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An integrated policy framework and plan of action to prevent and control plant invasions in India

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Abstract

Biological invasions are a major global challenge for the conservation of biodiversity, maintenance of ecosystem health and sustainable livelihoods. As the number of novel introductions of invasive species is predicted to increase due to rising trade volumes in the emerging economies, regulatory policies to prevent the introduction and spread of invasive species are of paramount importance. However, poor response capacities, lack of coordination between stakeholders, heavy dependence on biological resources and little public awareness are some of the formidable barriers in framing and implementing such policies in developing countries.

This study was conceptualized to establish common ground by considering the diverse interests of different actors and design a policy framework to control invasive alien plant species (IAPS) in the lower-middle income economies considering India as a case study. To achieve this objective, we evaluated the reasons for the introductions and current economic uses of IAPS in India and critically reviewed the infrastructure and current response capacity of the country for regulating pre- and post-border trading of these problematic species. We found that the majority of IAPS were introduced for ornamental purposes and some of them are still actively traded and used for several economic purposes. Despite having a rich legacy of environmental policies, a legal framework exclusively to deal with invasive species is non-existent in India. Here, we propose a set of policy interventions, for international and domestic trading, by integrating trade regulations based on a risk assessment framework with interests of both consumers and traders to ensure effective compliance from all stakeholders. Further, we identify potential hurdles for policy implementation in India and therefore, based on the existing biosecurity infrastructure, we outline an operable and dynamic decentralized system having a standard operating procedure to ensure coordination between different stakeholders, increase public awareness and guide further research direction.

Keywords: Developing country; Economic use; Invasive alien species; Legal framework; Risk assessment; Trade

1. Introduction

Biological invasions represent one of the major environmental challenges for the conservation of global biodiversity and continuation of ecosystem services, and have a serious impact on human and animal health and economic development (Pyšek et al., 2020; Simberloff et al., 2013). Increased demand for plant species for food, fodder, floriculture, forestry and other purposes has led to a global surge in trade and associated transport activities, thus providing the principal pathways for the introduction of plant species outside of their native ranges (Seebens et al., 2017). Identification of the introduction pathways and implementation of biosecurity measures are important regulatory tools for preventing the introduction of alien species associated with environmental and health risks (Nuñez et al., 2020). Notwithstanding differences in identifying species eligible for trading across geographic regions, the approach generally involves trading regulation of species based on their invasion risks using standard risk assessments and biosecurity policy framework.

Apart from mitigating the risks of invasive alien species (IAS), another rationale for policy formulation is to reconcile the conflicts of interest among different stakeholders (Novoa et al., 2018). For example, strict regulatory policies on trading alien ornamentals often face stiff opposition from the industry on the ground that it delivers significant economic benefits. Such contentious issues demand policy directions to be mutually agreeable for easy implementation and cost effectiveness. Several studies have been conducted to guide how this goal can best be achieved (Barbier et al., 2013; Hulme, 2015). In general, these studies have mostly focused on the developed world, thereby leaving large knowledge gaps for the developing countries. The latter's urgent need for IAS regulatory policies is further necessitated by the predicted increase in invasion levels in emerging economies due to the relative increase of trade volumes (Seebens et al., 2015). However, poor response capacities, little awareness among stakeholders and lack of coordination between agencies (Boy and Witt, 2013; Early et al., 2016) make the task of formulation and implementation of such policies difficult. Additionally, with the increasing trend of IAS denialism (Russell and Blackburn, 2017) and heavy dependence on biological resources in the emerging economies (Nunez and Pauchard, 2010), the conflict of interest among stakeholders often goes unresolved and becomes a major roadblock to the IAS policy formulation.

As the environment, economy and public health of developing countries are continuously being threatened by IAS, here we present some possible solutions to deal with it. In this study, we focused on India, a major economy in the developing world, which harbours 11% of the world's plant diversity and part of the four global biodiversity hotspots (Dar and Khuroo, 2020). Studies have shown that 8.5% of the total Indian vascular flora are alien, of which nearly 50% have either escaped from intentional cultivation or established in undisturbed natural ecosystems (Khuroo et al., 2012). In this context, our study specifically aimed to – 1) assess the existing biosecurity system in India to regulate the trading of invasive alien plant species (hereafter, IAPS), and 2) propose a set of policy interventions considering the interests of different stakeholders in the country. To achieve these objectives, we evaluated the past and present trading scenarios of IAPS in India and reviewed the biosecurity system for regulating pre- and post-border trading of these species. Based on our findings, we propose a set of scientific data-driven policy interventions considering the potential conflict of interest among different stakeholders. We also identify the likely impediments, starting from conception to implementation, and outline a standard operating procedure for successful implementation of this policy framework based on the existing biosecurity framework of the country.

2. Methods

We gathered the list of IAPS from the Global Register of Introduced and Invasive Species – India Version 1.3 (Sankaran et al., 2020). The database contains 2082 records of alien plant species out of which 264 species are classified as invasive. To avoid taxonomic ambiguity in the dataset, we standardised plant names using the *taxonstand* package ver. 1.8 (Cayuela et al., 2012) in R ver. 3.3.1; and the package is based on The PlantList (http://www.theplantlist.org). The distribution range of these 264 species was further checked from the Plants of the World Online database (http://powo.science.kew.org/, accessed 13 May 2020). To avoid any ambiguity regarding the origin status, the species identified as alien in India in both databases (n=180) were considered for further analysis (Table A.1).

