Proceedings of the Indian National Science Academy (2021) 87:19–35
https://doi.org/10.1007/s43538-021-00013-w

REVIEW PAPER

Plant invasion in protected areas, the Indian Himalayan region, and the North East India: progress and prospects

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Received: 22 April 2020 / Accepted: 5 September 2020 / Published online: 2 June 2021

Abstract

Global biodiversity is not uniformly distributed in terms of species richness. The global and national protected areas (PAs), the Indian Himalayan Region (IHR) and the North East (NE) India, are extremely rich in plant biodiversity, contributing to the environment and the socio-economy/livelihood prospects, linked with human health or well-being. However, the anthropogenic disturbances have modified the vegetation structure of PAs, IHR, and NE India, such that the pristine landscapes are now ripe for the encroachment of invasive alien plants (IAPs). The plants invasions is now increasingly being realised as a major threat to biodiversity globally and the ecologically sensitive mountain ecosystems are no exception. The abrupt spread of IAP in these regions can significantly exacerbate the biodiversity conservation problems, as these regions are already faced with challenges of habitat fragmentation and climate change. Also, the complex interactions among the plants invasion, habitat destruction and climate change can further impose a challenge to the restoration ecologists. Interestingly, the invading plants are equipped with several species or site or habitat-specific adaptive mechanisms like the presence of allelochemicals as novel weapons that facilitate their landscape spread and ecological dynamics. This review describes the theories or hypotheses which may account for the accelerated IAPs spread in IHR, NE India and PAs. The research progress in IHR and NE India is discussed with respect to worst invaders like *Lantana camara*, *Chromolaena odorata, Ageratum conyzoides, Parthenium hysterophorus, Mikania micrantha,* etc. In this respect, the outcome of preliminary research in NE India to identify the dominant invaders through quantitative methods is also mentioned. Lastly, the management strategies are described to mitigate the IAPs hazards for sustainable biodiversity conservation.

Keywords Biodiversity conservation · Invasive alien plants · Human health · Ecological dynamics · Allelochemicals · Climate change

Introduction

Biodiversity is an unifying concept, and comprises the totality of genes, species and ecosystems; represented in a time framework through the balance between rates of speciation and extinction (Singh 2012). It is well-known that the distribution of global biodiversity is not uniform, and exhibits latitudinal and altitudinal gradients. Indian Himalayan Region (IHR), protected areas (PAs) and North East (NE) India are rich repositories of biodiversity which offers vast array of direct values like timber, fibre, ethnomedicines, natural products, dyes/emulsifiers, industrial enzymes, botanical insecticides, etc. linked with human livelihood. In addition, biodiversity also provides indirect values through modulation of ecosystem services (e.g., carbon sequestration, nutrient/gaseous cycling, etc.) with

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This article is part of the Special Issue: Indian National Young Academy of Science (INYAS).

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aesthetic and recreational values (Singh 2002, 2012; Singh and Khurana 2002; Mandal and Joshi 2014).

Biodiversity forms the basis for other applied disciplines such as bio-prospecting of traditional indigenous wild varieties (as source of novel metabolites and potent genetic materials); bio or ecological indicators in assessing the environmental pollution; biomonitoring and bioremediation of emerging contaminants; thereby, safeguarding the environmental health, and concomitantly, giving an impetus to future biotechnology (Swaminathan 2003). Also traditional indigenous knowledge of ethnomedicinal plants is intimately linked with primary health care system in IHR and NE India (Kala et al. 2004; Rai and Lalramnghinghlova 2011a,b; Rai 2017a).

In the Anthropocene era, the changes in land-use and climate, nitrogen deposition, and biotic exchange have been recognized as major drivers of future changes in biodiversity (Sala et al. 2000; Singh 2012). Biotic exchange (invasion by exotic or alien plants) is considered to be one of the biggest threats to biodiversity, economy, biosecurity, agriculture sustainability, and human health/well-being (Rai and Singh 2020a, b). The anthropogenic disturbances allowed the global spread of invasive alien plants (IAPs) and, even the pristine/fragile ecosystems of Antarctica (Hughes and Convey 2010) or Galapogas Island (Jager et al. 2009) are no exception. It is believed that about 0.5–0.7% of global tree and shrubs are currently invasive (Rejmanek and Richardson 2013; Lamsal et al. 2018). Several noxious IAPs can trigger the cascade of adverse impacts through the disruption of abiotic environment and ecosystem services, thereby, escalating the rate of extinction of native plants.

The ranking of invasion, as a threat to biodiversity can be debatable (for 1st or 2nd rank) in view of region's specificity, however, its tight interrelationship with other environmental perturbations (e.g., habitat destruction and climate change) is beyond doubt (Young and Larson 2011). Herein, the inextricable association of IAPs with the global change further exacerbates the biodiversity conservation challenges (Didham et al. 2005). In light of these facts, United Nations-Global Assessment Report on Biodiversity and Ecosystem Services explicitly identified biotic invasion as the prime threat in global biodiversity depletion (IPBES 2019).

The IAP introduced either accidently or deliberately (as economic or ornamental plants) through human interferences can adversely impact the environment, economy, livelihood, human health, diminishing ecosystem services, thus, hampering the sustainable development (Rai and Singh 2020a, b) (Fig. 1). The IAP also adversely impacts the United Nations-sustainable development goals (SDGs) for environmental amelioration and human well-being through policy or guideline formulations in multifaceted sectors (e.g., sustainable agriculture, groundwater treatment, human health, etc.) (United Nations 2015; Haines 2016).

In the light of these perspectives, the international Convention on Biological Diversity (CBD) emphasized the threat of IAPs in its Article 8(h) on biodiversity and management strategies to contain their landscape spread. Likewise, other institutional mechanisms like Global Invasive Species Programme (GISP), CAB International

