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ORIGINAL PAPER

Alien flora of India: taxonomic composition, invasion status and biogeographic affiliations

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Abstract The wide knowledge gaps in invasion biology research that exist in the developing world are crucial impediments to the scientific management and global policymaking on biological invasions. In an effort to fill such knowledge gaps, we present here an inventory of the alien flora of India, based on systematic reviews and rigorous analyses of research studies (ca. 190) published over the last 120 years (1890–2010 AD), and updated with field records of the last two decades. Currently, the inventory comprises of 1,599 species, belonging to 842 genera in 161 families, and constitutes 8.5% of the total Indian vascular flora. The three most species-rich families are Asteraceae (134 spp.), Papilionaceae (114 spp.) and Poaceae (106 spp.), and the three largest genera are *Eucalyptus* (25 spp.), *Ipomoea* (22 spp.), and *Senna* (21 spp.). The majority of these species (812) have no report of escaping from cultivation. Of the remaining subset of 787 species, which have either escaped from intentional cultivation, or spread after unintentional introduction, casuals are represented by 57 spp., casual/naturalised by 114 spp., naturalised by 257 spp., naturalised/invasive by 134 spp., and invasive by 225 spp. Biogeographically, more than one-third (35%) of the alien flora in India has its native ranges in South America, followed by Asia (21%), Africa (20%), Europe (11%), Australia (8%), North America (4%); and cryptogenic (1%). The inventory is expected to serve as the scientific baseline on plant invasions in India, with implications for conservation of global biodiversity.

Keywords Biodiversity · Biological invasions · Alien plants · Taxonomy · Biogeography · India

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Introduction

In invasion ecology, both taxonomic and geographical knowledge gaps exist at a global scale (Pyšek et al. 2008), and countries of the developing world lag far behind countries of the developed world in

research on invasive species (Nuñez and Pauchard 2010). In the developing world, especially Asian and African countries, except South Africa, are poorly represented in the scientific literature on biological invasions. Such a data deficit in the invasion biology literature does not, however, indicate that developing countries are at a lower risk of being invaded by invasive alien species, because biological invasions are a phenomenon that transcends political boundaries (Rashid et al. 2009). Rather, the dearth of reported biological invasions from developing nations is the result of insufficient research efforts and inadequate data availability.

Over recent decades, many developing countries have become potential sources and recipients of invasive alien species to and from other countries of the world due to fast economic globalisation of the world and the associated acceleration in trade, travel, and transport. However, for the majority of these countries, even a preliminary inventory of alien species does not yet exist (Wu et al. 2010). This is even more crucial for the fast-emerging Asian economies of China and India, which are at a higher risk of biological invasions (Weber and Li 2008). Over the last two decades, the expanding economy of India has triggered large infrastructure development projects that have led to the loss of natural habitats and opening of disturbance corridors, providing favourable habitats to the establishment and spread of alien species (Sharma et al. 2005). Pertinently, a recent report projected that India's GDP per capita will quadruple by 2020, and that the Indian GDP will surpass that of the United States before 2050 (Podder and Yi 2007).

As a step towards filling such knowledge gaps in invasion biology research in developing countries, including India, an inventory of alien species assumes an urgent priority because it represents a critical starting point for the scientific understanding and systematic management of biological invasions at the local, regional and global scales (Hulme et al. 2009a). Such inventories, when compiled at the regional scale, provide basic data necessary for testing various scientific hypotheses in invasion biology (Cadotte et al. 2006). These inventories, however, have to be more than simple taxonomic checklists, and should reflect the process of biological invasion (Palmer et al. 1995; Pyšek et al. 2004). For this purpose, an inventory needs to characterise the alien species at different stages of the invasion process along the introduction-naturalisation-invasion continuum (see Richardson et al. 2000). Equally important is that each alien species in an inventory is provided with information about a suite of traits that captures the species invasiveness and habitat invasibility. Furthermore, the inventory must be dynamic to allow continuous updating. Once compiled, such an inventory would provide an essential tool for early detection and rapid response, informed decision-making and sound policymaking in long-term monitoring and systematic management of biological invasions. As an example, the recently compiled inventory of alien species of Europe under the project DIASIE is the first continental-scale research effort with far-reaching scientific, management and policy implications (Hulme et al. 2009b).

While a number of research studies that inventorize the alien flora have recently been carried out in China (Liu et al. 2005, 2006; Weber et al. 2008; Wu et al. 2010) and in some other Asian countries (Corlett 1992; Enomoto 1999; Koh et al. 2000; Wu et al. 2004), such type of studies are lacking for India. Surprisingly, the country's Third National Report submitted to Convention on Biological Diversity (CBD) states that 40% of Indian flora is alien to the country, of which 21% is invasive (CBD 2005). However, since a national alien species inventory has not been compiled, the CBD estimates are not based on reliable empirical data. Prior to this Report, the estimates projected for the proportion of alien plants in the Indian flora over the last half a century have greatly varied (Chatterjee 1940; Maheshwari 1962; Nayar 1977; Saxena 1991). In the absence of a baseline inventory, such estimates are unreliable. This has serious implications for the management of plant invasions because it hinders the development of global indicators of biological invasions (McGeoch et al. 2010). One of these indicators is the number of invasive species in a region, which can only be obtained by surveying and compiling alien species inventories.

More recently, a few research studies on the alien flora of some regions in India have been carried out (Khuroo et al. 2007a, 2010; Negi and Hajra 2007; Singh et al. 2010); and also, a preliminary list of 'invasive alien flora of India' has been compiled (Reddy 2008). However, these regional studies are narrow in scope and cannot be extrapolated for India as a whole. The majority of these studies lacks an

explicit standard terminology and definition to characterise the alien species at different stages of invasion (see Pyšek et al. 2004), which limits their applicability in comparative analyses, and in making robust generalisations at the national and global scales.

