost estimation has been done for Nepal, Bangladesh, and Afghanistan (Diagne et al. 2021).

Despite many individual studies, a comprehensive overview of plant invasions and their impacts and management has been missing from South Asia (Early et al. 2016; Shrestha et al. 2022). Due to high population density and ongoing environmental changes, including biological invasions, biodiversity in South Asia is under threat (IPBES 2019). Managing invasive species without baseline data and knowledge of their introduction pathways is difficult. Thus, region-wise or country-wise, detailed, up-to-date inventories of alien species are urgently needed. There is still a gap in the availability of data on alien species distribution in Asia, which is a constraint to synthesizing global data and trends and prevents the development of management strategies (Shrestha et al. 2022). Understanding the current state of plant invasions in South Asia will help to suggest new approaches for effective management.

To bridge the knowledge gaps in this region, we (i) analysed the temporal trends in topics associated with alien species research in South Asia and (ii) compiled a checklist containing the total number of naturalized and invasive species for the region. Further,

(iii) for the widespread and most problematic invasive plants, we collated information on their impacts, types of invaded habitats, control methods being used, and management implemented in South-Asian countries. The information presented in this paper can be used to improve the management of invasive plants and prioritize the most pressing research areas in this region.

Methods

We searched research papers from Scopus, CABI, Web of Science, and Google Scholar, published from January 1977 to January 2022. The keywords used for the search were "invasive/alien/non-native/exotic, plant/flora/species" in the X where X is the name of a South-Asian country (Afghanistan, Bangladesh, Bhutan, India, Nepal, Maldives, Pakistan, and Sri Lanka). A total of 468 research papers were identified. Abstracts were scanned to select the relevant papers that were inspected in detail to determine whether they contained relevant data; 96 papers were excluded as being not peer-reviewed, reports, theses, conference proceedings, published in predatory journals, or otherwise irrelevant. The remaining 372 papers were used for the analysis (Supplementary Material 1). Based on the year of publication, the articles were used to evaluate the research trend over time and classified into seven research topics: allelopathy (chemical substances of invasive plants that affect other plants), climate change (its effects on the distribution of invasive species), species distribution (studies on spatial patterns of alien species), ecology (relationships between invasive species and its environment), impacts (evaluating the risk from invasion on native diversity and ecosystems), inventory (checklist and identification of species), and management (efforts made to limit the spread of invaders).

In addition to the literature review, databases such as GISD (Global Invasive Species Database; www.iucngisd.org), CABI Invasive Species Compendium; CABI 2022), GloNAF (Global Naturalized Alien Flora; van Kleunen et al. 2015, 2019; Pyšek et al. 2017) and GRIIS (Global Register of Introduced and Invasive Alien Species; www.griis.org; Pagad et al. 2018) were used to explore the status of invasive species in South-Asian countries. The numbers of naturalized and invasive species for individual countries were taken from GloNAF; for Bhutan, which was not included in GloNAF, we used other published information (Dorjee et al. 2020). As there is a large variation in the area of South-Asian countries, to make the numbers of species more comparable, we standardized the species number per log area.

The list of the most problematic invasive plants analysed here was based on the book "Invasive Plant Species of the World" (Weber 2017) and resulted from including all species that this book reports to occur as invasive in the South-Asian countries under study. Selecting the most problematic species with reference to one comprehensive source evaluating regional invasions by using comparable rigorous criteria (i.e. distribution and impact; Weber 2017) provides a balanced perspective of the current invasion load in South Asia and allows for assessing the threat from ongoing and future invasions in a broader view.

To determine the impacts of the most problematic invasive species, we used the following categories: impacts on plant diversity, soil, biodiversity, agriculture, socio-economy, health, hydrology, and livestock; the information on impacts was compiled from Weber (2017), CABI (2022) and Global Invasive Species Database (2022). For each species, we present, based on information available in the literature (Suppl. material 1), the overview of management measures that are used against them and in which countries.

We classified the most problematic invasive species according to the habitats in which they grow based on information from the same sources that were used to compile the list. We used the following habitat categories: Disturbed sites are abandoned sites or areas affected by anthropogenic activities, and riverine or riparian are the habitats in stream corridors. Grasslands include rangeland and pastures. Forest and forest edges represent closed canopy and open forest, respectively.

Results

Temporal trends in research on South Asia

Until 2000, studies on invasive alien plants were scarce in South Asia. Only after 2001 did the number of studies start to increase rapidly (Fig. 1), and this trend still holds for all categories of research. Most research (41% of studies) was focused on the inventories of invasive plants, followed by studies on impacts (18%) and distribution of alien species (16%) in South-Asian countries (Fig. 2). Among all countries in South Asia, India was the first to start research on alien trees and shrubs in 1983.

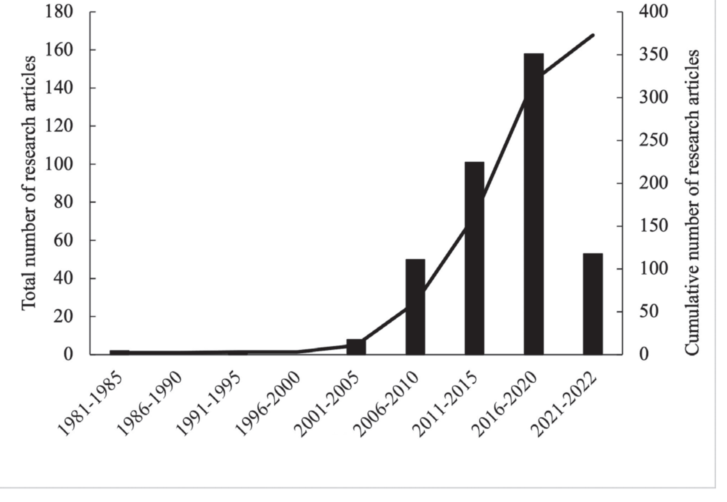

Figure 1. Numbers of research articles dealing with plant invasions in South-Asian countries in five-year periods and their cumulative number over the period of 1981–2022. See Suppl. material 1 for the articles on which the figure is based.

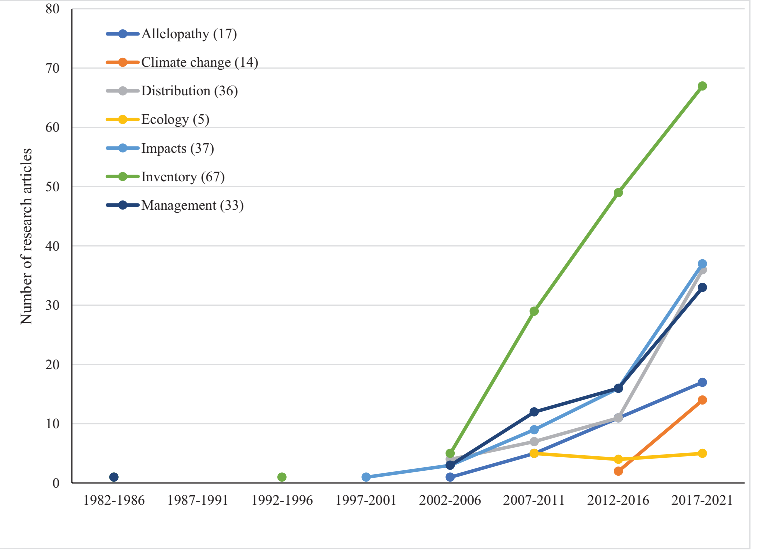

Figure 2. Number of articles addressing different research topics in South-Asian countries over time. See Suppl. material 1 for the articles on which the figure is based.