The introduction pathways of these IAPS were first ascertained from the Google Scholar database (https://scholar.google.com/#d=gs_asd; accessed 20 May 2020) by searching for species names with at least one of the search queries related to introduction pathway ("introduction history" OR "introduced" OR "introduction purpose" OR "introduction pathway") present anywhere in the article with the exact phrase "India". The screening of articles continued until information related to specific reason for introduction of a species was obtained. In addition to these sources, we also searched two regional journals, namely Tropical Ecology archives and Indian Forester, which are not indexed in the Google Scholar database. Information for the remaining species (for which there was no data available from the literature) was retrieved from the CABI Invasive Species Compendium (ISC) (https://www.cabi.org/isc, accessed 12 June 2020). If information for India was missing for a species, evidence of introduction pathways elsewhere outside the species' native range was included. The introduction pathways were further categorized by following the introduction pathway classification framework of the Convention on Biological Diversity (Harrower et al., 2018).

The uses of these IAPS were first curated from the book *Ethnobotany of India* (Pullaiah et al., 2016). The five volumes of this book provided detailed and updated information of plant uses focusing on major biogeographical zones of the country. The medicinal use in India was recorded from the online database of the Environmental Information System's Centre on Medicinal Plants (http://envis.frlht.org/; accessed on 14 June 2020), operational under the aegis of the Ministry of Environment, Forests and Climate Change (MoEFCC), Government of India. Two additional databases, namely the Germplasm Resource Information Network (https://www.ars-grin.gov) and CABI-ISC (both accessed on 12 June 2020), were also explored. These databases provided information on economic uses reported across the distribution range of each species. The thirteen level 1 states of plant uses as prescribed by TDWG in their Economic Botany Data Collection Standard (Cook, 1995) was then used as a template to categorize the uses for each of the species.

We collected trading information of IAPS for ornamental and medicinal purposes in the Indian market since these two categories of uses were found to have maximum number of IAPS (see Section 3.1). Ornamental trading data were collected from two online nurseries (https://nurserylive.com/en/ (nursery 1) and https://www.plantslive.in/ (nursery 2), accessed on 15 July 2020). These nurseries were chosen because of their prominence in the online ornamental plant trade in India, availability of national-level shipping facilities, and more importantly, presence of scientific names of the plants in their catalogues. The following data were obtained: (i) species' presence in catalogues (yes/no), (ii) plant material being sold (plant/seed) and (iii) unit price. For medicinal plants, trading data were obtained from the Indian Medicinal Plants Database maintained by the National Medicinal Plants Board (http://www.medicinalplants.in/aboutfrlhtdb, accessed on 14 June 2020). The following data were collected: (i) species' presence in the trading list (yes/no) and, (ii) the source of plant materials (wild/cultivated/both).

3. Results

3.1 Introduction pathways and trading of IAPS in India

Information on introduction pathways was available for 129 IAPS (71.67%), out of which 106 species were introduced through a single pathway, whereas 23 species were introduced through multiple pathways (Table A.1). Categorization of introduction pathways [$n_{\text{number of (species x pathway)}} = (106x1) + (18x2 + (5x3) = 157$] revealed that majority of the IAPS (n = 85) were purposefully imported to the confined conditions followed by their escape from such confinement accidentally (Fig.1a). Among these, 54 species were introduced for ornamental purposes followed by agriculture (n = 15) and forestry (n = 10). Some IAPS (n = 14) were released in the natural environment for human use, whereas few IAPS were introduced through transport contaminant (n = 20), predominantly as seed contaminant. A couple of species were introduced as transport stowaway whereas introduction pathways were reported as 'accidental' for 36 species.

Nearly 50% of the IAPS (n=90) were found to have ornamental values (Fig.1b), out of which 68 species are being actively sold by the online nurseries. The average prices of plants were INR 357.18 (~US$ 4.69) ± SE 5.24 in nursery 1 and INR 484.77 (~US$ 6.37) ± SE 15.19 in nursery 2. The average price for 0.5kg seed was INR 1324.67 (~US$ 17.39) ± SE 67.21 in nursery 2. Although nearly 114 species were found to have medicinal uses (Fig.1b), only 26 out of 180 IAPS were listed as traded medicinal plants in India, and only seven of these species were sourced from cultivation. The traded plant species (Table A.1) included some of the 'World's 100 Worst Invasive Species' (e.g., *Acacia mearnsii* De Wild., *Clidemia hirta* (L.) D. Don, *Melaleuca quinquenervia* (Cav.) S.T.Blake) (http://www.iucngisd.org/gisd/100_worst.php, accessed 13 July 2020) and also some of the IAPS recognized in India's 5th National Report submitted to the Convention on Biological Diversity (e.g., *Lantana camara* L., *Mimosa pudica* L., *Galinsoga parviflora* Cav.) (https://www.cbd.int/reports/nr5/, accessed 18 May 2020). Furthermore, among the 54 terrestrial plant species identified as invasive aliens in India by the National Biodiversity Authority (NBA), Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India (GOI) (http://nbaindia.org/uploaded/pdf/Iaslist.pdf, accessed 18 May 2020), 17 (e.g., *Ageratina adenophora* (Spreng.) R.M.King & H.Rob., *Parthenium hysterophorus* L., *Prosopis juliflora* (Sw.) DC.) were found to be actively traded in India.