To fill up this knowledge gap, here we present a comprehensive stage-based inventory of the alien flora of India. The main advantage of such a stage-based characterisation of alien flora is that it allows the integration of species invasion status with the relevant management option available (Khuroo et al. 2008). The specific objectives of the present study were (a) to prepare a taxonomic conspectus of the alien flora of India, (b) to characterise the alien species with regard to their stage of invasion, and (c) to explore biogeographic affiliations of the alien flora of India.

Materials and methods

Study area

With an area of 3,287,240 sq km, India is the 2nd largest country in Asia and 7th in the world, and has a coastline of over 7,500 km length. It is the 2nd largest populous country in the world, with human population of more than 1 billion and population density of 325 persons per sq km; 72% of the population rural and 28% urban. The country is administratively divided into 28 States and 7 Union Territories (http://www.censusindia.gov.in).

India lies to the north of equator between 6° 45′–37° 6′ N latitude and 68° 7′–97° 25′ E longitude. The terrain of the country varies considerably, with upland plains (the Deccan plateau) in the southern region, flat to rolling plains along the Ganges river, deserts in the west, and the Himalayan mountains in the north. Notwithstanding regional climatic variations due to the geographical expanse and topographical heterogeneity, the major part of the country experiences a tropical to sub-tropical climate. Three distinct seasons are usually recognised in India: hot summer (late April-late June), rainy monsoon (late June-mid September), and mild winter (mid November-late March). The country is situated at the confluence of three major terrestrial bio-realms, viz. the Indo-Malayan, the Eurasian, and the Afro-tropical. The vast geographical expanse of the country results in a striking bio-climatic diversity, which ranges from sea level to the highest mountain ranges in the world; hot-arid conditions in the West to tropical evergreen forests in North-east and Western Ghats; cold-arid conditions in the trans-Himalayas to mangroves of Sunderbans; and freshwater aquatic to marine ecosystems (Negi 1986). Because of these factors, the country shows a great habitat diversity represented by forests, grasslands, wetlands, coastal, marine and desert ecosystems harbouring a rich biodiversity. India represents one of the world's 12 Vavilovian centres of origin and diversification of cultivated plants, the "Hindustan Centre of origin of crop plants" (Vavilov 1951); and has a representation of 12 biogeographical provinces and 5 biomes (Udvardy 1975). In fact, the country is one of the 17 megadiverse countries, ranking 3rd in Asia and 11th in the world; and it shares four global biodiversity hotspots (Sharma and Singh 2000; Mittermeier et al. 2005).

Since its independence in 1947, India has been the world's largest democracy; and presently it is one of the fastest growing economies in the world. Despite gains in economic development, the country faces pressing problems, such as runaway overpopulation, and environmental degradation. During the last few decades, India has lost at least 50% of its pristine forests, polluted over 70% of its water-bodies, and converted much of its grasslands into agricultural fields or urbanised townships (Sharma and Singh 2000). It is estimated that about 7.7% of the Indian vascular-plant flora is facing risk of extinction (Rao et al. 2003).

History of plant introductions

The entry of alien plants into India has occurred through different pathways over time. A large number of alien plants have migrated along ancient and modern trade routes via land, sea and air, and with general migration of pastoral and nomadic tribes, with ballast, and as contaminants of food grains, seeds of crop plants, etc. India's colonial past and historical trade relations have led to the plant introductions by British, Portuguese, Spanish, French, and from the Middle East and Central Asian countries (Pandey 2000). During the sixteenth century, the Portuguese had established a commercial route from Lisbon to Brazil and thence from the Cape of Good

Hope (South Africa) to Goa in India. They introduced many tropical American plants, along with came a number of aggressive weeds. Later on, the Spanish, the Dutch, the French, and the British also brought many economic plants from South America, Mexico and Africa. There has also been intentional introduction of seeds and other propagules through botanic gardens, arboreta, private seed companies, etc. Seaports have always been a hub of alien plant introduction, as ballast, ore, and coal piles, lumberyards and docks afford favourable conditions for alien plants to establish in a new environment. The unintentional introduction of invasive aliens has resulted from contaminated garden seeds, food grains, forage, and also by human transport systems (Srivastava 1964).

Data sources

We developed this alien species inventory from an extensive review of the literature (ca. 190 studies) published over the last 120 years (1890–2010 AD). Research papers published in peer-reviewed and local journals, books, book chapters, scientific reports, forest management plans, regional exotic floras, weed floras, field guides, flower manuals, and other relevant publications were reviewed and analysed (supplementary material-I). The use of general Floras was mostly avoided for two reasons. First, since the publication of *The Flora of British India* (Hooker 1872–1897) more than a century ago, a complete and updated Flora of India is still lacking. Second, until recently, State and regional floras in the country rarely indicate native or alien status of the species listed therein. Very often, the naturalised alien species have been treated as native to the floras. Therefore, we focussed on the scientific literature dealing exclusively with the alien flora. To characterise the invasion status, the alien flora was annotated with information extracted from the original sources and additional literature such as research papers, local or regional weed floras of different States in the country. All species reported by earlier workers from different regions of the country as being 'exotic', 'non-indigenous', 'foreign', 'waifs', 'adventives', 'alien naturalised', 'introduced', and 'immigrants' have been included in our list of the alien plants of India. A number of agricultural weed species, whose native distribution range falls within the country have been excluded from the inventory. Also, alien plants grown exclusively under the green-house conditions, pots, indoors, and other such artificial conditions have been excluded from the inventory.

Only vascular plant species being alien to the territory of the whole country (i.e. 'Aliens to India') are included in the present study (see Pyšek et al. 2009). A large number of species recorded as aliens in different regions of the country, but whose native range falls within the political boundary of the country (i.e. 'Aliens in India') have been excluded in the present study. Example of an 'Alien in India' is the Himalayan Chir Pine (*Pinus roxburghii*) recorded as "exotic" in southern India (Matthew 1969).