The majority of the studies addressing the consequences of plant invasions were focused on the impacts of invaders on native plant diversity (46% of the total number of articles dealing with impact), followed by studies on soils (17%), biodiversity on other trophic levels (15%), agriculture (14%), socioeconomic impacts (6%), and human health (3%). Except for soil studies, there is very little research regarding the impacts on ecosystems, including hydrology.

South-Asian naturalized and invasive plants: the numbers

We recorded 392 alien plant species that are invasive in South Asia. India harboured the highest number of invasive plant species (145), followed by Bhutan (101), Sri Lanka (94), Pakistan (73), Bangladesh (61), Maldives (38), Nepal (28), and Afghanistan (26). The numbers of naturalized species followed a similar pattern, with India (471), Pakistan (439), and Sri Lanka (401) harbouring the most. The ranking of countries shifted if species numbers per log area were taken as a measure, with India appearing the richest in invasive and Sri Lanka, Pakistan, and India in naturalized species (Table 1). Although India, which is the largest country in the studied regions in terms of area, harboured the highest numbers of invasive and naturalized plant species, Maldives had the highest percentages of these species in its flora. Due to the rich flora of South Asia, the percentage of naturalized plant species across the whole region was rather low, only 3.9% of the total flora. Afghanistan is the third largest country (after India and Pakistan), but the number of naturalized and invasive species recorded there was the lowest; however, this may be due to a lack of research. The total numbers of naturalized, invasive, and native species reported from the reviewed countries are shown in Table 1.

Table 1. The number of invasive species, naturalized species, and percentage of naturalized species in the total flora of South-Asian countries as recorded in the GloNAF database (van Kleunen et al. 2019) and updated by other sources. Normalized invasive species value is obtained by dividing the number of invasive species (S_{inv}) by the logarithm value of the country area and for the naturalized species as S_{nat}/logArea.

Country	Invasive no. (S_{inv})	Naturalized no. (S_{nat})	Native no.	Naturalized %	Area	Invasive per log area	Naturalized per log area
Afghanistan	26	96	5,000	1.9	652,230	4.5	16.5
Bangladesh	61	139	5,000	2.8	147,570	12.2	26.9
Bhutan	101[c]	204[c]	5,446	1.9	38,394	22.0	22.5
India	145[a]	471[b]	18,664	2.5	3,287,590	54.0	72.3
Maldives	38	167	277	60.3	300	15.3	67.4
Nepal	28[d]	182[d]	6,973	2.9	147,181	5.2	35.2
Pakistan	73	439	6,000	7.3	881,912	12.3	73.8
Sri Lanka	94	401	3,368	11.9	65,610	20.1	83.3
TOTAL	**392**						

[a]Modified from Khuroo et al. 2021; [b]Modified from Inderjit et al. 2018; [c]Modified from Dorjee et al. 2020; [d]Modified from Shrestha et al. 2021 and Adhikari et al. 2022

The relationships between the number of naturalized and native species (Fig. 3A) and the number of invasive and naturalized species (Fig. 3B) were not significant. The numbers of naturalized and invasive species on the mainland significantly increased with the increasing area of the country (Fig. 3C, D).

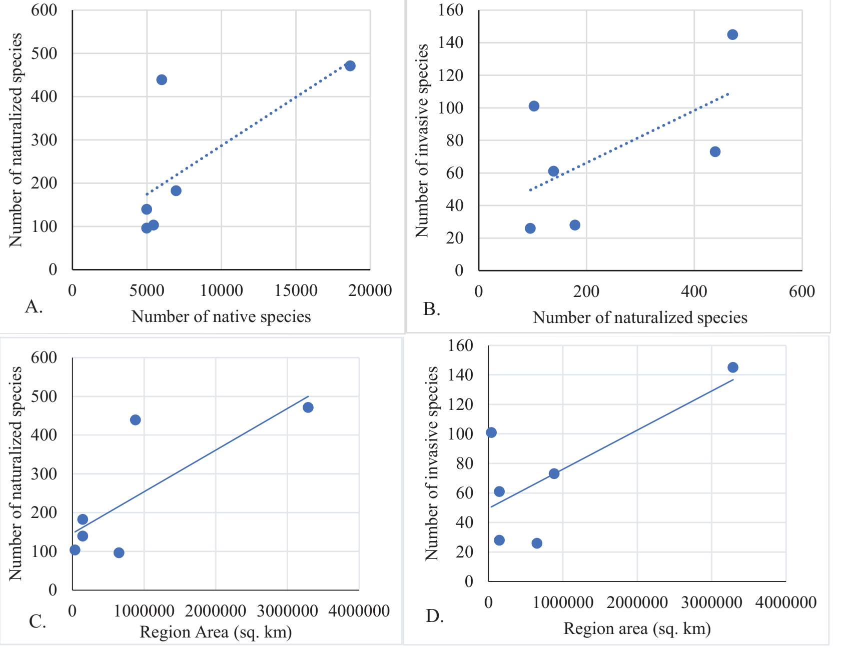

Figure 3. Relationships of alien plant species numbers in the South-Asian region for mainland states **A** naturalized species relationship with native species (mainland: r=0.77, t=0.59, p=0.12, df=5) **B** invasive species relationship with naturalized species (mainland: r=0.67, t=-0.11, p=0.91, df=5) **C** species area relationship for naturalized species (mainland: r=0.77, t=2.83, p=0.04, df=5) **D** species area relationship for invasive species (mainland: r=0.92, t=1.00, p=0.008, df=5).

The most widely distributed invasive plants in South-Asian countries

Forty-one invasive species occur in at least three South-Asian countries; we considered such species as widespread. *Lantana camara* and *Pontederia crassipes* are the most widely distributed, occurring in all eight South-Asian countries. *Parthenium hysterophorus* occurs in seven countries, *Chromolaena odorata* and *Mimosa pudica* in six countries, *Ageratum conyzoides*, *Argemone mexicana*, *Leucaena leucocephala*, *Mikania micrantha*, and *Ricinus communis* in five countries. Of the 41 widespread species, six are listed among 100 of the world's worst invasive species (see Table 2 for distribution of the most widespread invasive species in South-Asian countries).

Table 2. The distribution of widespread invasive plant species that were recorded in at least three of the eight studied countries. Based on GISD (www.iucngisd.org), CABI 2022, GloNAF (van Kleunen et al. 2019) and GRIIS (Pagad et al. 2018).