3.2 Existing trading regulations on IAPS in India

We critically reviewed the existing environmental policies and regulations that apply to IAPS. Since 1898, India has a rich legacy of policies and legislations to safeguard the country's environment and biodiversity. In the report on the transnational policy network submitted to the Convention on Biological Diversity in 2011, ten legislations related to IAS have been listed (https://www.cbd.int/invasive/doc/legislation/India.pdf, accessed 02 June 2020). Out of these, the regulation for import of plant materials into India has been addressed under The Plants, Fruits and Seeds (Regulation of Import into India) Order, 1989 and The Plant Quarantine (Regulation of Import into India) Order, 2003. Under the latter, the Directorate of Plant Protection, Quarantine and Storage was entrusted with the responsibility to issue biosecurity and phytosanitary import permits and for custom clearance following a set of standard operating procedures. Pest risk analysis is mandatory for importing plant or plant materials in the country and the import permits are issued for commodities for which such assessments have been indigenously done.

The list of quarantine plants (prohibited, restricted and regulated, Schedule VIII, amended in 2019) includes 57 species, many of which are hosts of important pests or diseases of arable crops and forestry (http://agricoop.nic.in/sites/default/files/Notification-on-Weed-Seed-Sch-VIII.pdf, accessed 02 June 2020), but surprisingly do not include any IAPS as recognized by other government and research agencies in the country. The list of 571 plants and plant materials mentioned in Schedule VI which are permitted to be imported in India with additional declaration and special conditions has only six recognized IAPS (*Acacia auriculiformis* Benth., *Calopogonium mucunoides* Desv., *Macroptilium lathyroides* (L.) Urb., *Mirabilis jalapa* L., *Pennisetum purpureum* Schumach. and *Ricinus communis* L.) (http://plantquarantineindia.nic.in/PQISPub/pdffiles/Schedule-VI-ason-4th-Oct2007.pdf, accessed 02 June 2020). Even these species (except *M. lathyroides* and *R. communis*) can be imported if the plant materials are free from seeds of 57 quarantined plant species listed under Schedule VIII. In India, where several governing bodies such as MoEFCC and Department of Biotechnology are responsible for regulating import of germplasms, GMOs, transgenics and biocontrol agents, no dedicated agency or governing body exists for regulating the pre-border movement of alien plant species. The Indian Council of Agricultural Research (ICAR) is the nodal agency for regulating plant imports in India. However, risk assessment of agricultural pests being the primary focus of their activities has led to large inaction on the IAPS, as evident from the absences of the recognized IAPS from the quarantine lists.

On the domestic front, India has nine policies focused primarily on agricultural pests and insects for different states and regions (e.g. The Assam Agricultural Pests and Diseases Act, 1950) (Kannan et al., 2013). At country scale, The Destructive Insects and Pests Act, 1914, has focused on preventing the transport of fungal or other plant pests destructive to arable crops and forestry within the country. However, national policy or legislation to regulate movements of IAPS and their management is lacking. In 2009, MoEFCC initiated the 'Integrated Forest Management (IFM)' scheme to control and eradicate IAPS in forested areas. Unfortunately, it failed to reach its full potential primarily because of lack of awareness about IAS at management level (Kannan et al., 2013). Additionally, the provisions of the IFM were in contradiction with the Wildlife Act, 1972 which prohibits the harvesting of any life-form from the protected areas of India.

4. Discussion

These findings corroborate that lack of overarching legal oversight coupled with complete or partial failure in the enactment of the existing policies has accelerated the unregulated import and domestic spread of IAPS in India. The absence of a legal framework has been acknowledged in many government documents, e.g. India's 5th National Report to CBD (https://www.cbd.int/reports/nr5/, accessed 02 June 2020), and the urgent requirement of an exclusive policy to deal with the issue of IAS in the country has been emphasized (Sandilyan et al., 2018b). Therefore, the present study proposes a scientifically informed and decision-based policy instrument by integrating a suite of options targeted for different stakeholders (importers, suppliers, consumers) involved in the trading of IAPS. Adopting a holistic approach by incorporating both prevention and control of plant invasions, the proposed policy measures involve: 1) restricting the import of IAPS and regulating their trade in the domestic market, 2) modifying the consumer behaviour by creating awareness, and 3) control or eradicate ongoing invasions.

4.1 Policies to prevent introduction and further spread of IAPS

Our study found that majority of IAPS were introduced to India for ornamental purposes, a pattern that is consistent with that reported from other countries [e.g., in Australia (Groves and Hosking, 1998); Germany (Kühn and Klotz, 2002)]. As per the United Nations Commodity Trade Statistics Database, the import value of live trees and other plants (commodity code: 06) to India has been steadily increasing for the last five years (2015-2019) and has reached US$ 310 million in 2019 (https://comtrade.un.org/, accessed 13 June 2020). High import volume without quarantine measures could facilitate unabated introductions of IAPS and associated contaminants. Therefore, on one hand updating the list of species to be quarantined based on existing knowledge and establishing a risk assessment framework for its regular update is clearly needed. On the other hand, the current trading scenario of IAPS in the Indian market, as inferred from the representative nursery sales, emphasizes the need for policy interventions for regulating domestic trade. A high number of potential uses of these species further necessitates reducing their propagule pressure.