Taxonomy

The scientific nomenclature of species was updated using taxonomic online databases, such as The Annual Checklist of World Plants (http://www.sp2000.org), International Plant Names Index (http://www.ipni.org), E-Floras (http://www.efloras.org), and Germplasm Resources Information Network (http://www.grin.org). The taxa were considered at the taxonomic rank of species; infra-specific taxa (subspecies, variety, and forma, wherever recognised) have been subsumed into their respective species, with the exception of a few infra-specific taxa of *Brassica oleracea*. For the arrangement of species within genera and of genera within families, Mabberley (1997) has been followed. However, the family Fabaceae (*sensu lato*) has been divided into three families (*sensu stricto*): Papilionaceae, Caesalpiniaceae and Mimosaceae.

Alien species recorded in the earlier literature with invalid names, such as incorrect author citation, misapplied name, etc., have been excluded from the inventory, if later workers failed to validate these species anywhere from the country. To ensure reproducibility of the data, inclusion of name records of alien species with conflicting taxonomy was avoided. A high number of 520 scientific names, previously recorded as distinct species, turned out to be synonyms. This emphasizes the fact that if synonymy is not taken into account, then it may lead to taxonomic inflation in biodiversity studies (Khuroo et al. 2007b).

Native ranges

In assigning the native ranges to all the species, a biogeographic approach has been followed. Only those species comprise the alien flora of India whose native ranges fall outside the borders of the Indian subcontinent. Instead of restricting to the narrow political boundaries of India, the broad geographical boundaries of the Indian subcontinent have been taken into consideration. Therefore, the native species from immediate neighbouring countries, such as Pakistan, Nepal, Bhutan, and Bangladesh, were excluded. Species native to one Indian region but recorded as aliens in some other region(s) were excluded from the present study. The native range for each species was primarily obtained from the original source of its record in India. However, in order to minimise the error of judgement by earlier workers about the alien status, and to cross-check the native range records, the native ranges for all the species were verified with data from the Germplasm Resources Information Network (www.grin.org), and some other recently published papers. After this extensive exercise and critical review in light of recent biogeographic evidences, a large pool of species previously recorded as aliens to India turned out to be native to the country and, therefore, were excluded from the present study. Those alien species where the recognition of native range was uncertain were grouped under the cryptogenic category (Carlton 1996).

The records of native ranges for alien species are of different quality in the literature. Historically, as the species native ranges have been recorded at the climatic, inter-continental, continental, sub-continental, country, provincial, regional, and sub-regional scales, a single scheme of native ranges was impracticable for the entire alien flora. Above all, under natural conditions, the species are distributed at varying spatial scales, from one extreme of cosmopolitan distribution to the other extreme of locally restricted distribution. Therefore, the native ranges for each species in the dataset were documented as per the records available. However, for the biogeographic analysis of the total alien flora and the invasive species separately, the native ranges were pooled together at the continental scale (see Khuroo et al. 2007a). In this scheme, the continent of South America includes all the parts of tropical Central America as well, and Asia includes all parts except the Indian subcontinent.

Invasion status

We have compiled the dataset of all the alien plant species in India, whether they grow only under cultivation or have escaped into the wild. All the alien species were designated as 'aliens under cultivation' (Cl), unless there was any published record or our own field observation of their escape from cultivation, or self-reproducing population. The remaining subset of alien species that escaped into the wild has been evaluated with regard to their invasion status in the country.

The terminology and definitions as proposed by Pyšek et al. (2004) for designating the species as casual (Cs), naturalised (Nt) and invasive (In) have been followed. In addition, we defined two more invasion status categories of casual or naturalised (C/N) and naturalised or invasive (N/I), because for many species information was not sufficient to unambiguously allocate species to Cs, Nt, or In. "C/N" refers to those casual alien species for which the current evidence is insufficient to be recognised as naturalised but have the potential to become naturalised in near future, and "N/I" refers to those naturalised alien species for which the current evidence is insufficient to be recognised as invasive, but have the potential to become invasive in near future. In summary, the present study uses six different categories: cultivated (Cl), casual (Cs), casual or naturalised (C/N), naturalised (Nt), naturalised or invasive (N/I), and invasive (In).

It is relevant to mention here that a large number of alien plant species which in earlier studies have been reported as casual, are reported as naturalised or invasive in recent papers. For example, the species reported as 'occasional escapes', or 'run wild' in earlier studies have now become fully naturalised, and many of these are spreading fast all over the country. In such cases, the recent reports and field observations have taken precedence in designation of the invasion status. Many cultivated species, in particular trees, that have long 'established' but have no record of self-reproducing populations have been called as 'naturalised' by earlier workers. All such alien plant species in the present dataset, however, have been put under the cultivated category (Cl), and

excluded from naturalised category (Nt) (see Richardson et al. 2000).

To compare the intensity of plant invasions in India with those of other countries of the world, we calculated the species density as $D = N/\log (A)$; where N is the total number of species at different stages of invasion (casual to invasive), and A is the area of the country (Rejmánek and Randall 1994).

Results

Taxonomic composition

The inventory includes 1,599 alien species in India; these belong to 842 genera in 161 families (see supplementary material-II). All the species are listed alphabetically in their respective genera. For each species is given its scientific name, author citation, family, invasion status, and native range. (An MS-excel file of the species list is available from the corresponding author upon request). The angiosperms are represented by 1,552 species belonging to 825 genera in 152 families; gymnosperms by 46 species belonging to 16 genera in 8 families; and whereas pteridophytes have a single species.