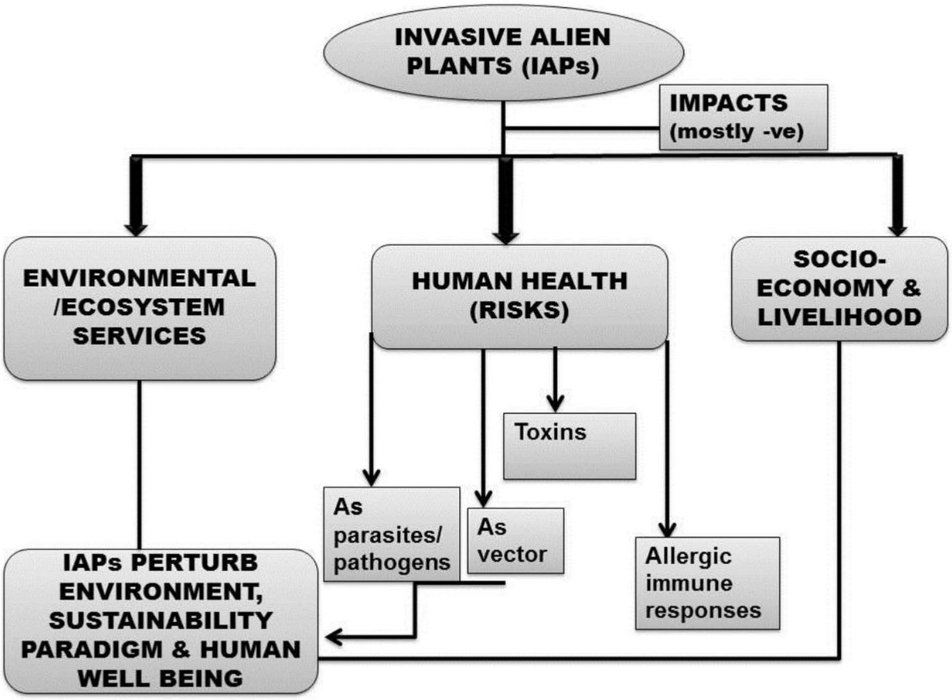


Fig. 1 Multifaceted adverse impacts of invasive alien plants (IAPs) on environment, ecosystem services, socio-economy (livelihood), and human health; the health hazards of IAPs can be either direct through release of toxins or indirect by acting as parasites or vectors; IAPs also induce allergic immune responses in humans through interaction with plant parts e.g., pollen; these adverse impacts in totality influence the sustainability paradigm and human well-being

(CABI), SCOPE (Scientific Committee on Problems of the Environment) and the International Union for Conservation of Nature (IUCN) also advised their management in biodiversity rich protected areas through ecosystem based processes (Sharma et al. 2005; Kushwaha 2011; Foxcroft et al. 2017).

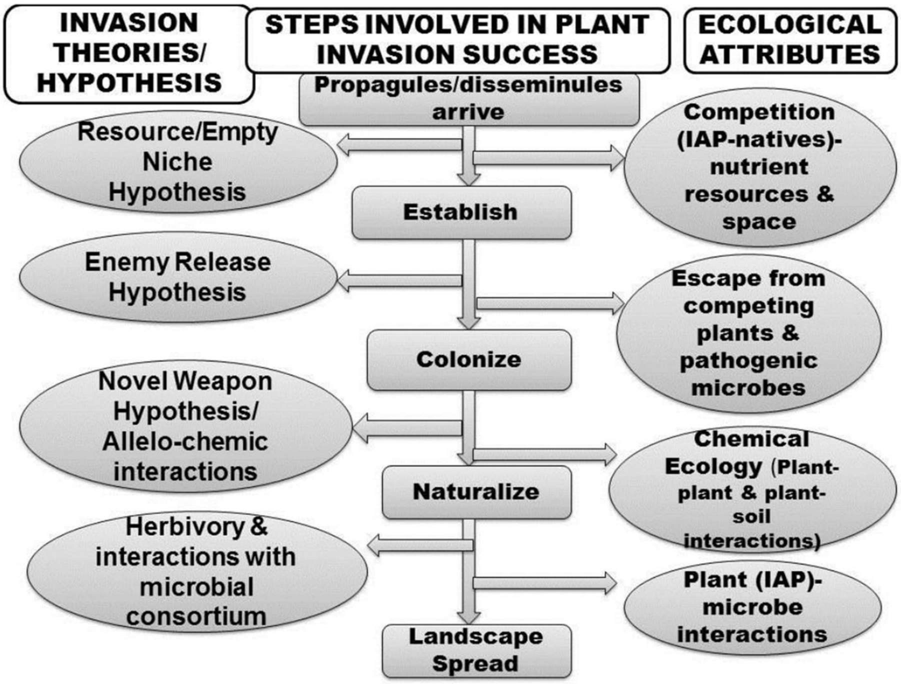
The present article aims to provide an overview on documentation of IAPs, the progress of plant invasion ecology and the mechanisms underlying their success in IHR, NE India and the PAs. These interrelated mechanisms remarkably impact the ecological dynamics of IAPs which in turn may be linked with genetic, phylogenetic, and evolutionary variations. The IHR is an extremely important hub for vegetation and conservation ecology researches. Similarly, the N.E. India is also an integral landscape of Indo-Burma hotspot of global biodiversity. Since the studies on IAPs in Mizoram have not been undertaken, an initial study was conducted to delineate prime plant invaders. In addition to listing of dominant IAPs in Mizoram, the preliminary case study elucidates the quantitative methods to study plant invasion ecology through phytosociology. The outcome of a preliminary research on the phytosociology of plant invaders in Aizawl, Mizoram (NE India) along a disturbance gradient is also presented. The IAPs management strategies and future prospects of plant invasion research are also discussed to fill the existing knowledge gap in general and in our proposed research perspectives, in particular.

Ecological mechanisms underlying the success of invasive alien plants

Quest of mechanisms, enabling IAPs to flourish in novel habitats, outside their potential native range, engaged the attention of invasion ecologists during the last couple of decades (Sharma et al. 2005; Blumenthal 2006; Rai and Singh 2020a, b). Interestingly, there exists a plethora of mechanisms associated with each step of IAP success in a particular geographical region (Fig. 2). Nonetheless, these ecological mechanisms can be site or IAP-specific and in fact no single mechanism can contribute to invasive spread in its totality (Sharma et al. 2005). Rather, these mechanisms act in unison as passengers to drive the successful IAP ride across the landscapes (Uddin and Robinson 2018). In Indian perspective, study on invasion mechanisms of IAPs (specifically *Lantana camara*) revealed the role of degrading forests, expanding niche (under the effect of climate change), and adaptive plasticity in facilitating their landscape spread (Mungi et al. 2020).

The first step in plant invasion is the arrival and dispersal of propagules (attached reproductive units)/disseminules (detached reproductive units) of IAP at the novel habitat. Notably, it has been demonstrated that in biotic invaders, genetic variations (through '*gene surfing*'/spatial sorting of alleles) can trigger the rapid evolution of dispersal ability, thereby, transmogrify their ecological dynamics (Ochocki and Miller 2017).