	Species	Afghanistan	Bangladesh	Bhutan	India	Maldives	Nepal	Pakistan	Sri Lanka
1	*Lantana camara* L.*	✓	✓	✓	✓	✓	✓	✓	✓
2	*Pontederia crassipes* (Mart.) Solms*	✓	✓	✓	✓	✓	✓	✓	✓
3	*Parthenium hysterophorus* L.	✓	✓	✓	✓		✓	✓	✓
4	*Chromolaena odorata* (L.) R.M. King & H. Rob.*	✓	✓	✓	✓		✓		✓
5	*Mimosa pudica* L.	✓	✓	✓	✓		✓		✓
6	*Ageratum conyzoides* L.		✓	✓	✓		✓		✓
7	*Argemone mexicana* L.	✓	✓	✓	✓		✓		
8	*Leucaena leucocephala* (Lam.) de Wit*	✓	✓			✓		✓	✓
9	*Mikania micrantha* Kunth*		✓	✓	✓		✓		✓
10	*Ricinus communis* L.	✓		✓	✓	✓		✓	
11	*Acanthospermum hispidum* DC.		✓	✓	✓				✓
12	*Ageratina adenophora* (Spreng.) R. M. King & H. Rob.			✓	✓		✓		✓
13	*Alternanthera philoxeroides* (Mart.) Griseb.		✓		✓		✓		✓
14	*Amaranthus spinosus* L.			✓	✓		✓	✓	
15	*Ipomoea carnea* Jacq. subsp. *fistulosa* (Mart. ex Choisy) D. F. Austin		✓		✓		✓	✓	
16	*Mesosphaerum suaveolens* (L.) Kuntze		✓	✓	✓		✓		
17	*Pistia stratiotes* L.		✓				✓	✓	✓
18	*Prosopis juliflora* (Sw.) DC.				✓	✓		✓	✓
19	*Senna occidentalis* (L.) Link		✓		✓		✓	✓	
20	*Xanthium strumarium* L.			✓			✓	✓	✓
21	*Acacia auriculiformis* A. Cunn. ex Benth.	✓	✓						✓
22	*Acacia mangium* Willd.	✓	✓						✓
23	*Ageratum houstonianum* Mill.				✓		✓		✓
24	*Alternanthera pungens* Kunth				✓			✓	
25	*Amaranthus viridis* L.							✓	✓
26	*Bidens pilosa* L.			✓	✓		✓		
27	*Cannabis sativa* L.			✓	✓			✓	
28	*Casuarina equisetifolia* L.				✓	✓			✓

	Species	Afghanistan	Bangladesh	Bhutan	India	Maldives	Nepal	Pakistan	Sri Lanka
29	*Croton bonplandianum* Baill.		✓	✓	✓				
30	*Datura stramonium* L.			✓	✓			✓	
31	*Erigeron karvinskianus* DC.				✓		✓		✓
32	*Eucalyptus camaldulensis* Dehnh.	✓	✓					✓	
33	*Galinsoga quadriradiata* Ruiz & Pav.			✓	✓		✓		
34	*Ipomoea quamoclit* L.			✓	✓	✓			
35	*Mikania scandens* (L.) Willd	✓	✓						✓
36	*Opuntia dillenii* Haw.		✓		✓				✓
37	*Oxalis latifolia* Kunth			✓	✓		✓		
38	*Portulaca oleracea* L.			✓	✓	✓			
39	*Robinia pseudoacacia* L.			✓	✓			✓	
40	*Senna alata* (L.) Roxb.			✓	✓	✓			
41	*Sphagneticola trilobata* (L.) Pruski*					✓	✓		✓

The names of the species are updated from the Catalogue of Life (https://www.catalogueoflife.org)
*Listed among 100 of the world's worst invasive alien species (Lowe et al. 2000)

The most problematic invasive species: habitats and impact

The 20 most problematic invasive plants in South Asia occurred in a range of habitat types (Table 3). The highest numbers were found in disturbed habitats (13 species), followed by riverine habitats and grassland (11 each), forests (10), wetlands (8), and woodland (7). Forest edges, ponds, shrubland (3 each), and ditches (2) harbour the least problematic invasives. *Lantana camara* is a species that is widespread in the greatest number of habitats, i.e. disturbed sites, forests, forest edges, riverine habitats, pastures, and woodland (Fig. 4).

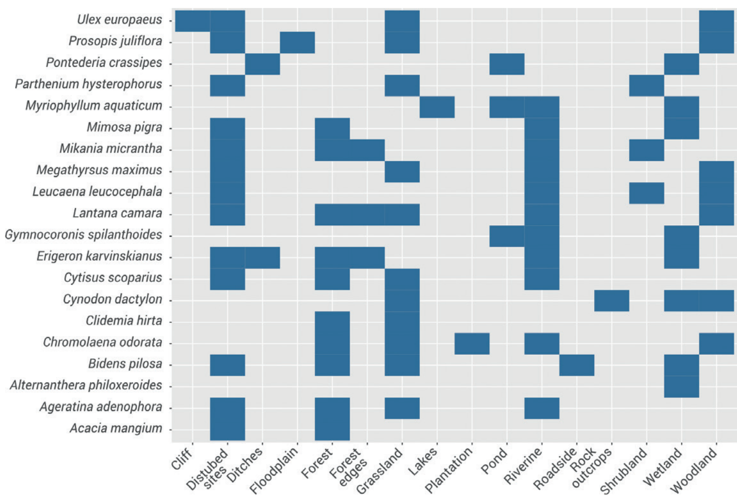

Figure 4. The occurrence of the most problematic invasive species in different habitat types. The presence of the species in a habitat is indicated by a blue cell. The classification of habitats of particular species is based on Weber (2017).

Table 3. The most problematic invasive plant species of South Asia with information on the region of origin, invaded range, invaded habitat, growth form, introduction history, and negative impacts. Habitats: Cl, Cliff; Ds, Disturbed sites; Dws, Disturbed wet sites; Di, Ditches; Fo, Forest; Fo ed, Forest edges; Fp, Floodplain; Gr, Grassland; La, Lakes; Ps, Pastures; Pl, Plantation; Po, Ponds; Rd, Roadside; Rv, Riverine; Ro, Rock outcrops; Sr, Shrubland; Wd, Woodland; Wt, Wetland. The information was retrieved from Weber (2017), CABI (2022), and the Global Invasive Species Database (2022), where the original references can be found.