The three most species-rich families are Asteraceae (134 spp.), Papilionaceae (114 spp.), and Poaceae (106 spp.). Of the total 161 families represented in this inventory, the 20 largest families disproportionately contribute 959 species, thereby showing a higher average family:species ratio of 1:48 (Table 1). For the remaining 141 families, sharing 640 species, the ratio of family:species is very low (1:4.5). The first three species-rich genera are *Eucalyptus* (25 spp.), *Ipomoea* (22 spp.), and *Senna* (21 spp.). Of the total 842 genera represented in the inventory, the largest 15 genera disproportionately contribute 215 species, thereby showing a higher average genus:species ratio of 1:14.3 (Fig. 1). For the remaining 827 genera, sharing 1,384 species, the genus:species ratio is very low (1:1.7). Monospecific taxa, (i.e. taxa represented by a single species in the inventory) are 546 genera and 49 families, which contribute 65% and 30% of the total

Table 1 Distribution of different invasion status categories, including cultivated, in the largest 20 families in the alien flora of India

Family	Number of species						
	Total	Cultivated	Casual	Casual or naturalised	Naturalised	Naturalised or invasive	Invasive
Asteraceae	134	25	9	6	25	26	43
Papilionaceae	114	48	3	5	38	9	11
Poaceae	106	19	15	10	34	15	13
Caesalpiniaceae	64	45	0	4	2	4	9
Solanaceae	63	24	3	4	12	7	13
Myrtaceae	59	51	0	3	5	0	0
Euphorbiaceae	52	23	1	3	7	4	14
Rubiaceae	42	30	0	0	5	5	2
Malvaceae	40	19	1	1	6	7	6
Apocynaceae	33	25	0	6	1	0	1
Convolvulaceae	30	7	1	1	11	0	10
Brassicaceae	29	9	6	0	7	2	5
Verbenaceae	29	14	1	9	1	1	3
Bignoniaceae	29	26	1	0	2	0	0
Amaranthaceae	28	2	1	3	3	5	14
Arecaceae	28	24	0	1	2	0	1
Rosaceae	23	16	0	5	2	0	0
Scrophulariaceae	20	9	1	1	4	0	5
Caryophyllaceae	18	4	4	0	3	4	3
Cupressaceae	18	15	0	3	0	0	0

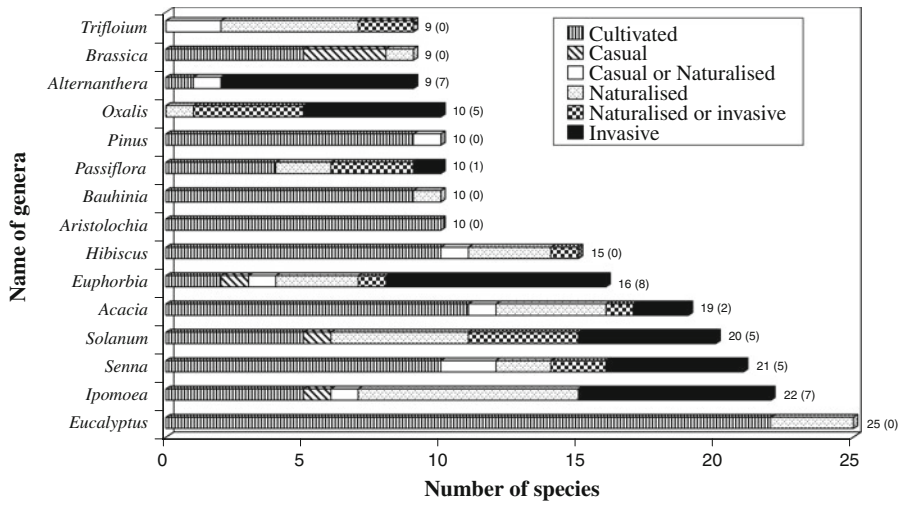

Fig. 1 Number of species at different stages of invasion, including cultivated species, in the largest 15 genera in the alien flora of India (total number of alien species, and number of invasive species is given in *parentheses*)

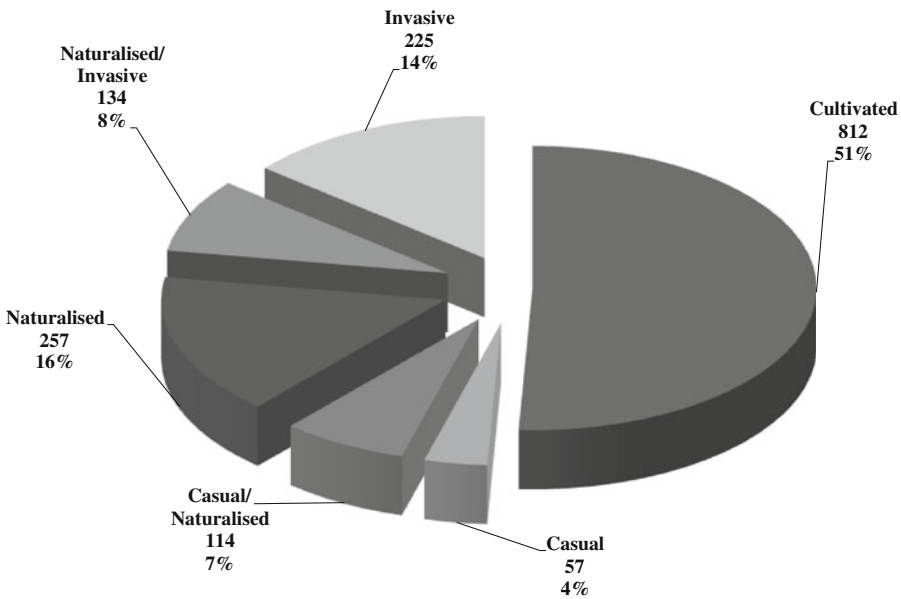

Fig. 2 Numbers and percentages of species at different stages of invasion, including cultivated species, in the alien flora of India

number of genera and families in the inventory, respectively.

Invasion status

Out of the total alien species in the inventory, more than half (812 spp., 51%) belong to the cultivated category, i.e. having no report of their escape from the cultivation. The distribution of the remaining 787 (49%) alien species under different stages of invasion, with their species numbers and percentage in the total alien flora, is as follows: casual (57 spp., 4%), casual or naturalised (114 spp., 7%), naturalised (257 spp., 16%), naturalised or invasive (134 spp., 8%), and invasive (225 spp., 14%) (Fig. 2).