Two approaches have been proposed and implemented by different countries to restrict the inflow of IAPS – prohibiting the introduction of potential IAPS [blacklist – generally adopted by, e.g., European countries (Essl et al., 2011), North America (Simberloff, 2006)] and prohibiting species introduction until they are approved by experts [white list, adopted by, e.g., Australia and New Zealand (Auld, 2012)]. On the domestic front, legislation to ban the trading of blacklisted species has been implemented in other countries [e.g., in South Africa (van Wilgen, 2012)]. Ideally, a weed risk assessment protocol should be established to identify the alien species' invasiveness and subsequently integrated in the national policy framework, as has been practised in many countries [e.g., (Pheloung et al., 1999)]. However, risk assessments of a large pool of alien species require deployment of sufficient resources. Besides, a lack of consensus among stakeholders (experts, policy makers and traders) regarding the blacklisting criteria (Hulme, 2015) will inevitably delay the decision-making processes. One solution could be that the already recognized IAPS in India based on expert judgement should be blacklisted, put in the quarantine list to restrict entry in the country (Fig.2a) and to impose ban on their domestic trade (Fig.2b).

The risk assessment framework should ideally follow a global standard (Leung et al., 2012), use consistent metrics for recording spatial abundance (Bradley et al., 2018), and should neither be too conservative nor too flexible to avoid omission and commission errors, respectively. However, IAPS are sometimes used by local communities for subsistence and income-generating purposes, e.g., *L. camara* has been used for domestic and agro-forestry purposes (Negi et al., 2019) and *P. juliflora* for fodder and fuelwood (Patnaik et al., 2017). Therefore, the risk assessment framework solely based on the spatial distribution, spread potential and negative impacts on biodiversity of the alien species, as adopted by most European assessment systems (Essl et al., 2011), may have limited practicality in India. Rather, the framework must include the socio-economic impacts of alien species [e.g., using the SEICAT framework, (Bacher et al., 2018)]. Cost-benefit analysis (CBA) considering the cost of inaction as well as the cost-benefit ratio of the management strategy at a landscape level should be an important decision-making component of the risk assessment framework (Reyns et al., 2018). For example, species having higher damage costs and/or costs of inaction than management costs and/or economic benefits should be considered having high risk. Further, factors like time of introduction, propagule pressure, mode of dispersal, invasive elsewhere and adaptability to climate change should be included in the risk assessment framework for the alien plant species (Catford et al., 2016; Dehnen-Schmutz, 2011).

The high invasion risk species thus identified, should be blacklisted whereas those identified as low risk could be permitted to enter the country (whitelist) (Fig.2a) and allowed trading in the domestic market (Fig.2b). Species with uncertain risk should be considered as 'guilty until proven innocent' (Genovesi and

Shine, 2004) and included in the grey list. International trading of these species should be restricted and voluntary trade ban in the domestic market should be implemented. However, given the economic importance of many of these species, implementation of any legislation that prevents the sale of certain plants would generate strong resistance from the traders and consumers alike. For effective implementation of the domestic trading policy, we propose that the policy framework incorporates another layer of decision-making by considering the extent of spread and mode of dispersal of IAPS in the country (marked as b1 in Fig.2b). Among the high invasion risk species, policymakers should first consider legislating a trade-ban on the species whose distribution is still localized and those having potential for long-distance dispersal (Nathan et al., 2008). For species with widespread distribution, voluntary sales ban can be proposed with support from the industry. The landowners using these species should be held accountable for any unintended impact and legal provisions can be proposed to engage them in management actions. More importantly, the legislative framework should be dynamic in nature, because if an introduced species, either previously white-listed or a black-list escapee, is reported as invasive within the country or elsewhere, the focus of the legislation should move from preventing introduction to regulate domestic trade to prevent its further spread. Similarly, the grey list species should be subjected to continuous surveillance and properly categorized based on the available information with time.

4.2 Taking consumer perspective in the policy framework

It is often difficult to impose a trading ban (both international and domestic) for species that have already been introduced and/or escaped in the wild as the traders could argue the justification and feasibility of the ban. In such circumstances, consumers' perspective should be included in the policy framework, either by shifting their preferences towards native species or making them aware of the potential impact of their choices and the consequences thereof.

Shifting focus from alien to native species, particularly in a developing country like India which harbours rich biodiversity, can be an effective strategy to prevent the introduction and propagation of IAPS. Plant traders and suppliers should be sensitized to discourage the sale of IAPS and promote alternatives. As consumers are sensitive to price, any substantial difference between the prices of natives and alien species could help in shifting their preferences (Yue et al., 2011). Imposing taxes on selling alien plant species (i.e., the widespread species with voluntary sales ban), regardless of whether they are imported or grown domestically, and incentivising sale of native species may encourage traders to revise their inventories. These tax brackets could be linked with the risk assessment protocol to allow changes in the levied tax rate automatically with the change in species' invasion risk status. The traders dealing exclusively with native plants can also be encouraged by promoting their businesses on government portals. Increasing awareness among citizens can be an effective mechanism to reduce the risk of plant invasions (Cordeiro et al., 2020; Novoa et al., 2017). For example, to minimize risk of invasions consumers can be informed to prevent flowering and seed production in certain species which are primarily utilized for biomass production. Use of colour coded labels along with the traded items could be introduced for clear designation of species at different levels of invasion risk (e.g., 'red labels' for high invasion risk species, 'green labels' for whitelisted species and 'brown labels' for species with unknown-risk; marked as b1 in Fig.2b) which might aid in making an informed purchase decision and eventually could reinforce public opinion about such risks.