Species name, family, origin	Invasive range in SA	Invaded habitat	Growth form	Introduction history	Negative impacts
Acacia mangium; Fabaceae; Australia, Papua New Guinea and Irian Jayaand the Maluku Islands of Indonesia	Bangladesh	Fo, Ds	Evergreen tree	Vector transmission, intentional as it is a commercially important species in SE Asia	**Native diversity:** threatens native diversity, prevents germination, outcompetes native species for water and light, and changes the fire regime. **Soil:** alters soil macrofauna; increases nitrogen availability.
Ageratina adenophora Asteraceae; Central Mexico	India, Nepal, Bhutan, Bangladesh	Fo, Rv, Gr, Ds	Perennial herb, subshrub	Seed contaminant, as an ornamental during the 1800s	**Native diversity:** eliminates native vegetation and prevents regeneration. **Agriculture:** inhibits germination and seedling growth of rice. **Soil:** allelopathy affects soil microbes.
Alternanthera philoxeroides Amaranthaceae; South America, Argentina	Bangladesh, India, Nepal, Sri Lanka	Wt, Dws	Aquatic perennial herb	Natural dispersal, accidentally introduced in ballast water, boats, vehicles, and by animals; intentionally as an ornamental and aquarium plant	**Native diversity:** replaces native species; competes with pastures. **Hydrology:** creates dense mat in water; affects floating aquatic plants; impairs water flow and light penetration; promotes sedimentation and flooding; disease vector; degrades aesthetic value. **Agriculture:** causes problems in rice fields.
Bidens pilosa Asteraceae; South and Central America	Bhutan, India, Nepal	Gr, Fo, Wt, Ds, Rd	Annual herb	Contaminant in crop seeds and agricultural products, intentionally for ornamental and agricultural purposes	**Native diversity:** eliminates native vegetation by suppressing germination; acts as a host and vector of harmful parasites; crosses with native and endemic species on Hawaii island; allelopathic. **Agriculture:** declines crop yields.
**Chromolaena odorata* Asteraceae; Tropical Central and South America, from Mexico and the Caribbean to Brazil	India, Nepal, Sri Lanka, Bangladesh	Fo, Rv, Gr, Wd, Pl	Shrub	Introduced to the Calcutta Botanical Garden as an ornamental plant in the 19th century, further movement by the military in World War II	**Native diversity:** eliminates native diversity; prevents the establishment of other species due to competition and allelopathy; increases fire hazards. **Human health:** skin complaints and asthma. **Soil:** change invertebrates' community.
**Clidemia hirta*; Melastomataceae; Central and South America, Caribbean islands	India, Sri Lanka	Fo, Ps	Evergreen shrub	Accidentally by people as an ornamental plant	**Native diversity:** reduces diversity and leads to the extinction of native species, and affects ecosystems. **Livestock:** poisonous to animals. **Soil:** affects soil water-holding capacity.
Cynodon dactylon; Poaceae; Africa	India, Bhutan (Virtually present at every tropical and subtropical country)	Gr, Wd, Wt, Ro	Perennial herb	Unclear	**Native diversity:** alters ecosystem functioning, fire regimes, hydrological cycles, nutrient cycling, and community composition.
Cytisus scoparius; Leguminosae; Europe	India	Gr, Rv, Fo, Ds	Perennial shrub	As an ornamental plant, horticulture species, movement of farm equipment	**Native diversity:** declines native plant diversity; alters nutrient cycling; affects wildlife; increases fire hazards; changes species number and composition; prevents reforestation.

Species name, family, origin	Invasive range in SA	Invaded habitat	Growth form	Introduction history	Negative impacts
Erigeron karvinskianus; Asteraceae; Central America, Mexico	India, Sri Lanka, Bangladesh, Nepal	Gu, Cr, Fo ed, Dws, Ds	Perennial herb	As an ornamental plant in Botanical Garden in Sri Lanka, then in India as a commodity contaminant	**Native diversity:** replaces native plants, affects regeneration, replaces vulnerable species in the alpine regions, habit alteration, damages ecosystem services.
Gymnocoronis spilanthoides; Asteraceae; America from Mexico to Argentina	India	Wt, Po, Rv	Aquatic perennial herb	Introduced as an aquarium plant and as an ornamental pond plant	**Native diversity:** displaces native plants, degrades natural wetlands, affects birds, and affects natural and recreational beauty. **Hydrology:** floating mats impede water flow, decline its quality, reduce light and block channels, decrease oxygen level, and cause flooding by blocking streams and drainage.
Lantana camara; Verbenaceae; Neotropics	Nepal, India, Pakistan, Bhutan, Bangladesh, Sri Lanka, Maldives	Fo, Fo ed, Wd, Rv, Ps, Ds	Evergreen shrub	Ornamental shrub, cultivated as a hedge plant	**Native diversity:** removes native vegetation and affects productivity; threatens endemics, affects the regeneration of tree seedlings; increases fire hazards; changes bird assemblage; a host for pests and diseases; deteriorates habitats of wildlife. **Livestock:** poisonous to livestock. **Agriculture:** the invasion on cultivated lands led to the shift of villages. **Soil:** in the stands of lantana, the water absorption capacity of soil declines, which increases the risk of soil erosion.
Leucaena leucocephala; Leguminosae; Mexico	India, Pakistan, Sri Lanka, Maldives, Bangladesh	Sr, Rv, Wd, Ds	Evergreen shrub, tree	By the late 1880s, it was widespread throughout Asia, promoted by the development of agricultural and forestry	**Native diversity:** suppresses native vegetation; prevents regeneration of native trees; promotes the establishment of other invasive species; alters nutrient cycling and ecosystem services; threatens endemic species. **Livestock:** toxic to livestock if consumed in high quantities.
Megathyrsus maximus; Poaceae; Africa	Sri Lanka	Gr, Wd, Ps, Rv, Ds	Perennial grass	Introduced as a fodder plant, contaminant to seeds	**Native diversity:** replaces native vegetation; increases fire hazards; displaces natural grassland; retards seedling growth; habitat deterioration; competes with native species.
Mikania micrantha; Asteraceae; Central and South America	Nepal, India, Sri Lanka, Bangladesh, Pakistan	Fo, Fo ed, Rv, Sr, Ds	Perennial vine	In 1918, this weed entered India during World War I to camouflage airfields	**Native diversity:** replaces native vegetation; decreases productivity in agriculture; prevents forest regeneration; shades other species; competes for water and releases allelochemicals which inhibit the germination of seeds; suppresses the growth and kills other species; in Chitwan National Park of Nepal *Rhinoceros unicornis* is under threat due to its invasion. **Livestock:** decreases livestock production. **Agriculture:** the worst weed of tea in India and Nepal and of rubber in Sri Lanka.
Mimosa pigra; Fabaceae; Neotropics	Sri Lanka, Nepal	Wt, Fo, Rv, Ds	Evergreen shrub	Introduced as an ornamental and seed contaminant; in Sri Lanka it was noted in 1997	**Native diversity:** removes native diversity and affects regeneration; infests wetlands; interferes with irrigation system; affects electric power lines; deteriorates recreational value; transforms floodplains into species-poor scrub; makes area inaccessible to wildlife; affects grazing area. **Agriculture:** negative impacts in rice cultivation.

Species name, family, origin	Invasive range in SA	Invaded habitat	Growth form	Introduction history	Negative impacts
Myriophyllum aquaticum; Holaragaceae; South America	Nepal	La, Po, Wt, Rv	Submersed aquatic perennial	Aquatic garden plant but escaped cultivation	**Native diversity:** native macrophytes are outcompeted, causes water deoxygenation. **Hydrology:** restricts water flow; affects fisheries and recreation value; suitable habitat for mosquitoes; alters physical and chemical properties of lakes.
Parthenium hysterophorus; Asteraceae; Mexico, Central and South America	Bangladesh, Bhutan, India, Pakistan, Nepal	Gr, Sr, Ps, Ds	Annual herb	Accidental introduction in India as a contaminant to cereal grains	**Native diversity:** declines native biodiversity, degrades natural ecosystems, and changes wildlife habitat. **Soil:** changes soil chemistry by increasing soil nutrients and P^H, **Agriculture:** reduces crop productivity; affects crop production. **Livestock:** removes grass species; allelopathic properties decline meat and milk quality. **Human health:** causes dermatitis.
**Pontederia crassipes*; Pontederiaceae; Tropical South America	India, Nepal, Sri Lanka, Maldives, Bangladesh	Wt, Po, Di	Floating aquatic	Water ornamental in botanical gardens, used in aquariums	**Native diversity:** thick mats cover the water surface, affect the ecosystem and water quality, interfere with water transport, halt fishing; light reduction kills macrophytes, alters temperature; reduces habitats for fishes and birds; clogs irrigation channels; reduces oxygen level and increases nitrogen level; allelopathic effects; affect hydroelectric plant; breeding site for disease-carrying insects.
Prosopis juliflora; Leguminosae; Mexico, Central and northern South America	India, Pakistan, Sri Lanka	Gr, Rg, Wd, Fp, Ds	Evergreen shrub, tree	Introduced as a fodder and fuel species, occurred in the 19^{th} century in India, accidentally introduced to other countries	**Native diversity:** reduces native species diversity; affects wildlife movement; hybridization with others; blocks paths and makes them impenetrable; alters nutrient cycling. **Soil:** changes soil chemistry and soil microbial community; promotes soil erosion; lowers water tables. **Agriculture:** loss in agricultural productivity. **Livestock:** death of livestock due to its consumption.
**Ulex europaeus*; Leguminosae; Atlantic maritime regions	India, Sri Lanka	Gr, Wd, Rv, Cl, Ds	Evergreen shrub	Intentionally spread as a hedge plant, ornamental and forage plant, or as a contaminant	**Native diversity:** grows on forest edges; eliminates native vegetation and prevents regeneration; affects wildlife; increases fire hazards; removes pastoral vegetation; damages ecosystem services. **Soil:** acidifies soil and alters its condition by fixing nitrogen. **Hydrology:** hydrological conditions; habitat alteration.