There is a clear difference in the number and percentage of species belonging to different families and genera at various stages of invasion. The proportion of species belonging to different invasion categories shows great variation among the larger families. While analysing contribution of the first 20 larger families to the Indian alien flora at different stages of invasion in terms of number of species, Myrtaceae has largest number of cultivated species (51spp.), followed by Papilionaceae (48 spp.), and Caesalpiniaceae (45 spp.). In contrast, Poaceae has

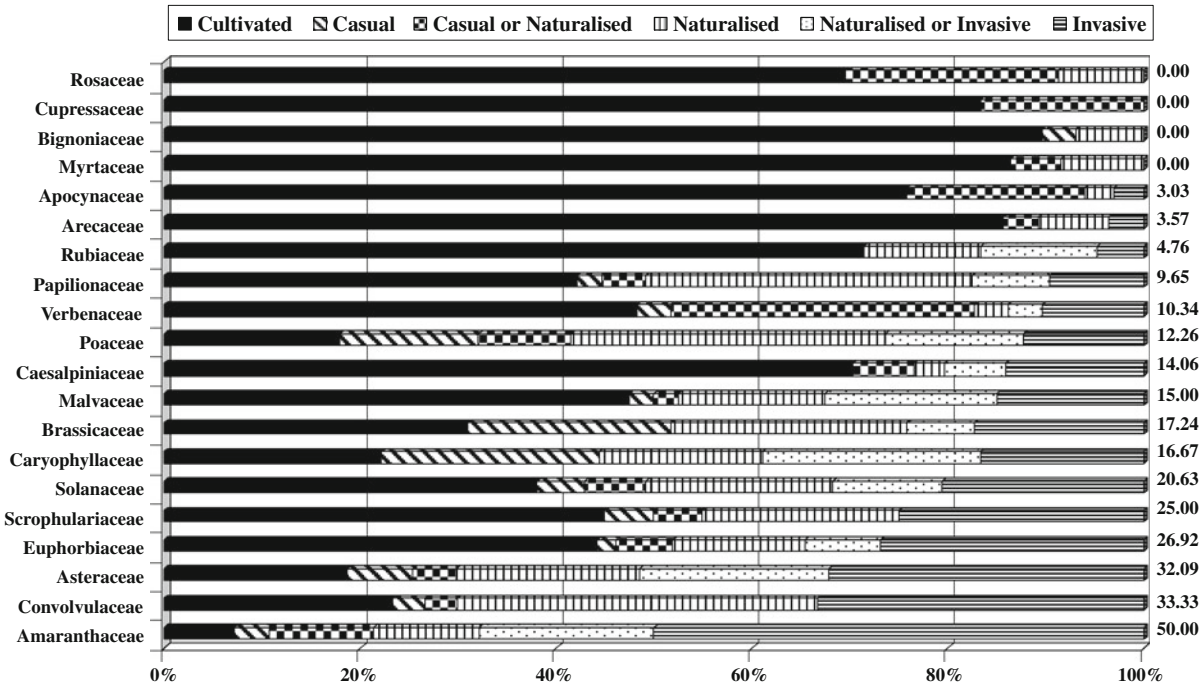

Fig. 3 Percentage contribution of the first 20 larger families to the different invasion status categories, including cultivated, in the alien flora of India (percentage of invasive species in the families is given on the *right hand side*)

the largest number of casual species (15 spp.), followed by Asteraceae (9 spp.), and Brassicaceae (6 spp.). In the case of casual or naturalised category, again Poaceae has the largest number of 10 species, followed by Verbenaceae (9 spp.), and Asteraceae and Apocyanceae (6 spp. each). In the case of naturalised category, Papilionaceae has the largest number of 38 species, followed by Poaceae (34 spp.), and Asteraceae (25 spp.). In the case of naturalised or invasive category, Asteraceae has the largest number of 26 species, followed by Poaceae (15 spp.), and Papilionaceae (9 spp.). Finally, in the case of invasive category, again Asteraceae has the largest number of 43 species, followed by Amaranthaceae and Euphorbiaceae (14 spp. each), and Poaceae and Solanaceae (13 spp. each) (Table 1).

While as Asteraceae contributes the largest number of species (43 spp.) to the list of 225 invasive species, it ranks third (32%) much after Convolvulaceae (33%) and Amaranthaceae (50%), in terms of proportion of invasive species to the total number of species in the alien flora. Similarly, while Papilionaceae and Poaceae rank third in terms of species numbers, these families have rather few invasive species and rank distant eleventh and twelfth in their percentage contribution to the invasive species. There are eight families having more than 70% of cultivated species (Fig. 3). Whereas *Eucalyptus* (25 spp.) is the largest genus in the alien flora, it does not contribute even a single invasive species. On the other hand, *Euphorbia* (16 spp.) contributes 8 invasive species. Some other species-rich genera, such as *Alternanthera* (9 spp.) and *Ipomoea* (22 spp.) have 7 invasive species each; and *Oxalis* (10 spp.), *Senna* (21 spp.) and *Solanum* (20 spp.) have 5 invasive species each (Fig. 1).

In the alien flora of India, 49 families are represented by a single species, the majority of which (28 spp.) belongs to the cultivated category. The remaining 21 species are distributed among different stages of invasion (Fig. 4a). Interestingly, some of these families comprise only invasive species in India (e.g., Balsaminaceae, *Impatiens balsamina* L.; Cannabaceae, *Cannabis sativa* L.; Ceratophyllaceae, *Ceratophyllum demersum* L.; Martyniaceae, *Martynia annua* L.; Menispermaceae, *Cissampelos pareira* L.; Salvinaceae, *Salvinia molesta* Mitchell; and Potamogetonaceae, *Potamogeton crispus* L.).