4.3 Policies for controlling ongoing invasions

In addition to preventive action and early warning mechanisms, eradication of established IAPS is required to avoid future damage costs (Wittenberg and Cock, 2001). Therefore, the sales ban of IAPS should be complemented with active eradication campaigns with gradually limiting consumer dependence or shifting their preference to minimize impacts of eradication on local communities. The decision for eradicating the IAPS should be taken considering the spread and abundance of the IAPS, cost and effectiveness of the management programs, and understanding of both private (e.g., landowner) and social (e.g., public) perspectives towards proposed eradication measures (Booy et al., 2017). The CBA can be useful for such decision-making processes (Courtois et al., 2018; Shackleton et al., 2007) (marked as b2 in Fig.2b). The economic impacts of IAPS measured directly from the market prices often characterizes more private perspective of costs and benefits. The social perspective must consider both market and non-market (environmental) valuations. A suite of techniques (e.g., stated preference approach, revealed preference approach, production function method) is available for estimating such non-market prices in monetary terms (Hanley and Roberts, 2019). For example, in a landscape invaded by *L. camara*, public perception about its effects on the surrounding natural environment can be judged through a choice modelling approach. People can make choices between benefits (e.g., increased household income) and losses (e.g., loss of native biodiversity, high management costs) incurred by the species which may eventually be integrated with the policy framework, either in the form of implementing eradication measures or supporting public research programs to find alternate management techniques (Shackleton et al., 2017). From a landowner perspective, if the cost of managing a landscape invaded by a species (e.g., clearing a forest patch for uninterrupted movement of animals) overruns the benefit obtained from exploiting that species (e.g., by local industrial scale operation), the policies can focus on eradication programs and discouraging further use of the species.

4.3.1 Control by economic exploitation – certitude or conjecture?

For widespread IAPS with positive utility impacts (e.g. use of abundant aliens for supplementing household income) and/or production efforts (e.g. exploiting alien tree species to increase timber yields), control via overexploitation has been envisaged in India (Sharma and Raghubanshi, 2012) and in other developing economies, e.g., in Africa (Borokini and Babalola, 2012). In India, many such initiatives are already in action, being supported and often promoted by non-governmental organizations for the welfare of local people. For example, *L. camara* has been widely used for making handicrafts (Negi et al., 2019) whereas *P. juliflora* biomass has been used as an energy source in several small-scale electricity generating plants (Sato, 2013). Although this sounds promising, scientific evidence to support this management approach is rare, if not absent. For example, although harvesting *L. camara* reduced its density at a local scale in a particular season, it's abundance in the study area was found to be too high (Kannan et al., 2016). Besides, the monetary incentives associated with this approach could induce introductions and spread of IAPS to hitherto uninvaded regions (van Wilgen and Richardson, 2014). In such cases, policy interventions are required to discourage promoting IAPS as a form of income. While the policy framework can allow exploitation of established stands of these species at a small scale, it should also focus on scientifically informed (e.g., based on cost-benefit analysis) eradication strategies for widespread IAPS, safeguarding the broad societal and environmental interests, finding alternative sources of income for the people involved and prohibiting the introduction of these species to other areas. Use of IAPS both for subsistence livelihood and economic benefit should be a part of integrated management, and all stakeholders including the local communities should be made well-informed of this approach.

4.4 Policies to prevent unintentional introduction

Analysis of the introduction pathways revealed that many IAPS were accidentally introduced, predominantly as transport contaminant (Fig. 1a). Policy interventions are required at both pre- and post-border movement of alien plant species to prevent such unintentional introductions. International trading regulation should include screening a certain percentage of cargo imports at the ports of entry for presence of black- and grey-list species (Fig. 2a). Similar measure was incorporated in the biosecurity infrastructure of North America to prevent accidental introductions of invasive species(Lehan et al., 2013). The existing standard operating procedure for issuing custom clearance for importing plant material in India can include a declaration from the importers about the stock being free from black- and grey-listed plant material, and legal provisions can be proposed to hold them accountable for any unintended impact. Further, to prevent unintentional introduction and spread of IAPS from equipment, policy measures should include specific guidelines for inspection and cleaning of vehicles and heavy machineries used in industries, especially related to forestry, agriculture, construction, land management (e.g., urban parks and recreational trails) and public utilities (e.g., roadsides). A large number of IAPS were also found to escape from human control (Fig. 1a), which could be due to accidental or irresponsible release of live plant materials from confinement to the natural environment. Policy interventions are therefore required for continuous monitoring of the white-list (international import permitted) and green-risk (domestic trading allowed) alien plant species (Fig. 2). Any observation of these species in the wild should trigger policy actions to categorize these species as grey-list (for international trading) and brown risk (for domestic trading), thereby imposing trading regulation and prompting research and further risk assessment analyses.

4.5 Solidarity in action is all it takes

For effective implementation of these policies in India, we felt the need for a transparent and dynamic decentralized system tasked with the formation of a National Invasive Species Strategy and Action Plan (NISSAP). The system is envisaged to develop a coordinated and multisectoral network of different stakeholders to prevent future introductions and spread of IAPS through timely and efficient enforcement of policies, laws and regulations, control or eradicate ongoing invasions, increase awareness and citizen participation in responding to the IAPS issues, and strengthen response capacities through scientific research and knowledge sharing. Here, we outline a standard operating procedure of the system built on the existing biosecurity infrastructure of the country (Fig.3).