All the most problematic invasive plants in South Asia affect native species diversity (Table 3). In addition, eight species are reported to reduce the productivity of agricultural fields and alter soil properties, hence directly affecting the economy (Fig. 5). *Clidemia hirta*, *Lantana camara*, *Leucaena leucocephala*, *Mikania micrantha*, *Parthenium hysterophorus*, and *Prosopis juliflora* were reported to affect livestock and their products. Species like *Alternanthera philoxeroides*, *Gymnocoronis spilanthoides*, *Myriophyllum aquaticum*, and *Ulex europaeus* are responsible for hydrological changes that subsequently affect aquatic ecosystems. Only two invasive plants (*Chromolaena odorata* and *Parthenium hysterophorus*) are reported to have an impact on human health (Fig. 5).

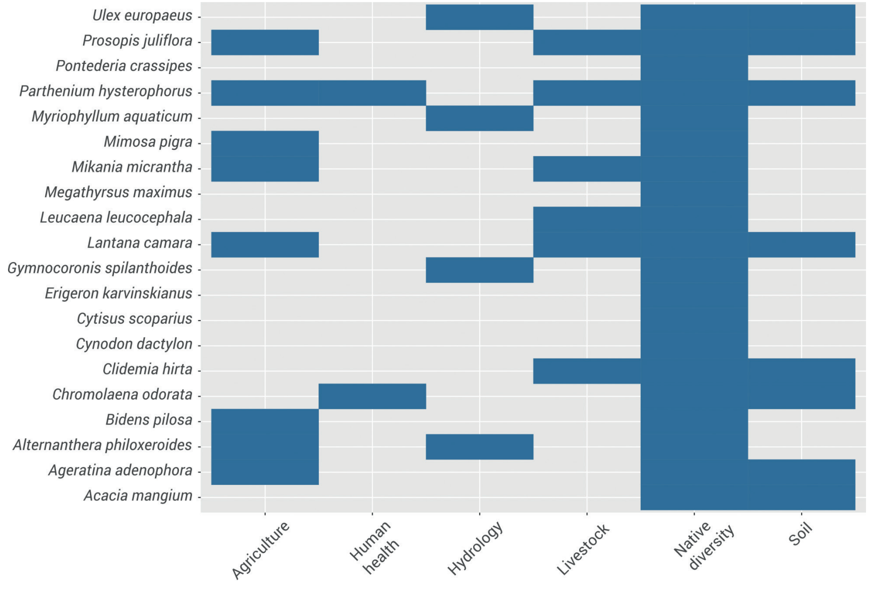

Figure 5. The impact of the most problematic invasive plants in South Asia classified into impact categories. The recorded impacts are indicated by blue cells. The information on impacts was taken from Weber (2017), CABI (2022) and Global Invasive Species Database (2022). See Table 3 for detailed description of impacts of particular species.

Implemented management approaches for selected invasive species in South Asia

Only 17% of research papers focused on the management of invasive plants in South Asia, most of them on a single species (i.e. *Ageratina adenophora*, *Chromolaena odorata*, *Lantana camara*, *Mikania micrantha*, *Parthenium hysterophorus*, *Pontederia crassipes*; Sullivan et al. 2017; Raj et al. 2018; Poudel et al. 2019; Sharma et al. 2022). Physical or mechanical removal was the most widely used management method. Manual slashing, use of tractors, plowing, hand pulling, sickle weeding, repeated cutting, and burning were commonly applied. The physical methods were labour-intensive and effective only in a small area. Therefore, chemical methods, i.e. herbicides, were also used to limit the spread of invasive species (Tables 4, 5).

Table 4. List of the invasive plants with their management methods in South Asia. Public awareness (by informing local people about the impacts), biological control, competition (removing invasive species by competing with native species), drivers (by knowing factors that import invasive species), physical (manual removal), and uses (using plants as green manure or for bedding of livestock).

Species name	Awareness	Biological control	Competition	Chemicals	Drivers	Physical	Uses	References
Ageratina adenophora	✓	✓	✓	✓		✓	✓	Negi 2016; Balami and Thapa 2017; Poudel et al. 2019
Chromolaena odorata		✓	✓	✓		✓	✓	Saikia and Deka 2017; Sharma et al. 2022
Clusia rosea						✓	✓	Hitinayake et al. 2018
Cyperus rotundus				✓		✓		Raj et al. 2018
Lantana camara	✓	✓		✓	✓	✓	✓	Love et al. 2009; Kannan et al. 2014; Kannan et al. 2016; Raj et al. 2018
Mikania micrantha	✓	✓		✓		✓		Sapkota 2007; Paudel 2011; Khadka 2017; Sullivan et al. 2017; Aryal et al. 2018
Mimosa pigra			✓	✓		✓		Marambe et al. 2004
Opuntia stricta		✓						Shen et al. 2018
Opuntia monocantha		✓						Sushilkumar 2015
Parthenium hysterophorus		✓	✓	✓		✓	✓	Javaid et al. 2006; Shrestha et al. 2011; Khan et al. 2014; Shabbir 2014; Shabbir et al. 2015; Rana et al. 2017; Dolai et al. 2019; Iqbal et al. 2020; Adnan et al. 2021; Weyl et al. 2021b
Pontederia crassipes		✓		✓		✓	✓	Kafle et al. 2009; Mathiventhan et al. 2018; Raj et al. 2018; Gupta and Yadav 2020
Prosopis juliflora				✓	✓	✓		Ratnasekera 2016
Ulex europaeus		✓	✓	✓	✓	✓		Jayasekara et al. 2021
Xanthium strumarium		✓				✓		Shen et al. 2018
Number of species for which a given method is applied	3	10	5	10	3	12	6	

Biological control was used less often than physical methods. Biological control programs were implemented only in India and Pakistan. Due to open and porous international boundaries between India and other South-Asian countries, some of the biological agents like *Zygogramma bicolorata* have naturally reached Nepal, Bhutan, Pakistan, and Bangladesh. Although some biological control agents have established in South Asia, their impacts were not strong (Shrestha et al. 2022). Removing invasive species before flowering, sowing competitive species after their removal, raising awareness among people about the negative impacts, and identifying the factors responsible for the spread of invasive species are other ways to manage invasive species (Table 5).