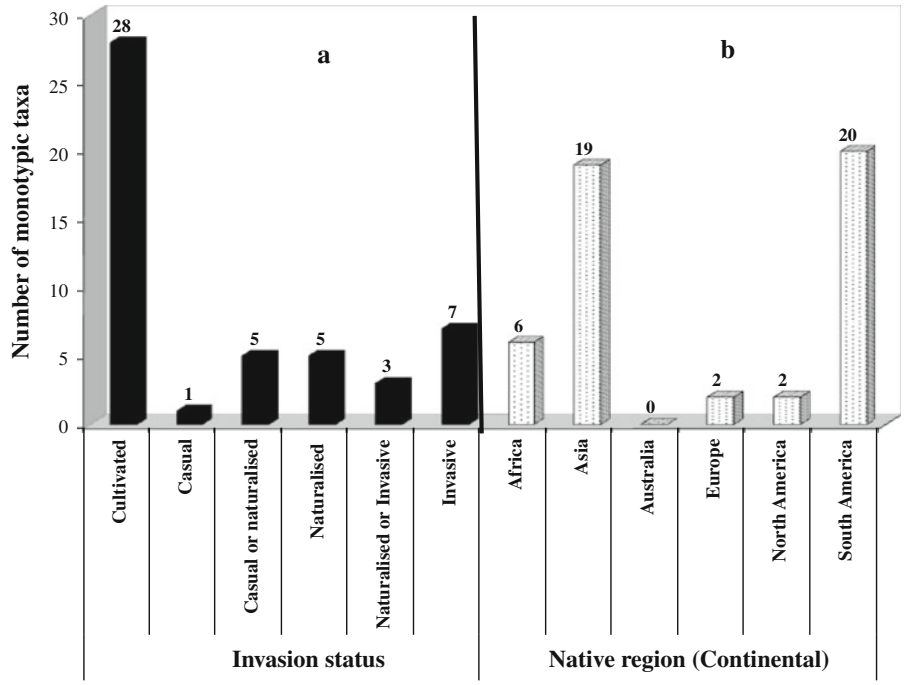

Fig. 4 Number of monospecific families **a** by their invasion status and **b** by their native region (continental) in the alien flora of India

In terms of percentage of alien species to the total number of species in India, only two families, Martyniaceae and Turneraceae show a value of 100%; and six families (Caesalpiniaceae, Oxalidaceae, Pontederiaceae, Portulacaceae, Solanaceae, Typhaceae) show a value of more than 50%. However, when analysed in terms of percentage of invasive species to the total number of alien species in India, seven families have a value of 100%, e.g. Balsaminaceae, Cannabaceae, Martyniaceae, Pontederiaceae, Potamogetonaceae, Salvinaceae and Tureraceae. Three families (Asclepiadaceae, Capparaceae and Oxalidaceae) show more than 50% values (Table 2).

Out of the 36 plant species recognised among the "world's worst invasive alien species" (Lowe et al. 2000), the present inventory of alien vascular plant species in India includes 17 species. Of these, the present study characterized 11 species as invasive to India: *Acacia mearnsii*, *Arundo donax*, *Chromolaena odorata, Clidemia hirta, Imperata cylindrica*, *Lantana camara, Leucaena latisiliqua* (syn. *Leucaena leucocephala*), *Mikania micrantha, Opuntia stricta, Ulex europeus* and *Sphagneticola trilobata (*syn. *Wedelia trilobata);* of the remaining 2 species—*Mimosa pigra* and *Prosopis glandulosa*, are recognised as naturalised or invasive, whereas the four other species (*Cinchona pubescens*, *Psidium cattleyanum, Schinus terebinthifolius, Spathodea campanulata*) are among the cultivated species in India.

Biogeographic affiliations

More than one-third (35%) of the total alien flora of India has its origin in the South American continent. Most South American species come from Mexico and Brazil (75 and 54 species, respectively). The percentage contribution by other continents greatly varies (Fig. 5); other important source areas are Asia and Africa. Cryptogenic species make 1%. More specifically, while analysing the native ranges of 225 invasive species, more than half (52%) are from South America. The contribution of other continents is as follows: Africa (16%), Asia (16%), Europe (9%), North America (4%), Australia (2%) and cryptogenic (1%) (Fig. 5). The pattern of origins is very similar if only those families represented by single species in the Indian alien flora are considered (Fig. 4b).

Discussion

The 1,599 alien species recorded in this study lead to a proportion of 8.5% alien species in the vascular

Table 2 Numerical and proportion values of families with representation of invasive species in the alien flora of India, with reference to the total number of alien species, and total number of species in India

Family	Total number of species in India	Total number of alien species	Proportion of alien species to total number of species	Total number of invasive species	Proportion of invasive to alien species
Acanthaceae	500	16	3.20	1	6.25
Amaranthaceae	60	28	46.67	14	50.00
Apiaceae	288	10	3.47	2	20.00
Apocynaceae	119	33	27.73	1	3.03
Araceae	126	9	7.14	1	11.11
Arecaceae	94	28	29.79	1	3.57
Asclepiadaceae	260	5	1.92	4	80.00
Asteraceae	800	134	16.75	43	32.09
Balsaminaceae	200	1	0.50	1	100.00
Boraginaceae	209	13	6.22	1	7.69
Brassicaceae	207	29	14.01	5	17.24
Cactaceae	NA	13	NA	2	15.38
Caesalpiniaceae	92	64	69.57	9	14.06
Cannabaceae	NA	1	NA	1	100.00
Capparaceae	55	5	9.09	4	80.00
Caryophyllaceae	122	18	14.75	3	16.67
Casuarinaceae	12	3	25.00	1	33.33
Ceratophyllaceae	2	1	50.00	1	100.00
Chenopodiaceae	71	4	5.63	2	50.00
Convolvulaceae	199	30	15.08	10	33.33
Cyperaceae	1,545	15	0.97	3	20.00
Euphorbiaceae	527	52	9.87	14	26.92
Lamiaceae	435	16	3.68	3	18.75
Liliaceae	214	10	4.67	1	10.00
Malvaceae	93	40	43.01	6	15.00
Martyniaceae	1	1	100.00	1	100.00
Melastomataceae	150	3	2.00	1	33.33
Menispermaceae	43	1	2.33	1	100.00
Mimosaceae	127	44	34.65	7	15.91
Moraceae	122	9	7.38	1	11.11
Nyctaginaceae	15	5	33.33	1	20.00
Oxalidaceae	19	11	57.89	6	54.55
Papaveraceae	27	7	25.93	2	28.57
Papilionaceae	973	114	11.72	11	9.65
Passifloraceae	24	10	41.67	1	10.00
Pedaliaceae	4	2	50.00	1	50.00
Piperaceae	101	3	2.97	1	33.33
Poaceae	1,291	106	8.21	13	12.26
Polygonaceae	164	12	7.32	1	8.33
Pontederiaceae	3	2	66.67	2	100.00
Portulacaceae	8	5	62.50	2	40.00
Potamogetonaceae	18	1	5.56	1	100.00