Fig. 2 Step-wise illustration of plant invasion (invasion continuum) and interrelated or associated mechanisms; Plant invaders tend to arrive at new site, establish, colonize, naturalize before the successful landscape spread and each and every step is tightly linked with biotic/abiotic filters and ecological mechanisms



At the first step, the IAP reproductive units face the hindrance/abiotic filters, as they require space (empty niche) and resources (e.g., soil nutrients) for the accomplishment of second step i.e., establishment. The proposed associated invasion mechanisms or theories with transportation of IAP propagules are resource (R) and empty niche hypothesis (ENH), facilitating their establishment (Blumenthal 2006; Rai 2015a, b; Uddin and Robinson 2018). Nonetheless, in the third step (colonization), IAP can face site-specific hindrance in the face of competition from natives (biotic filters) and in this context it has been interestingly observed that they out-compete the natives due to being away from their natural enemies/competitors. Hence, the release from enemies (e.g., the competing plants and harmful microbes) in native range, significantly favour the IAP colonization, thus, this step is closely associated with enemy release hypothesis (ERH) (Blumenthal 2006). For example, the seeds of *Impatiens glandulifera* in newly invaded landscapes were free from fungal pathogens common in its native region (Najberek et al. 2018).

After successful colonization, the next step i.e., naturalization followed by the landscape spread requires the potential IAP attributes which can vigorously harm the natives. This facilitates them to cross all geographical/environmental hindrances or biotic/abiotic filters. Interestingly, in this context, the releases of several allelochemicals (e.g., phenols, terpenoids, etc.) from IAP are demonstrated as deleterious to the native plants, thereby, perturbing their growth and reproduction (Singh et al. 2014). Herein, there exists a biotic interference through bio-active (chemical) compounds such as (–)-catechin from *Centaurea maculosa* or spotted knapweed (Callaway and Ridenour 2004), and odoratin released by *Chromolaena odorata* (Zheng et al. 2015). Thus, these species specific chemical entities from IAP, leading to mortality of natives, are considered to be novel weapons, thereafter, termed as novel weapon hypothesis (NWH) (Singh et al. 2014; Pinzone et al. 2018).

The interaction of IAP with belowground microbial consortium in invaded regions can also be inextricably linked with their successful spread (Jack et al. 2017). The role of microbial diversity in accelerating the invasive spread can be explored with advancement in molecular oromic tools, as demonstrated in the cases of *Eupatorium adenophorum and Ageratina adenophora* (Kong et al. 2017) and *Impatiens glandulifera* (Gaggini et al. 2018). Moreover, these steps in plant invasion ecology and associated mechanisms can be impacted by various abiotic environmental factors, particularly, global warming (Didham et al. 2005; Blumenthal et al. 2016; Hulme 2017). Hence, the underlying mechanisms associated with plant invasions can be IAP specific, tightly linked with habitat heterogeneity and environmental disturbances.

Plant invasion ecology research in Protected Areas

SCOPE investigated the presence of 2000 IAPs in 24 global protected areas (PAs), four decades back while GISP also reported the issue of IAP spread in 487 protected ecosystems (Foxcroft et al. 2017). India has vast array of PAs: 509 Wildlife Sanctuaries, 96 National Parks, 27 Tiger Reserves, 15 Biosphere Reserves, 5 natural World Heritage Sites, 25 Wetlands as Ramsar Sites and Several Sacred Groves and Lakes (MoEF 2008; Singh 2012). It is known that PAs collectively constitute a useful sample of the world's ecosystems. It has been rightly stated that PAs also provide ideal outdoor laboratories (Foxcroft et al. 2017) for ecosystem analysis as well as a strategy for in situ biodiversity conservation (Singh 2012). Therefore, in this section, a brief perspective on IAP issue in global PAs is mentioned.

Protected areas in mountain ecosystems/forested landscapes play a vital role in mitigating climate change and environmental degradation (Hannah et al. 2007; Gaston et al. 2008; Conroy et al. 2011; Foxcroft et al. 2017). Nonetheless, it has been estimated in Indian context, that since 2000 out of 60% studies on IAPs, only 20% were confined to PAs (Hiremath and Sundaram 2013). Moreover, among these IAP studies in PAs, only *L. camara* and *Prosopis juliflora* were widely studied (Babu et al. 2009; Sharma and Raghubanshi 2010; Kaur et al. 2012; Hiremath and Sundaram 2013). Ecological investigation on IAP spread in PAs of forests which were initially assumed to be resilient towards biotic invasions is an urgent need of the hour (Foxcroft et al. 2017). Incidentally, the spread of IAPs in mountain PAs with extreme abiotic environment can be attributed to anthropogenic disturbances and the climate change, facilitating their upward movement (Diez et al. 2012; Dainese et al. 2017).

While India's 668 PAs covering ca 4.9% of its geographic area (Hiremath and Sundaram 2013), in Himalayan context, about 105 PAs covering > 6% of the total geographic area are rich storehouse of biodiversity (Green 1993; Dhar et al. 1997; Ghosh-Harihar et al. 2019). Initial studies in highly managed PAs reported them to be less prone to plant invasion, as noted for Kruger National Park of South Africa (Jarosık et al. 2011; Foxcroft et al. 2017), however, in recent years, plant invasion is revealed to be a major threat to forest biodiversity in PAs as demonstrated also in Gros Morne NP in boreal Canada (Rose and Hermanutz 2004) as well as through survey of The Nature Conservancy (TNC) in global context (Randall 2012).

In IHR- PAs also, IAPs became an integral component of biodiversity structure, as observed in Askot Wildlife

Sanctuary (a PA in Kumaun Himalaya), deserving conservation measures (Dhar et al. 1997). Interestingly, an ecological study in high altitude PA in western Himalaya (Valley of Flowers National Park) revealed that certain indigenous plants [e.g., *Polygonum polystachyum* (Himalayan knotweed) and *Impatiens sulcata*] can also be invaders, altering its ecological dynamics and biodiversity structure (Kala et al. 2004). The oldest PA in IHR i.e., Corbett National Park has also been observed to be invaded with *L. camara* and an ecological solution (mixing the invaded landscapes with native productive grasslands and mixed woodlands) has been reported to have assisted in biodiversity restoration of the Park (Babu et al. 2009).