Table 5. Specific control measures for selected invasive species with significant negative impacts on the environment. The information was retrieved from Weber (2017), CABI (2022), and Global Invasive Species Database (2022), where the original references can be found. *Listed among 100 of the world's worst invasive alien species.

Species name	Control measures
Acacia mangium	Uprooting seedlings, cutting trees, and use of herbicides retard growth; triclopyr herbicide mixed with oil used on cuttings.
Ageratina adenophora	Slashing, ploughing, and sowing of other species after removal; herbicides; stem gall fly (*Procecidochares utilis*), fungus (*Passalora ageratinae*).
Alternanthera philoxeroides	Repeated leaf removal; herbicides like metsulfuron-methyl, glyphosate, dichlobenil and a mixture of glyphosate and metsulfuron-methyl; biocontrol by flea beetle (*Agasicles hygrophila*) successful in Australia.
Bidens pilosa	Persistent mowing and hand pulling, prevent germination by mulch; herbicides such as glyphosate-trimesium, oxyfluorfen, atrazine, 2,4-D glyphosate, pendimethalin, metribuzin, diuron, paraquat, nicosulfuron and simazine.
**Chromolaena odorata*	Manual slashing, use of tractors to remove as hand pulling is labour intensive; repeated cutting and burning; chemicals 2,4-D, ester, picloram, imazapyr or 2,4,5-T applied at the seedling stage; triclopyr is the most effective.
**Clidemia hirta*	Hand pulling, less soil disturbance, and cuts treated with triclopyr and glyphosate are effective.
Cynodon dactylon	Dug out and remove all rhizomes and stolons; infestation can be controlled by covering with plastic and applying paraquat or glyphosate.
Cytisus scoparius	Slashing, less soil disturbance, pulling out, goats and rabbits stunt growth and prevent regeneration; planting tall and competitive plants may contribute to reducing growth; use of chemicals like picloram, triclopyr, glyphosate, fluroxypyr, and metsulfuron-methyl.
Erigeron karvinskianus	Avoid soil disturbance; herbicide glyphosate, hexazinone, tebuthiuron.
Gymnocoronis spilanthoides	Mechanical removal and hand pulling lead to further spread; herbicides are effective only on the upper part; following herbicide application, the removal with machinery can be effective; dry and burn.
**Lantana camara*	Mechanical clearing and hand pulling suitable for small areas; periodic burning; cleared areas should be revegetated; use of herbicides- 2,4,-D, MCPA, dicamba, triclopyr, glyphosate or picloram on cuts; well established biological agents: *Uroplata girardi*, *Ophiomyia camarae*, *Aconophora compressa*; integrated approaches are recommended; in India, the control by spraying glyphosate on regenerated growth was effective.
**Leucaena leucocephala*	Grazing by goats; solarization was found effective in killing all plants and seeds; pulling out roots and shading leads to seedling mortality; treating of cutting with picloram; cutting stems and treating them with diesel and other chemicals.
Megathyrsus maximus	Pulling out, heavy grazing; herbicides glyphosate prevent new growth; pathogens like *Drechslera gigantea*, *Exserohilum rostratum*, and *E. longirostratum* are highly effective.
**Mikania micrantha*	Sickle weeding and uprooting prior to seed maturity; slashing or repeated cut from the ground; herbicide like paraquat and 2,4-D amine, glyphosate + picloram; parasitic plant *Cuscuta campestris* suppresses its growth; rust fungus (*Puccinia spegazzinii*); increasing shade in forests makes the habitat unsuitable for its growth; potential biological control: *Liothrips mikaniae.*
**Mimosa pigra*	Complete digging out; killed by cutting at a depth of 10 cm; slashing and burning with the use of herbicides picloram, hexazinone, dicamba, triclopyr, linuron, and glyphosate; biological control *Nesaecrepida infuscata* released in Australia; restriction of the movement of vehicles, soil, and sand from infested areas; integrated approaches are beneficial.
Myriophyllum aquaticum	Biomass removal; cleaning boats; herbicides 2,4-D, diquat, or fluridone can be effective when plants are young; in South Africa, biological control by *Lysathia* was found effective.
Parthenium hysterophorus	Manual uprooting before flowering; mowing, slashing, plowing; herbicides 2,4-D, picloram and hexazinone; biocontrol agents: the leaf-feeding beetle *Zygogramma bicolorata*, the stem-galling moth *Epiblema strenuana*, the stem-boring beetle *Listronotus setosipennis*, and the seed-feeding weevil *Smicronyx lutulentus*.
**Pontederia crassipes*	Physical or mechanical removal by machine can stop its spread, reduce the nutrient level in the water, chemicals 2,4-D, glyphosate; biological control by *Neochetina* weevils is effective; use of boom to control the movement of weed; utilization of biomass.
Prosopis juliflora	Control is highly expensive and unsuccessful; mixed mechanical and chemical control; hand pulling effective only on a small scale; stems cut at least 10 cm below ground will not resprout; herbicides: clopyralid, picloram, triclopyr, 2,4-D amine suppress the growth.
**Ulex europaeus*	Hand pulling and repeated cutting; herbicides: glyphosate, picloram, triclopyr, and 2,4,5-T; prescribed burning; planting native trees and competitive grass suppress growth; intensive grazing by goats; biological control: *Sericothrips staphylinus*, *Exapion ulicis*, *Tetranychus lintearius*; integrated control reduces the spread.

Discussion

Research focusing on plant invasions in South Asia has steadily increased in the last two decades, which corresponds to the increase worldwide (e.g. Pyšek and Richardson 2010; Ramírez-Albores et al. 2019; Muñoz-Mas et al. 2021). Still, despite the recent dynamic increase in research effort, plant invasions in Asia, especially in its tropical part, remain greatly understudied compared to other continents, particularly North America and Europe (Foxcroft et al. 2017). Most plants were introduced to South Asia as ornamental species, followed by those introduced for agriculture and horticulture, as contaminants of seed and transport machinery, or as stowaways (Banerjee et al. 2021). Australia, New Zealand, and South Africa focus more on management, but Asia lags behind, still describing basic patterns (Pyšek and Richardson 2010; Hulme 2020). Moreover, research effort is uneven in Asia; for example, no literature exists for Afghanistan and the Maldives. The capacity of most Asian countries to combat emerging plant invasions is poor compared to the countries in North America, Western Europe, and Oceania (Early et al. 2016).

India is also known as one of the global hotspots of invasive alien species (Pyšek et al. 2017). India has the largest economy and makes up more than 70% of the South-Asian economy (https://www.worldbank.org/en/region/sar/overview retrieved on 5 Jan 2023). This country has the highest number of invasive and naturalized plant species among South-Asian countries (Inderjit et al. 2018). This is due to its large area and rapidly growing economy. However, the percentage of invasive and naturalized species is higher on the island of Maldives. This could be due to the continuous oceanic border, which increases the propagule pressure (Brock and Daehler 2022), and the greater vulnerability of islands to invasions (Pyšek et al. 2017; Moser et al. 2018). Afghanistan has the lowest number of invasive and naturalized species, but here, the most likely reason is inadequate research effort.