4.5.1 Networking and information sharing

Initiatives have been taken by several agencies to identify the IAPS of India; however, lack of coordination and consensus persists. For example, the National Biodiversity Authority (NBA) has recognized 63 IAPS in India (http://nbaindia.org/uploaded/pdf/Iaslist.pdf, accessed 18 May 2020), the ENVIS Centre on Floral Diversity, an agency under the same Ministry (MoEFCC) has recorded 173 IAPS (http://www.bsienvis.nic.in/Database/Invasive_Alien_species_15896.aspx, accessed 18 May 2020), and a recent scientific study has listed 145 IAPS (Khuroo et al., 2021). While there are certainly overlaps between these databases, this discrepancy highlights the need for a baseline data and standardized framework to designate alien species as invasive (Fig.3a). The agency should also consider interests of different stakeholders to formulate the risk assessment (Fig.3b) and policy frameworks (Fig.3c) to avoid future conflict of interests, ensure public compliance and effective implementation of the eradication programs. For example, the framework for prioritizing IAS for management developed by the NBA (Sandilyan et al., 2018a) should include the economic use component (both private and social perspectives). Risk assessment is an expensive exercise and the decision of bearing the cost, either solely by the government (e.g., Australia)

or by the trading agencies (e.g., New Zealand), should be taken with high priority. While both these strategies have their merits and demerits, risk assessment cost when borne by the industry significantly reduced the number of alien species introductions in New Zealand (Hulme et al., 2018). In addition, risk assessments paid for the industry may increase the cost of alien species in the market which can shift the consumer preference towards native species.

This platform should also ensure information sharing and maintain uniformity across different levels of operations (Fig.3d). The necessity of this coordination is more relevant now than ever before with increasing global and domestic trade. Furthermore, environmental initiatives across the country (e.g., Green India Mission) are now mushrooming with a focus on plant species having faster growth or higher timber values. In absence of proper guidelines, these initiatives could compromise the ecological balance by promoting alien species with high invasion risk. For example, the list of tree species promoted for plantation by the Department of Forest, Government of Tamil Nadu (in south India) includes several Australian *Acacia* species which have been designated as IAPS in India (https://www.tntreepedia.com/, accessed 18 May 2020). Information sharing among different stakeholders and their compliance with the legislation can be achieved through the existing national network of the State Biodiversity Boards and the local Biodiversity Management Committees, operational under the NBA. Given that India shares border with most of the South Asian countries and trade volume is extremely high through these open (e.g., Nepal) or porous (e.g., Bangladesh) borders, the agency should also establish regional collaborations with the neighbouring countries for cross-border exchange of information and harmonizing policies and plans for effective trade regulation and management of the IAPS.

4.5.2 Legal enforcement and capacity development

Similar to the Biological Diversity Act of 2002 and Biological Diversity Rules of 2004 which focused on access and benefit sharing of biological resources (http://nbaindia.org/content/25/19/1/act.html, accessed 18 May 2020), a legal framework to deal with the IAPS problem should be formulated. Most likely, the framing of a legal framework for banning trade or use of IAPS will invariably incite conflict of interests between stakeholders. The central agency (and its subsidiaries) should warrant compliance of all actors to the legislation and modify the framework as and when required (Fig.3e). Furthermore, the platform should also emphasize corporate responsibility and voluntary codes of conduct for the industry associated with the trading of IAPS following global best practices and guidelines (Sethi, 2011) (Fig.3f). Their compliance should be audited regularly, and the industry cooperation can be ensured by giving market incentives for promoting native species over aliens and/or shifting consumer preference to native species. The effective execution of these tasks will require a dedicated and trained task force. Similar to the already established Centre for Biodiversity Policy and Law (http://nbaindia.org/content/332/31/1/cebpol.html, accessed 18 May 2020), training divisions can be formed for capacity-building and strengthening the existing biosecurity infrastructure of the country (Fig.3g). Preventing accidental introductions often demands continuous vigilance and strict adherence to the established protocols, which can be achieved by conducting regular training sessions for the concerned agencies. For example, capacity building programs like the one organized by the National Institute of Plant Health Management under the Ministry of Agriculture and Farmers Welfare, Government of India (https://niphm.gov.in/bspq.html; accessed 28 December 2020) should be promoted widely and conducted at a regular basis. Similarly, an information technology cell should be developed to deal with the inflow of information from different stakeholders and dissemination of agency activities.

4.5.3 Building public awareness through scientific research

The agency needs to leverage its key resources toward developing an effective communication strategy, increasing public awareness, and ensuring their compliance with the legal framework (Fig.3h). A national mission on the topic, publishing articles in popular newspapers and magazines, preparing field guides in vernacular languages and encouraging conservation organizations to educate people will help in building awareness among the public. Advertising regulations related to the alien species policy of the country at the entry ports and the national facilities, as well as encouraging the visitors to check for plant materials attached to their personal belongings and report to the concerned agencies, may help to prevent accidental introduction and spread of alien plant species. Social media, interactive web portal and mobile applications can be used to attract voluntary participation of people (e.g., by encouraging people to share their experience about difficulties in managing 'once cultivated but eventually escaped' species). The agency should also promote citizen science initiatives (Fig.3h), which can be a valuable tool for real time observations and data enrichment for the IAPS as well as to identify potentially problematic alien species like the ones accidentally escaped from cultivation.

The agency should also encourage research activities to identify native species with similar consumer benefits, since unavailability of suitable alternative options may hinder the promotion of native species. For example, high annual water use by alien *Eucalyptus* species, which have been widely used for afforestation programs and community economic development in the arid and semi-arid regions of central India, threaten dryland water and livelihood security. A recent study has found that native *Azadirachta indica* A. Juss., with similar benefits and acceptability in the community, can be used for replacement initiatives in these regions (Everard, 2020). Such research activities should be promoted to conduct comparative assessments between native and alien species by considering both economic and ecological perspectives, build baseline data, and ensure effective and timely communication of the findings with the local communities and relevant stakeholders. Similar initiatives have been taken up by many countries. For example, in North America, a 'National Seed Strategy' has been developed after taking several stakeholders on board for promoting the use of native plant materials to restore plant communities (https://www.usda.gov/media/blog/2017/03/13/usda-supporting-national-native-seed-strategy, accessed 15 June 2020).