In addition to PAs in terrestrial ecosystems, aquatic PAs e.g., Ramsar wetlands are also threatened with IAPs (Saunders et al. 2002; Ramsar Convention 2018; Rai 2018; IPBES 2019). Loktak Lake in Manipur (NE India) with unique *phoomdi* (floating mats of soil-vegetation system) is also infested with *Eichhornia crassipes* (water hyacinth), *Pistia stratiotes* (water lettuce), *Arundo donax*, *Phragmites karka,* etc. (Singh and Rai 2016; Rai 2019; Rai and Singh 2020a), which are considered to be worst plant invaders as per the IUCN Invasive Species Specialist Group (ISSG 2017) and others (Nentwig et al. 2018). Further, Keoladeo National Park, India is also a classical example of aquatic PA (integrated National park, Ramsar site and also bird sanctuary) needing protection from IAP like *Eichhornia crassipes* and *Hydrilla verticillata* (Gopal 1994; Saunders et al. 2002).

Thus both terrestrial and aquatic PAs of IHR deserve adequate ecosystem analysis in view of the IAPs spread. Evidently, the efforts towards biodiversity conservation should be encouraged, based on long-term irreversible ecological restoration within the sustainability framework (Babu et al. 2009; Rai and Kim 2020). In terms of policy measures, IUCN Vth World Parks Congress during 2003 also stated that ‘‘management of invasive alien species is a priority issue and must be mainstreamed into all aspects of PA management”. Further, this issue with sound implementation strategies in context of PAs was restated during IUCN World Conservation Congress of 2012 and IUCN World Parks Congress during 2014.

While invasions have been the subject of intensive ecological research during the last two decades, this research has largely been ignored in tropical forests (e.g., Drake et al. 1989; Rai 2015a, b), especially in IHR and NE India. The growing body of literature on PAs in India is beset with the paucity of scientific data and warrants sustained ecological monitoring, especially, in less explored NE India; participation of local tribal people; and evaluation of eco-tourism prospects in buffer zone to raise the livelihood opportunities (Ghosh-Harihar et al. 2019).

A cascade of reviews and growing body of literature exists on forest invasion ecology; however, no research has addressed the causes, global impacts, mechanisms and sustainable management of invasive plants of forest in an integrated manner, particularly in IHR and NE India. Therefore, after providing a glimpse of IAPs issues in PAs, our discussion will now focus on IHR and NE regions.

Plant invasion ecology in Indian Himalayan Region and biodiversity hotspots

Forest biodiversity is an integral component of environment and is inextricably linked with sustainable development. Interestingly, the 34 global terrestrial biodiversity hotspots cover only 2.3% of the earth’s geographical area, but harbour over 50% of the world’s plant species as endemic (Singh 2012). India is one among the ten mega-biodiversity countries in the world having four lobal biodiversity hotspots i.e., the Himalaya, the Indo-Burma, the Western Ghats and Islands or Sundaland (Padalia et al. 2014). IAPs can alter the ecological dynamics of biodiversity hotspots (comprising threatened habitats which lost about 70% of primary vegetation but support at least 0.5% of the world’s flora as endemics), and thus deserve urgent research attention. India occupies only 2.4% area of the world while housing 11% of world’s floral forest biodiversity with over 45,500 plant species and 147 endemic genera (Singh 2012; Padalia et al. 2014).

Previously, it was assumed that in view of geographical constraints, mountain ecosystems of IHR are resistant to spread of IAPs, unlike lowlands in view of dispersal limitations. However, in view of rapidly evolving traits under the changing climate, their phenotypic plasticity and increasing anthropogenic disturbances in mountain/alpine regions, IAPs are now threatening the biodiversity of these ecologically sensitive regions (Dietz 2005; Alexander et al. 2016) and IHR is no exception (Raghubanshi et al. 2005; Pathak et al. 2019). Out of the existing 47 eco-regions in India, 19 comprise invasion hotspots (Adhikari et al. 2015; Lamsal et al. 2018). The Asia Pacific Forest Invasive Species Network (APFISN) has documented 111 IAP from forests in India (Kumar et al. 2019).

The biodiversity of India’s hotspots is under extreme anthropogenic pressure as demonstrated through case study on Niligiri biosphere reserve (Baskaran et al. 2012) and another case study (Rai 2012) from forests of an Indo-Burma hot spot. Another hotspot of biodiversity i.e., Western Ghats faced remarkable changes in vegetation structure due to IAPs, particularly, *L. camara* (Kannan et al. 2014, 2016; Soumya et al. 2019). In the light of growing IAP threats in such global biodiversity rich regions, Conservation International (CI-United States) prioritized the biodiversity conservation in these hotspots as cost-effective approach termed ‘silver bullet’ strategy (Jepson and Canney 2001).

The documentation of IAPs and study on their invasion ecology in IHR are necessary to assess the threats to biodiversity and for devising management strategies. The Indian forest flora has 173 alien invasive species (e.g., *L. camara, Hyptis suaveolens, Ageratum conyzoides, Parthenium hysterophorus, Chromolaena odorata,* etc.) having potential to perturb the native forest biodiversity (Reddy 2008; Padalia et al. 2014). In IHR, 190 IAPs have been documented from varying habitats and altitudinal gradients (Chandra Sekar 2012).

The Uttarakhand state of IHR comprised 163 IAP species from 46 families and about 50% of these numbers were recorded from wasteland, thus, signifying the role of disturbance in the invasive spread (Chandra Sekar 2012). The state of Himachal Pradesh alone recorded 497 IAP species from 85 families with Asteraceae being the dominant family (Jaryan et al. 2013). In this respect, it is worth mentioning that these IAP in India derive their origin mostly from Tropical America (74%) and Tropical Africa (11%) (Kohli et al. 2011).

Pathak et al. (2019) in a survey on biodiversity of IHR reported 297 naturalized IAP, and, state-wise, Himachal Pradesh recorded the maximum (232; 78.1%) followed by Jammu & Kashmir (192; 64.6%) and Uttarakhand (181; 60.90%). In this respect, *A. conyzoides*, *L. camara, P. hysterophorus* and *A. adenophora* were observed as most ubiquitous IAP across the IHR (Pathak et al. 2019). Another potential plant invader i.e., *C. odorata* was investigated in the Himalayan hot spot by Mandal and Joshi (2014) while *H. suaveolens* was ecologically mapped and modelled by Padalia et al. (2014). For *H. suaveolens* in western Himalaya, it has been observed that spatial heterogeneity plays a remarkable role in its landscape spread (Kumar et al. 2019). Also, *Anthemis cotula,* a member of family Asteraceae is reported to be invasive in forests of Indian Himalaya with the assisted mycorrhizal association (Shah et al. 2008).