Our review revealed that there are at least 392 invasive plant species in South Asia. Among them, 41 species occur in at least three countries, and 20 species are considered the most problematic in terms of having negative ecological impacts (Weber 2017). This number is most likely to be higher as the impacts of many species have not yet been known. Species like *Mimosa diplotricha* and *Sphagneticola trilobata* are invasive in Nepal (Sharma et al. 2020; Shrestha et al. 2021) and India (Choudhury et al. 2016) but not mentioned in the GloNAF database. The impacts of invasive plants are of great concern in South Asia because the majority of people directly depend on natural resources. *Chromolaena odorata*, *Clidemia hirta*, *Lantana camara*, *Leucaena leucocephala*, *Mikania micrantha*, *Mimosa pigra*, *Pontederia crassipes*, *Sphagneticola trilobata*, and *Ulex europaeus* are among the 100 of the worlds' worst invasive species, and they are widespread in South Asia. Unfortunately, most impact studies focus on a single species and are carried out at a small geographic scale. To quantify the real impacts of invasive plants, studies should be carried out in open and extensive landscapes and under natural conditions.

Studies on impacts of invasive plants in South Asia

In South Asia, research on the impacts of invasive species started only after 2001. Most of the studies have focused on the impacts of single invasive species such as *Pontederia crassipes*, *Lantana camara*, *Mikania micrantha*, and *Parthenium hysterophorus* (Kohli et al. 2006; Ahmed et al. 2007; Murphy et al. 2013; Rawat et al. 2019; Bhatta et al. 2020). The impacts of invasive plant species on native vegetation are reported from South Asia, and studies showed that invasive plants commonly reduced the richness, diversity, and evenness of native species (Thapa et al. 2016; Bhatta et al. 2020; Kumar and Garkoti 2021) and changed the species composition. However, studies focusing on impacts on socioeconomy, agriculture, health, and hydrology are not sufficiently represented. The particular findings from South Asia, reported in detail below, correspond to the global analyses by Vilà et al. (2011) and Pyšek et al. (2012).

Impacts on native plant diversity in natural ecosystems

Plant invasions have serious impacts on the environment of Asia, including natural habitats. In forests, dense patches of invasive plants inhibit seedling growth by blocking sunlight and stimulating the growth of other alien plants (Dogra et al. 2009a, b; Rupasinghe and Gunaratne 2017). In the Himalayas, invasive species like *Ageratina adenophora* and *Lantana camara* are problematic in pine forests and riparian forests because they enhance the soil nutrient cycling in invaded microsites and spread rapidly (Parveen et al. 2011; Kumar et al. 2021). In Indian forests, *L. camara* has posed a threat by replacing native understorey vegetation and hindering tree regeneration (Kohli et al. 2006). Similarly, in Nepal's Bardia National Park, the invasion of *Lantana camara* has been responsible for over 50% reduction in native plant richness and diversity (Bhatta et al. 2020). Invasive species richness was reported to be inversely proportional to the tree canopy (Thapa et al. 2020); therefore, maintaining a closed tree canopy can prevent the invasion problem.

Invasion in grasslands suppressed palatable grasses and decreased their regeneration, threatening wildlife and making their habitat unsuitable (Akter and Zuberi 2009; Sullivan et al. 2017; Chhogyel and Kumar 2018). *Parthenium hysterophorus* is highly problematic in the grasslands of Nepal, India, and Pakistan (Javaid and Riaz 2012; Shrestha et al. 2015; Rokaya et al. 2020). The presence of invasive *Centaurea iberica* in the mountain grasslands of India suppressed native plant species diversity and changed their species composition (Reshi et al. 2008).

Thickets of invasive plants prevent the exchange of sunlight and heat, leading to poor oxygenation and the presence of carbonic and bicarbonic acids (Nguyen et al. 2015; Pandey et al. 2020). *Pontederia crassipes* is one of the world's worst invasive weeds, which alters the physicochemical properties of water (Basaula et al. 2021) and competes with native hydrophytes for oxygen (Rashid et al. 2014). It damages aquatic ecosystems and deteriorates their aesthetic value (Pathak et al. 2021) and was reported to alter hydrological regimes and replace aquatic flora (Gupta and Yadav 2020; Pathak et al. 2021). Moreover, plant invasions in wetlands negatively affect crop production by hampering irrigation systems, blocking fishing areas, declining fish production, setting barriers to boating, and altering the water cycle (Keller et al. 2018; Pathak et al. 2021).

Impacts on agriculture, soil, and human health

Plant invasions decrease agricultural productivity by reducing nutrient levels in the soil (Yakandawala and Yakandawala 2011; Paini et al. 2016; Chhogyel and Kumar 2018; Chhogyel et al. 2021). The fluctuation in agricultural production affects national economies and threatens food security (Kohli et al. 2006). Economic costs due to invasive species in agriculture are estimated in some countries, such as India and Pakistan (Diagne et al. 2020), but the estimates are still missing for other countries, for example Bangladesh (Mukul et al. 2020). The increased impact of *Phenacoccus solenopsis* on the cotton yield of India caused a loss of about US$ 1.217 billion and is forecasted to increase in coming years (InvaCost; Diagne et al. 2020). *Ageratum conyzoides*, *Ageratum houstonianum*, and *Parthenium hysterophorus* cause problems in the agricultural fields of South Asia (Kohli et al. 2006; Shrestha et al. 2019), and their impacts are reported in Nepal and Pakistan (Javaid and Riaz 2012; Shrestha et al. 2015; Rokaya et al. 2020). *Ageratum conyzoides* invading agricultural fields has caused a decline in crop productivity (Kohli et al. 2006; Shrestha et al. 2019; Shah et al. 2020). The impacts of invasive species are more pronounced in developing countries because local people depend more on agriculture, fisheries, and forestry (Mungi et al. 2018; Shah et al. 2020).

Some invasive plants produce allelopathic substances that affect plant diversity as well as soil microbial diversity by leaching allelochemicals into the soil (Inderjit et al. 2011; Thapa et al. 2020). Research has shown that invaded soils have high microbial biomass and rapid litter decomposition, which increases the availability of nutrients and, as a result, invasive species grow rapidly (Ahmad et al. 2019; Zhao et al. 2019; Kumar et al. 2021). These toxic chemicals help invasive species establish and spread rapidly (Kumar and Garkoti 2022).

Besides declining native plant diversity and changing ecosystem properties, invasive plants cause several diseases to humans and livestock in South Asia (Kumar and Prasad 2014; Rashid et al. 2014; Negi 2016). *Parthenium hysterophorus* is known to have negative impacts on human health, causing skin allergy, rhinitis, and irritation to the eyes (Kohli et al. 2006; Adkins and Shabbir 2014; Shrestha et al. 2015; Chhogyel et al. 2021). Due to direct exposure to invasive plants, health problems are also greater in developing countries. Several other species, like *Ageratum houstonianum* and *Mimosa diplotricha*, negatively affect human health and livestock conditions (Shrestha et al. 2019; Sharma et al. 2020), but there is very little research in this respect. On the other hand, some invasive plant species are used in traditional medicine as antimicrobial, antiseptic, and blood coagulants (Negi 2016).

Management

Despite the recent increase in the number of published studies, research on the management of invasive plants in South Asia is still insufficient. Chemical, physical, and mechanical removal of invasive species are the most common practices in South-Asian countries (Raj et al. 2018). There are attempts to manage invasive species by physical removal with the participation of the local people (Sullivan and York 2021), which is labour intensive. For instance, the management of *Pontederia crassipes* by utilizing its biomass for various purposes has been adopted but was unsuccessful because of the absence of continuous funding (Patel 2012).