The agency should also identify research gaps and encourage active participation of the scientific community in furthering the research activities and policy discussion (Fig.3i). Notably, knowledge of pathways and vectors of IAPS spread should be considered in the NISSAP to prioritize species for management actions. Future research should also focus on identification of the casual aliens and naturalized non-invasives in the country, and to assess their probability to become invasives based on their biological, ecological, and socio-economic attributes. The 'emerging invasives' thus identified should be prioritized for risk assessment analyses and subsequent integration in the national policy framework to prevent their further introduction, establishment and spread in the country. This information can be especially valuable since a large number of plant species (n = 1818) have been recognized as alien, but not invasive yet, in the country (Sankaran et al., 2020). Finally, there has been practically no empirical evidence available (or at least not accessible by the wider audience) of economic costs associated with IAPS in India, except a general estimate by Pimentel et al. (2001). These general estimates by Pimentel et al. (2001) have been found to differ considerably from more detailed calculations, both globally (Diagne et al., 2021) and at a national scale [e.g., in Australia (Hoffmann and Broadhurst, 2016)]. Dissemination of such findings (e.g., the number of IAPS and their economic impact) and information about the regular activities and

achievements of the agency are expected to portray a better picture of the risks associated with the IAPS and might help in creating the much-needed awareness among the public as well as across the wide spectrum of stakeholders.

5. Conclusion

Our study found that the majority of IAPS were introduced intentionally and some of them are still actively being traded in the Indian market and used for several economic purposes in absence of a dedicated policy framework for these species. We propose a set of scientifically-informed and decision-based policy interventions by considering interests of different stakeholders. For effective implementation of these policies, we felt the need of a dynamic decentralized system tasked with developing a coordinated network of different stakeholders to develop a standardized risk assessment and policy framework, enforce legal regulations, increase public awareness, and strengthen response capacities through scientific research and knowledge sharing.

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Legends to Figures

Fig.1: a) Introduction pathways of invasive alien plant species present in India, bars in different colours in indicate the four categories of introduction pathways identified by the Convention on Biological Diversity; b) uses of invasive alien plant species in India (uses associated with more than five species shown) arranged according to Level-2 (left) and Level-1 (right) states of the Economic Botany Data Collection Standard.

Fig.2: Framework for – a) international and b) domestic policy interventions proposed for regulating trade and managing invasive alien plant species in India. The diamonds (a1, b1, b2) are for reference in the text.

Fig.3: Visualization of a decentralized system tasked with coordination of different agencies involved in trading of invasive alien plant species in India. The solid arrows indicate inflow of information to the system for decision making whereas the dotted lines depict the dissemination of information for effective management of invasive alien plant species in India. The small letters (a-i) are for reference in the text.