The invasion of *Leucanthemum vulgare* in Kashmir Himalaya led to significant reduction in the micronutrient (e.g., iron, copper, manganese and zinc) levels in soil system (Ahmad et al. 2019a, b). Therefore, plant invaders can remarkably influence the nutrient cycling processes in soil systems of PAs. Interestingly, *A. conyzoides* infestation and contribution to altered vegetation structure in north-western Himalaya (Himachal Pradesh) was recorded higher than that of *P. hysterophorus* and *L. camara* (Kohli et al. 2004). The dominance of *A. conyzoides* was attributed to climate adaptability, especially, in agro-ecosystems while dreaded global invader *P. hysterophorus* was observed still in the colonization stage. In this study by Kohli et al. (2004), the colonization refers to multiplication of *P. hysterophorus* subsequent after the transport and establishment stages (Fig. 2). However, unlike *A. conyzoides* the naturalization and landscape spread was not observed in *P. hysterophorus*.

In addition to altering the vegetation structure, IAP can therefore impact the soil physico-chemical and biological attributes significantly (Raizada et al. 2008; Ahmad et al. 2019a, b; Min and Suseela 2020; Ni et al. 2020). Though most of the researches on plants invasion were limited to autecology, the soil attributes impacted by IAP are of paramount importance in elucidating the ecological mechanisms. The alterations in soil properties can reverberate up to landscape level and are inextricably linked to bio-geochemical cycling, microbial diversity, ecosystem structure, native/IAP recruitment potential, ecological dynamics and hydro-geomorphology (Raizada et al. 2008). Further, an IAP, *Polygonum cuspidatum* (Japanese knotweed) influenced the soil stability through alterations in Michaelis–Menten kinetics (V_{max} and k_m) of microbial hydrolytic and oxidative extracellular enzymes (Min and Suseela 2020). Another IAP (*Mikania micrantha*) impacted the soil attributes through enhanced carbon (C) transfer from plants to soil with concomitant shift in microbial communities, thereby, modulating the soil C accumulation (Ni et al. 2020).

The climate change scenarios observed in Himalayan region are also inextricably linked with IAP spread and exacerbate the biodiversity conservation threats (Lamsal et al. 2018). Several ecological/climate change models predicted the susceptibility of the Himalayan region to spread of IAPs like *L. camara* (Priyanka and Joshi 2013; Shrestha et al. 2018), *A. houstonianum, C. odorata, Hyptis sp., P. hysterophorus* (Barik and Adhikari 2011; Adhikari et al. 2015; Shrestha et al. 2018; Lamsal et al. 2018; Ahmad et al. 2019a, b), *A. adenophora* and *A.conyzoides* (Lamsal et al. 2018). In Indian perspective, the effects of climate change such as shift in moisture availability was observed to facilitate the IAPs (*L. camara* and *Cassia tora*) to northern and north-eastern directions (Panda et al. 2018). A recent ecological modelling study also predicted the synergistic influence of climate anomaly (climate change records of past) in triggering the spatial spread of IAPs in NE/IHR region (Tripathi et al. 2019). The climatic shifts (in terms of temperature and precipitation variability) in Himalayan region can impact the range shift of IAPs. Thus IAP ecology is complicated by climate/other abiotic changes; therefore, in IHR the implementation of Long-Term Ecological Monitoring (LTEM) with well-defined indicators is the need of the hour (Negi et al. 2019).

Prospects of research on plant invasion ecology in North East India

The North East (NE) India, being a part of the Indo-Burma hotspot of global diversity as well as ecologically sensitive region, calls for the panoramic ecological researches on plant invasion. Pioneering description of certain IAPs like *Mikania micrantha* in N.E. India rated these species as aggressive invaders, covering the canopy of even the tallest trees (Tripathi et al. 2011; Poudel et al. 2019). This aggressive spread of *M. micrantha* (family Asteraceae) in N.E. India can be attributed to its unique reproductive biology (Swamy and Ramakrishnan 1987) and allelopathic potential (several sesquiterpenoid chemicals) (Shao et al. 2005).

The first-hand information on ecological impacts of shifting cultivation/slash and burn/*jhum* agriculture by Ramakrishnan and his team (Ramakrishnan 1993, 2001) in N.E. India also included the IAPs (Kushwaha et al. 1981; Swamy and Ramakrishnan 1987). The population dynamics of IAP like *M. micrantha* (Swamy and Ramakrishnan 1987) and *Eupatorium odoratum* (Kushwaha et al. 1981) were investigated under the event of shifting cultivation. Interestingly, it was observed that this ethno-agricultural practice facilitated the recruitment of IAPs at the shifting cultivated site in view of larger seed bank, when compared to other land-use (e.g., terrace agriculture) (Misra et al. 1992; Rai 2017b). Table 1 lists the dominant IAP recorded in NE India and IHR.

Ecological Niche Modelling (ENM) with assistance of Global Biodiversity Information Facility (GBIF) was used to predict invasion trend/hotspots under various climatic scenario and anthropogenic perturbations (Barik and Adhikari 2011; Adhikari et al. 2015). However, this research of paramount importance was of modelling/simulation nature, rather than field invasion science confined

Table 1 Invasive alien plants (IAP) recorded in Indian Himalayan Region (IHR) and North East India which perturb the environmental sustainability

Serial No	Invasive alien plant (IAP)	Description on invasive spread and impact	Related references
1	*Mikania micrantha* (Mile a minute weed)	Worst IAPS due to tremendous spread in last decade (North East India & China) with harmful impact on environment/ economy, especially under the changing climate	Guo et al. (2018), Poudel et al.(2019), Rai and Singh (2020a, b)
2	*Lantana camara*	Rapidly invading North East India/Himalayan region; considered as one of the 10 most noxious IAPS in the world	Kannan et al. (2014, 2016), Shrestha et al. (2018); Pathak et al. (2019)
3	*Arundo donax*	Wetland IAPS, listed among top 100 invasive flora/fauna; Recorded in North East India from Loktak Lake, Manipur India	Plaza et al. (2018), Rai and Kim (2020)
4	*Ageratina adenophora* (= *Eupatorium adenophorum* Sprengel) and *Eupatorium odoratum*	Belonging to family Asteraceae, one of the worst IAPS in North East India	Tripathi and Yadav (1982), Fu et al. (2018), Pathak et al (2019), Rai and Singh (2020a, b)
5	*Parthenium hysterophorus L.* (Ragweed)	Commonly known as parthenium weed, that now has a pan-tropical distribution; High expansion area in Himalayan mountain under the climatic change	Shrestha et al. (2018), Pathak et al. (2019), Ahmad et al. (2019a, b)
6	*Chromolaena odorata*	An IAPS of diverse landscapes including Himalayan region; Basically novel weapons/allelochemicals are responsible for its invasion and native vegetation decline	Nkambule et al. (2017), Shrestha et al. (2018), Rai and Singh (2020a, b)
7	*Ageratum conyzoides* (Billy goat weed)	Emerging invasive plant in North East India in view of allelopathic potential and reproductive biology; Exert phytotoxic impacts on crops like wheat	Sakachep and Rai (2021), Singh et al. (2003), Kohli et al. (2011), Rai (2013); Pathak et al. (2019)
8	*Tithonia diversifolia*	Aggressive spread is observed in North East India, especially, Mizoram due to seed dispersal and strong allelopathic potential	Kohli et al. (2011), Miranda et al. (2015)
9	*Leucanthemum vulgare* (ox-eye daisy)	Drastic alterations in soil physic-chemical Characteristics on its invasion in Kashmir Himalaya	Ahmad et al. (2019a, b)
10	*Hyptis suaveolens*	Dominant IAP of Himalayan region and spatial heterogeneity in concert with climate change accelerated its spread	Adhikari et al. (2015); Kumar et al. (2019)