Experiences from other parts of the world show that control of invasive plants by physical and chemical methods is expensive and needs continuous long-term effort. Great Britain spent about ~£90 million annually on chemicals for controlling invasive weeds in agricultural land (Williams et al. 2010). On the other hand, biological control is the most effective and sustainable method to control invasive species because once established, it perpetuates itself and does not need continuous financial inputs for management (Clewley et al. 2012). Most of the countries which are successful in the eradication of invasive plants have adopted biological methods. For example, *Azolla filiculoides* have been controlled for over a decade in South Africa by a North American frond-feeding weevil, *Stenoplemus rufinasus* (Hill et al. 2008). In Australia, nine insects and two fungal pathogens are used as biological control agents against *Parthenium hysterophorus* (Dhileepan et al. 2019). Unfortunately, biological control is in the early stage and poorly developed in South Asia due to the high initial cost and long time required for screening. However, some biological control agents for *Ageratina adenophora*, *Chromolaena odorata*, *Lantana camara*, *Mikania micrantha*, *Parthenium hysterophorus*, and *Pontederia crassipes* were introduced to South Asia (Dhileepan and Senaratne 2009; Poudel et al. 2020; Shrestha et al. 2022). In Papua New Guinea, a gall fly *Cecidochares connexa* was found to successfully control the populations of invasive *Chromolaena odorata* (Day et al. 2013). In South Africa and some neighbouring countries, the flowering galling mite *Aceria lantanae* reduced the flower production of *Lantana camara* by up to 97% (Simelane et al. 2021).

Most alien species were introduced to South Asia for ornamental purposes, soil improvement, or as a fodder crop for animal husbandry; some were introduced as contaminants (Tiwari et al. 2005; Ekanayake et al. 2020). For instance, *Lantana camara* and *Pontederia crassipes* were introduced to botanical gardens in India as ornamentals (Kohli et al. 2006). Similarly, *Spermacoce alata* seeds entered Nepal along with the seeds of forage plants distributed to farmers (Shrestha 2016). There is abundant evidence showing that disturbance increases resource availability, making a plant community susceptible to invasion (Davis et al. 2000; Dogra et al. 2009b). Forest edges, agricultural land, grasslands, fallow land, roadside vegetation, and wetlands are susceptible to invasion as they feature higher levels of disturbance (Biswas et al. 2007; Shrestha and Dangol 2014; Rupasinghe and Gunaratne 2017). Moreover, lack of natural enemies, physical disturbance, and open forest canopies are also among the causes of the success of invasive plants (Mandal and Joshi 2014). Passenger air travel is considered one of the introduction vectors in South Asia (Early et al. 2016). Identifying the major drivers and pathways of plant invasions is important for their management.

Species like *Lantana camara* are very widespread and difficult to eradicate by mechanical, chemical, and biological methods (Love et al. 2009). In South Asia, the eradication of *L. camara* is nearly impossible, but the negative impacts could be reduced through management. Additionally, efforts should be made to prevent invasions in new areas. In Pakistan, chemicals like glyphosate and metribuzin are effective in controlling *Parthenium hysterophorus* when treated in a rosette stage (Khan et al. 2012). Herbicide treatment and competitive plants are also used in Pakistan to manage this species (Adnan et al. 2021). The chemical method is effective but not recommended because of its detrimental effects on other biota (Love et al. 2009; Rana et al. 2017). Allelopathic evaluation of invasive plants is important for the biological control of *P. hysterophorus* (Shinwari et al. 2013). Biological control using *Zygogramma bicolorata* has successfully retarded the growth of invasive *P. hysterophorus* by defoliating the plants (Shrestha et al. 2011; Shabbir et al. 2015; Weyl et al. 2021a, b). In addition to this, winter rust, *Puccinia abrupta* var. *partheniicola* is also reported to control *P. hysterophorus* by damaging leaf tissues (Iqbal et al. 2020; Maharjan et al. 2020; Weyl et al. 2021a). Australia has deliberately released this biological control, but countries like Nepal, India, Pakistan, and China have reported this rust to occur without intentional introduction (Iqbal et al. 2020). Laboratory experiments with *Listronotus setosipennis* in Pakistan have shown that this weevil is specific to *P. hysterophorus* (Weyl et al. 2021a). Similarly, *Procecidochares utilis* causes stem galling and suppresses the growth of *Ageratina adenophora* (Poudel et al. 2019). However, its effectiveness is low in the Himalayan region (Poudel et al. 2019). The main benefit of biological control methods is that they perpetuate by themselves but need rigorous research on host-ranging tests before releasing them in nature (Paterson et al. 2021). Countries have implemented different ways of eradication and management of invasive species, but biological control is still in its early stages in South Asia.

Australia and New Zealand have successfully managed some of the problematic invasive alien species that are also widespread in South Asia by focusing on prevention (Raj et al. 2018). In Australia, every dollar spent on the prevention of invasion benefits $25.60–38.30 (Sinden et al. 2004). Countries of Asia should adopt integrated methods of biological and chemical control, along with making use of competition with native plants, to effectively manage already established invasive plants (Shabbir 2014; Shabbir et al. 2015); identifying competitive native species and actively planting them can help in effective management (Khan et al. 2014; Balami and Thapa 2017). Moreover, the identification of dispersal pathways, high biosecurity, local community participation, and awareness among locals play a vital role in limiting the spread of invasive species (Kannan et al. 2016; Shrestha 2019). Another option could be using invasive species for biogas, firewood, and biofertilizer production, such as *Pontederia crassipes* (Kafle et al. 2009; Raj et al. 2018). However, it is essential to be cautious in order not to unintentionally promote the invasive species.

Conclusions: management recommendations

South Asia harbours a substantial proportion of global biodiversity, making it imperative to exert every possible effort in safeguarding it against current and potential future plant invasions. The region is part of a biodiversity hotspot area, yet the impact of invasive species is poorly understood. In this paper, we assess the most problematic invasive plant species in South Asia, their impacts, and management. There is no information about the effectiveness of management and policies adopted in South Asia. We show that South Asia still focuses on inventories and descriptive approaches, whereas the impacts of invasive species on the economy, hydrology, and human health are little explored and identified only for a few invasive species. Ecosystem impacts are also understudied; for example, how invasive plants affect ecological processes such as productivity, nutrient dynamics, and pollination have been poorly covered. Thus, by identifying the less explored research areas with regard to the most abundant and problematic invasive species in South Asia, this review contributes to bridging the data gap for global databases and identifies the priority areas for future research. There is an urgent need to quantify the impacts of all widespread and problematic species in South Asia, which is crucial for allocating resources for management. The management should prioritize invasive species with the highest environmental impacts and regions that are suffering the greatest loss.

Biological control is the most effective and sustainable way of retarding the spread of invasive species, but unfortunately, research on biological control is not adequate in South Asia. Our review suggests that research on biological agents should be increased, and community awareness is needed to make the management effective. It is important to recognize that the implementation of biocontrol measures can leverage insights from studies conducted in other regions, underlining the essential need to prioritize specific targets for effective biocontrol strategies.

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Supplementary material 1

372 papers were used for the analysis

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