Table 2 continued

Family	Total number of species in India	Total number of alien species	Proportion of alien species to total number of species	Total number of invasive species	Proportion of invasive to alien species
Primulaceae	183	2	1.09	1	50.00
Rubiaceae	616	42	6.82	2	4.76
Salvinaceae	NA	1	NA	1	100.00
Sapindaceae	55	11	20.00	1	9.09
Scrophulariaceae	368	20	5.43	5	25.00
Simaroubaceae	16	3	18.75	1	33.33
Solanaceae	75	63	84.00	13	20.63
Tiliaceae	53	9	16.98	6	66.67
Turneraceae	2	2	100.00	2	100.00
Typhaceae	3	2	66.67	1	50.00
Urticaceae	153	3	1.96	1	33.33
Verbenaceae	140	29	20.71	3	10.34
Zygophyllaceae	15	5	33.33	1	20.00

NA not available

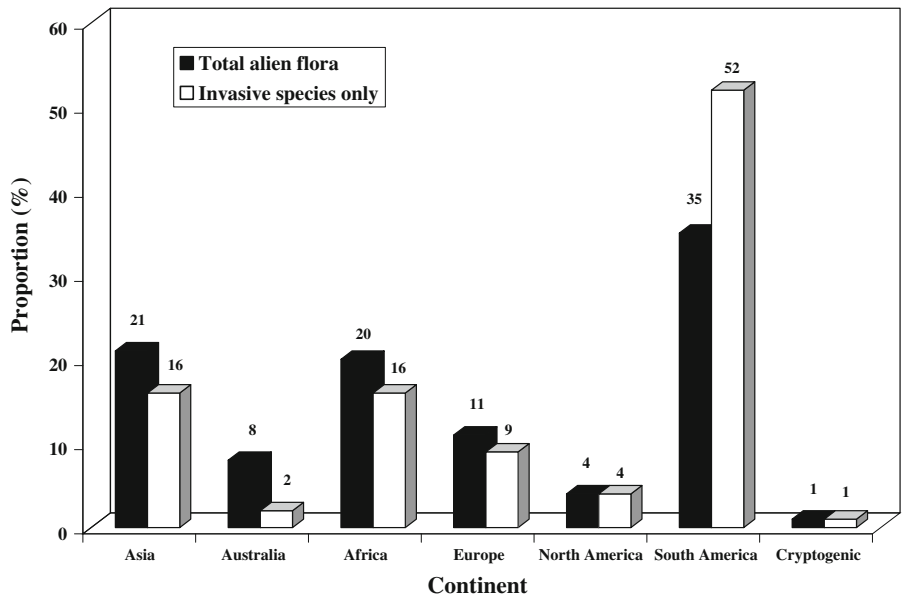

Fig. 5 Proportion of total alien species and only invasive species from different continents (including cryptogenic) contributing to the alien flora of India

flora of India, based on a total number of 18,748 vascular plant species (Arora and Bhatt 2008). The percentage is only 4.2% when calculated for the alien flora excluding cultivated species (i.e. total number of species from casual to invasive status is 787 spp.) to the total vascular flora of India; and 14% (225 spp.) of the total alien flora having reached the invasive stage (Fig. 2). These percentages are significantly lower than previously published estimates. For instance, according to the Third National Report, 40% of the Indian flora is alien, out of which 21% is invasive. That would lead to ca.7,500 alien species in

India, out of which ca. 1,575 would be invasive species. These estimates, however, are more likely based on assumptions without sound empirical data.

The percentage of 4.2% calculated for the alien flora of India, excluding cultivated species, is much higher than that reported for China (1.4%) (percentage based on 420 species reported in Wu et al. (2010), and 31,000 vascular plant species recorded in Flora of China) (http://hua.huh.harvard.edu/china/). The total number of 1,599 species alien in India is lower than the 28,866 species recorded as alien in Australia (Randall 2007), 25,049 species in New Zealand (Diez et al. 2009), and 2,843 species in Europe (Lambdon et al. 2008). Such a lower number and percentage of alien species in the Indian flora compared to numbers from the developed world may possibly be due to: (1) non-inclusion of archaeophytes in the present study, (2) poor record-keeping of alien species introduced into the country by various governmental and private agencies, (3) the records of introduced plants having been traditionally least-reported and/or excluded from the floristic works, and (4) very scarce taxonomic research effort in developing countries, including India.

In concordance with the alien floras of Europe (Lambdon et al. 2008) and China (Wu et al. 2010), Asteraceae is the most species-rich family in the alien flora of India. However, Papilionaceae is the second species-rich family, in contrast to Poaceae in Europe and China, which ranks third in India. Brassicaceae, which is the fifth largest family in Europe and the sixth in China, does not appear among the top ten largest families in India. Rosaceae, which is the third largest family in the European alien flora, has rather few species (rank 17) in India. Brassicaceae and Rosaceae are the families mostly concentrated in the northern temperate hemisphere and their lesser representation in India compared to Europe may possibly be due to only few montane areas in northern India, having influence of temperate climate.