to forested landscapes of NE India. Therefore, there is paucity of systematic investigations on plant invasion ecology in forest divisions/protected areas. Even outside the protected areas (urban forests), there are scanty researches on plant invasion ecology which is rather unfortunate.

In forests of an Indo-Burma hot spot region, Rai (2015a) investigated the role of disturbances in influencing the invasion ecology of *L. camara, M. micrantha*, and *A. conyzoides*. In aquatic ecosystems of North East India several invasive plants like *Eichhornia crassipes* and *Arundo donax* have been reported (Rai and Kim 2020). However, to the best of our knowledge, detailed study is not on record for the tropical forests in relation to IAPs (such as *Tithonia diversifolia*, *C. odorata*, *L. camara, M. mikrantha, A. conyzoides*) which are prevalent in NE India particularly Mizoram (Rai 2015a, b). The other N.E. state i.e., Arunachal Pradesh, equipped with diverse vegetation types (tropical, sub-tropical, temperate, and alpine) also recorded IAPs like *C. odorata*, *E. crassipes*, *L. camara*, and *A. conyzoides* (Saikia et al. 2017). In Arunachal Pradesh, IAP success was attributed to the construction of roads and the resulting anthropogenic pressure (Kosaka et al. 2010). Nonetheless, no ecological investigation on IAPs has been undertaken to our knowledge in Arunachal Pradesh; therefore, it deserves research on it in future.

Methods in studying plant invasion ecology: a case study in Mizoram, N.E. India

In IHR, the documentation of native plants as per their IUCN threatened status can help in IAPs induced threat assessment, prioritization and biodiversity conservation (Mehta et al. 2020). Also, IAPs are identified as key indicators in vulnerability assessment in IHR (Thakur et al. 2020). Methods for studying the plant invasion ecology comprise qualitative approach like seasonal species inventory and quantitative approach using phytosociological methods (as mentioned in the present case study) (Chandra Sekar 2012). Several indices such as relative alien species richness (RAR) and relative alien species abundance are used as indicators to assess the intensity of plant invaders (Catford et al. 2012; Campos et al. 2013). Further, large vegetation plot databases using multi-scale approach is preferred method in studying plant invasion ecology (Campos et al. 2013). Documentation of IAP, their sustained monitoring, and ecological assessment through vegetation analysis must be done adequately in biodiversity rich regions of India to prevent their landscape spread and for formulating policy measures for biodiversity conservation (Fig. 3). In the context of monitoring the threat of IAPs in Indian Himalayan region, the role of geospatial technologies (remote sensing and geographical information system) can be of paramount importance. Kushwaha (2011) assessed the invasive spread of *L. camara* in Doon valley of Indian Himalayan Region. Further, several remote sensing and GIS tools e.g., Pleiades 1A, Rapid Eye and Landsat-8

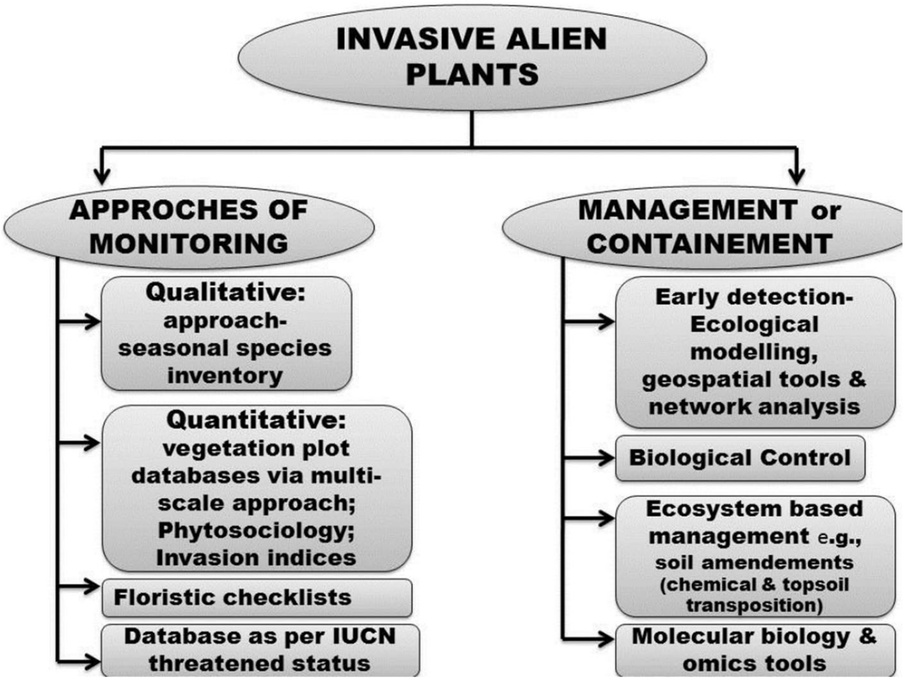


Fig. 3 Ecological methods (quantitative and qualitative) in monitoring the spread of IAPs and their management strategies for biodiversity conservation and restoration

OLI also monitored and assessed the spread of *L. camara* in the IHR (western Himalaya) (Khare et al. 2018). Also, aerial photos and high resolution multi-spectral digital data acquired through geo-spatial tools can be useful in monitoring and assessment of IAPs in IHR (Chandra Sekar 2012). In this context, species distribution modelling (SDM) demonstrated to be useful in monitoring the IAP spread (e.g., *Heracleum mantegazzianum* or giant hogweed) (Shackleton et al. 2020).