Figure 1

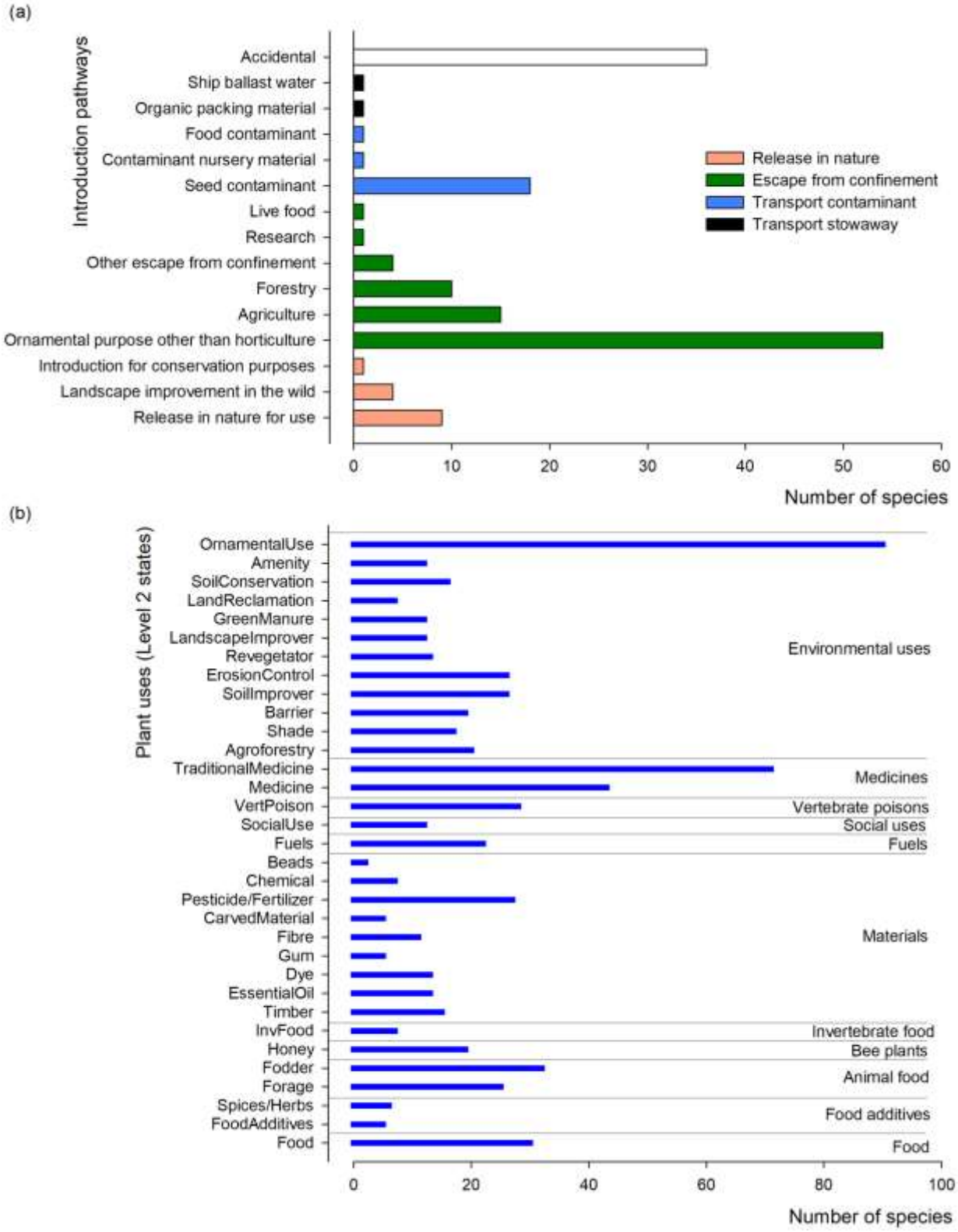
(a)
Introduction pathways
Accidental
Ship ballast water
Organic packing material
Food contaminant
Contaminant nursery material
Seed contaminant
Live food
Research
Other escape from confinement
Forestry
Agriculture
Ornamental purpose other than horticulture
Introduction for conservation purposes
Landscape improvement in the wild
Release in nature for use
Release in nature
Escape from confinement
Transport contaminant
Transport stowaway
0
10
20
30
40
50
60
Number of species
(b)
Plant uses (Level 2 states)
OrnamentalUse
Amenity
SoilConservation
LandReclamation
GreenManure
LandscapeImprover
Revegetator
ErosionControl
SoilImprover
Barrier
Shade
Agroforestry
TraditionalMedicine
Medicine
VertPoison
SocialUse
Fuels
Beads
Chemical
Pesticide/Fertilizer
CarvedMaterial
Fibre
Gum
Dye
EssentialOil
Timber
InvFood
Honey
Fodder
Forage
Spices/Herbs
FoodAdditives
Food
Environmental uses
Medicines
Vertebrate poisons
Social uses
Fuels
Materials
Invertebrate food
Bee plants
Animal food
Food additives
Food
0
20
40
60
80
100
Number of species

Figure 2

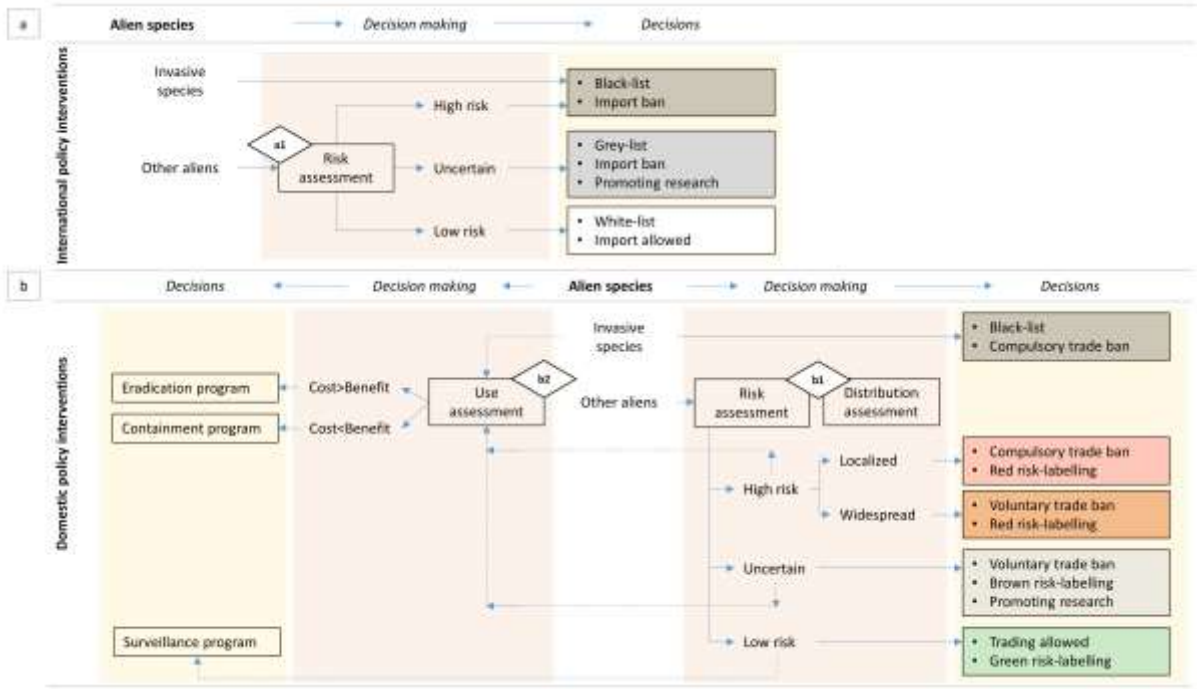

Figure 3