It is a well known fact that the higher species contribution of families such as Asteraceae, Papilionaceae or Poaceae to the alien floras is mainly due to a sampling effect. These families are globally known to be species-rich and, therefore, higher number of alien species belonging to these families is expected. However, the percentage contribution of the taxonomic families to the invasive species is disproportionate. Thus, half of the species (50%) in the family Amaranthaceae are invasive, followed by nearly one-third species in Convolvulacaeae (33%), and Euphorbiacaeae (27%). Such a higher predisposition of species from Amaranthaceae, Convolvulacaeae and Euphorbiaceae to be invasive than others has also been reported from China (Wu et al. 2010). On the other hand, Papilionaceae and Poaceae, ranking 2nd and 3rd in terms of species number, show a lesser percentage contribution of 10 and 12% to the invasive species, respectively.

Amongst the highly represented genera in the alien flora of India, only *Euphorbia*, *Solanum* and *Trifolium* are reported in Europe; while in China, predominance of genera such as *Euphorbia*, *Senna*, *Alternanthera, Ipomoea* has been reported. However, *Oenothera* and *Amaranthus*—predominant genera in the alien flora of Europe and China—are interesting exceptions, as these are not amongst the species-rich genera in the alien flora of India (Fig. 1). Taxonomic distribution of nearly 60% of total species in the first 20 largest families indicates a phylogenetic clustering in the alien flora of India (Table 1). Whether this is due to human preference for the introduction of particular type of taxa, or something else, merits detailed investigation, which is beyond the scope of the present study.

Our study is significant in the sense that it includes the alien cultivated plant species, which have often been ignored in most of studies on alien floras. It is this species pool of cultivated plants which is the potential source of future invasive species. In essence, many alien species presently escaped from cultivation and recognised at different stages of invasion were under cultivation at some point of time. Comparative analyses of failure and success of species to escape from cultivation is possible only with the inclusion of 'species under cultivation' in the alien flora inventories (Diez et al. 2009). Moreover, rigorous testing of hypotheses and robust scientific understanding in invasion biology can be achieved only when the data is made available for the entire pool of alien species, their residence time, and extent of naturalisation.

Among the 36 plant species belonging to the "world's worst invasive alien species", 17 species also occur in India. Of these, the recognition of 11 species as invasive and two species as naturalised or invasive is a considerably higher number. Immediately relevant from the management perspective is

that the four alien species *Cinchona pubescens*, *Psidium cattleyanum, Schinus terebinthifolius* and *Spathodea campanulata,* which are not reported to have escaped from cultivation in India, need to be monitored strictly and at best, their cultivation should be discouraged as a preventive measure.

The total number of naturalised species has been used as a reliable predictor of invasive species. Rejmánek and Randall (2004) concluded that 15–30% of the total naturalised species were invasive in the US, a proportion higher than the 10% proposed by Williamson and Fitter (1996). Our results are in concordance with those of Rejmánek and Randall (2004), as 31% (225 spp.) of the total naturalised species (730 spp.) belonged to the invasive category, when the 869 species (cultivated 812 spp., casual 57 spp.) were excluded from the analysis.

On analysing the intensity of plant invasions, using the density index (Rejmánek and Randall 1994), India shows a lower value of 120.76 as compared to 298.95 for New Zealand, 197.13 for Japan, and 175.36 for British Isles (Wu et al. 2004). On the other side, the density value of 120.76 for India is much higher than that for China (60.14), (Wu et al. 2010). Such a higher value may be the result of relatively longer history of colonisation by the Europeans, and rulers from the Central Asia in India than in China. In addition, until the recent past, China was much more isolated from rest of the world than India.

By and large, the Indian alien flora has a South American origin; though the floristic elements of Asian, African, European, Australian, and North American origin are also well represented in the total alien flora, as well as in the list of invasive species. Nevertheless, the proportion of South American species, in particular tropical Central America, is disproportionately higher in the case of invasive species (52%), as compared to the total alien flora (35%). Opposite to this trend, the proportion of Australian species is disproportionately higher in the case of total alien flora (8%), as compared to invasive species (2%). The possible explanation for the maximum proportion of species from South America can be (1) the higher propagule pressure from different countries, such as Brazil and Mexico, to India via historical trade routes through the human agency of European colonisers and traders, and (2) more or less matching of similar tropical climate. When considering that 56% of species originate from the Americas, the results in the present study are similar to those reported for China, wherein 58% of species have their origin from the Americas (Wu et al. 2010). On the other hand, however, the share of American species in the alien flora of Europe is 34.8% (Lambdon et al. 2008), much lower than in the present study. Such a varying trend can be explained in terms of larger influence of tropical climate in India and China, rather than in Europe.

Future implications

The inventory of the alien flora of India will help in bridging the geographical knowledge gaps in invasion biology research. The inventory will serve as a scientific baseline for investigating the patterns, pathways, extent, impacts and effective management of plant invasions in India. As the inventory is based on the synthesis of knowledge accumulated over the last one century, it will stimulate the much-needed research on invasion biology, invite attention of policymakers and raise public awareness in the developing world, including India. The characterization of alien flora at different stages of invasion, as attempted in the present study, will help in targeted prioritisation of research and management efforts required at the country scale. It will also pave way for formulation of a predictive management framework that includes elements of risk analysis, early detection and warning systems which are pre-requisites for taking informed decisions for the eradication and control of invasive species. Finally, the availability of data on invasive alien plant species in India will contribute to the larger goal of setting robust Global Biodiversity Targets and Indicators, with far-reaching policy implications for the conservation and sustainable use of biodiversity.

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