In methodological perspectives of plant invasion ecology, a phytosociological study was performed in an Indo-Burma hotspot region. The present case study along the disturbance gradient also aimed to identify the dominant plant invaders of this region. The study was performed in Aizawl District (the capital of Mizoram level in North Eastern India) which is 21 58′–2435′ N Latitude and 92 15′–93 29′ E Longitude; 850 m above mean sea. It is situated on a ridge 1132 m (3715 ft) above sea level, with the Tlawng river valley to its west and the Tuirial river valley to its east. Aizawl has a mild, sub-tropical climate due to its location and elevation. Under the Köppen climate classification, Aizawl features a humid subtropical climate, but observe extended rainy season (Rai 2009). In the summer the temperature ranges from 20 to 30 °C (68–86°F), and in the winter 11–21 °C (52–70°F).

The study was conducted during the winter season (November, 2019) at two differentially disturbed sites. Site 1 (Mizoram University, Botanical Garden) was selected as moderately disturbed site while Site 2 (Roadside, Near Ramrikawn-*ca* 4 km away from Mizoram University campus) was the intensely disturbed one. For the quantitative phyto-sociological analysis, 30 quadrats were laid randomly for herbs (1 × 1 m) and for shrubs (5 × 5 m) as per the standard methods devised by Misra (1968) and Muller-Dombois and Ellenberg (1979). The phytosociological analysis has been done by calculating the density, frequency, abundance, relative density, relative frequency, relative abundance and important value index (IVI) by using the following formulae:

$$\text{Density} = \frac{\text{Total number of individual of a species in all quadrats}}{\text{Total number of quadrats studied}}$$

$$\text{Frequency}(\%) = \frac{\text{Number of quadrats in which species occrured}}{\text{Total number of quadrats studied}} \times 100$$

$$\text{Abundance} = \frac{\text{Total number of individuals of a species in all quadrats}}{\text{Total number of quadrats in which the species occured}}$$

$$\text{Relative density (R. D)} = \frac{\text{Number of individual of species}}{\text{Number of inddividuals of all the quadrats}} \times 100$$

Table 2 Site 1: Botanical Garden (Moderately disturbed site under Department of Environmental Science of School of Earth Science & Natural Resource Management, Mizoram University, Aizawl, Mizoram, NE India)

Name of species	No of individuals	Density	Frequency	Abunda-nce	Relative density	Relative frequency	Relative dominance	IVI
Achyranthes aspera	16	3.2	60	5.3	3.3	6	4.5	13.8
Ageratum conyzoides	63	12.6	100	12.6	13.1	10	10.8	33.9
Alpinea bracteata	22	4.4	60	7.3	4.6	6	6.2	16.8
Biden pilosa	34	6.8	80	8.5	7.1	8	7.3	22.4
Impereta cylindrical	54	10.8	100	10.8	11.2	10	9.2	30.4
Kyllingia brevifolia	51	10.2	100	10.2	10.6	10	8.7	29.3
Lycopodium cernuum	29	5.8	60	9.6	6.0	6	8.2	20.2
Mikinia micrantha	89	17.8	100	17.8	18.6	10	15.3	43.9
Stellaria media	23	4.6	60	7.6	4.8	6	6.5	17.3
Lantana camara	18	3.6	80	4.5	3.7	8	3.8	15.5
Mimosa pudica	45	9	100	9	9.4	10	7.7	27.1
Spilanthes oleracea	24	4.8	60	8	5.0	6	6.8	17.8
Sida acuta	10	2	40	5	2.0	4	4.3	10.3

$$\text{Relative frequency (R.F)} = \frac{\text{Number of quadrats in which species occured}}{\text{Total number of individual of all the species}} \times 100$$

$$\text{Relative abundance(R.A)} = \frac{\text{Total number of individual of the species}}{\text{Number of quadrats in which the species occured}} \times 100$$

$$\text{Important Value Index(IVI)} = \text{Relative density} + \text{Relative frequency} + \text{Realative abundance}$$

The results of the vegetation analysis revealed that among IAP, *M. mikrantha* recorded highest number of individuals, 89 and 75 in numbers (Tables 1 and 2) collected from site 1 and site 2 respectively. In contrast, other plants like *Sida acuta* (10) and *Dioscorea alata* (8) were recorded with lowest number of individuals at the selected sites. Among the recorded plants, the density assessment also revealed that *M. micrantha* was the dominant. Further, it was observed that on site 1 IAP (*A. conyzoides* and *M. micrantha*) were found in all the quardats with 100% occurrence. Likewise, from site 2, both the IAPs (*A. conyzoides* and *M. micrantha*) recorded 100% occurrence. Also, from all the quadrats studied, it was found that *M. micrantha* (17.8 and 15) was found the most abundant on both the sites while *S. acuta* (5) *D. alata* (4) were least abundant on site 1 and site 2, respectively (Tables 2 and 3).

It is evident from the results that there were significant difference in the relative density of the invasive as well as native species collected from site 1 and site 2. At site 1, the highest relative density was recorded for *M. micrantha* (18.6%) followed by *A. conyzoides* (13.1%) and *B. pilosa* (11.2%) while the lowest was recorded for *S. acuta* (2%). Likewise, at site 2, the highest relative density was again recorded for *M. micrantha* (16.5%) followed by *C. dactytlon* (15.4%) and *A. conyzoides* (14.3%) while the lowest was recorded for *D. alata* (1.7%) (Tables 2 and 3).

The results of the relative frequency estimation from the quadrats also revealed that there was a significant difference among the different species of native as well as invasive species of weeds. *A. conyzoides*, *I. cylindrica, K. brevifolia*, *M. micrantha* and *M. pudica* had maximum relative frequencies with 10% each while the lowest was recorded for *S. acuta* with 4% from site 1. On site 2, *A. conyzoides*, *C. dactytlon*, *M. micrantha*, *O. coniculata* and *M. pudica* had the highest relative frequencies with 9.6% each while the lowest was recorded for *L. camara* and *D. alata* with 3.8% each (Tables 2 and 3).

The results further revealed that *M. micrantha* on site 1 had the highest relative dominance (15.3%) while *L. camara* had the lowest with 3.8%. The rest of the species were recorded in the range between 4.3% (in case of *S. acuta*) to 10.8% in case of *A. conyzoides* from site 1. On site 2, the highest relative dominance was recorded for *M. micrantha* with 14.1% while the lowest for *D. alata* with 3.7%

Table 3 Site 2: Road Side (Disturbed site near Ramrikawn, Aizawl, Mizoram, NE India)

Name of species	No of individuals	Density	Frequency	Abundance	Relative density	Relative frequency	Relative dominance	IVI
Ageratum conyzoides	65	13	100	13	14.3	9.6	12.2	36.1
Alpina bracteata	24	4.8	80	6	5.3	7.6	5.6	18.4
Cyperus cyperoides	20	4	80	5	4.4	7.6	4.7	16.7
Cynadon daetylon	17	14	100	14	15.4	9.6	13.2	38.2
Dioscorea alata	8	1.6	40	4	1.7	3.8	3.7	9.2
Biden pilosa	36	7.2	80	9	7.9	7.6	8.5	24
Lantana camara	12	2.4	40	6	2.6	3.8	5.6	12
Paspalum comjugatum	26	5.3	60	8.6	5.7	5.7	8.1	19.5
Mikania micrantha	75	15	100	15	16.5	9.6	14.1	40.2
Lycopodium cernnuum	32	6.4	100	6.4	7.0	9.6	6.0	22.6
Oxalis coniculita	28	5.6	100	5.6	6.1	9.6	5.2	20.9
Mimosa pudica	44	8.8	100	8.8	9.7	9.6	8.3	27.6
Scoparia dulcis	13	2.6	60	4.3	2.8	5.7	4.0	12.5

dominance. The rest of the species ranged from 4.0% (in case of *S. dulcis*) to 13.2% (in case of *C. dactylon*) (Tables 2 and 3).

The result of the IVI analysis revealed there was a significant difference among the different invasive as well as native species collected from the two sites *i.e.* site 1 (botanical garden-moderately disturbed) and road side (near Ramrikawn-disturbed). In case of site 1, the highest IVI value was recorded for *M. mikrantha* (43.9) followed by *A. conyzoides* (33.9) and *I. cylindrica* (30.4) while the lowest was recorded for *S. acuta* (10.3). On site 2, the highest IVI value was again recorded for *M. micrantha* (40.2) followed by *C. dactylon* (38.2) and *A. conyzoides* (36.1) while the lowest was recorded for *L. camara* (12) (Tables 2 and 3).

Present case study revealed the *M. micrantha* and *A. conyzoides* as dominant plant invaders. As per the field observation, *M. micrantha* is the potential invader which can climb even on the top of the canopy of tall trees and thus impede the incident solar radiation necessary for metabolism. Interestingly, it has been observed that the moderate disturbance site (Botanical Garden) encouraged the rapid spread of *M. Micrantha* (IVI-43.9%) than the heavily disturbed roadside (IVI-40.2%). In contrast, the disturbed roadside was more feasible for the spread of *A. conyzoides* (IVI-36.1%), when compared to moderately disturbed site (33.9). If early intervention is not implemented and these IAP species become widespread, eradication may not be feasible since the damages are permanent. It is therefore important to take into consideration all the important strategies and methods to control these IAP and prevent them from further multiplication and establishment.

Management and mitigation strategies of invasive alien plants

The best biodiversity conservation and management strategy can be an early detection of IAPs in initial successional stages (Shah et al. 2012). This early detection of IAPs can be possible with integrated efforts of invasion biologists, taxonomists, local people and forest stakeholders (Chandra Sekar 2012). In this respect, ecological modelling of IAPs in Kashmir Himalaya was identified as a cost- effective management strategy, as plant invaders can be detected at initial growth stages (Shah et al. 2012) (Fig. 3). The preparation of database of IAPs in IHR can also assist in formulating biodiversity management strategies (Shah and Reshi 2014).

Several IAPs are considered to be pseudo-indigenous and cryptogenic in view of biogeographic origin and ecological functions (Jaric et al. 2019). The crypticity of IAPs in terms of species, ecological functions and spatio-temporal perspectives is the constraint in studying their ecological distribution, impacts and management (Jaric et al. 2019). Further, the management strategies are further impeded with complex social–ecological systems particularly, under the global climate change regime (Jaric et al. 2019; Sun et al. 2020). In this respect, the mitigation strategies can be focused on biological filters or barriers for IAPs (from introduction to spread as shown in Fig. 2) along the invasion continuum. To this end, network topology and ecological modelling or network studies can assist in IAPs management (Hui and Richardson 2019; Shackleton et al. 2020).

In management prospects of IAPs, holistic research on abiotic and biotic factors is required (Machado et al. 2020). For sustainable management of IAPs their invasion ecology attributes (e.g., seed banks, dispersal, distribution, life history, phenotypic/adaptive plasticity, phenology, morphology, succession, reproductive biology, biochemistry and physiology) need to be elucidated (Callaway and Ridenour 2004; Chandra Sekar 2012; Zheng et al. 2015; Machado et al. 2020; Mungi et al. 2020; Funk et al. 2020). In IHR, the regular slashing of *E. adenophorum* reduces flowering and seed set, thereby, minimizing the infestation potential (Negi 2016). Further, variations in phenotypic traits among four species of an aquatic IAP i.e., *Potamogeton* in Kashmir Himalayan lakes resulted in their differential invading potential (Wani et al. 2020).

Plant invaders can lead to drastic change in vegetation structure and soil attributes which need to be monitored for sustainable restoration implications (Ahmad et al. 2019a, b). The soil amendment studies (via integrated chemical and topsoil transposition) were found effective in management of Himalayan IAP *Hedychium coronarium* (Machado et al. 2020). Thus, soil attributes need to be characterized in terms of physico-chemical and biological characteristics for the effective IAPs management measures (Raizada et al. 2008; Ahmad et al. 2019a, b; Min and Suseela 2020; Ni et al. 2020).

Biological control of IAPs is also used as an effective management strategy (Machado et al. 2020; Sun et al. 2020; Kurose et al. 2020). However, the efficacy and risk assessment of biological control or IAP-natural enemy interactions should be adequately examined under the event of global climate change (Sun et al. 2020). Biological control of Himalayan balsam (*I.glandulifera*) through rust fungus can be further improved through molecular and phylogenetic studies (Kurose et al. 2020). Also, in genetic prospects, the IAPs in Kashmir Himalaya demonstrated higher ploidy level variations when compared with natives (Dar et al. 2020b). Therefore, the higher ploidy level variations were tightly linked with IAPs spread. The mutualistic association of beneficial microbes and endophytes (e.g., mycorrhiza) with IAPs can also facilitate their spread (Shah et al. 2008; Dar et al. 2020a). Further, the molecular approaches such as environmental (e) DNA detections or surveillance and decision-support trees are being investigated as IAPs management strategies (Sepulveda et al. 2020).

In management perspectives of IAPs, geospatial technologies (remote sensing and GIS) are of paramount importance (Vaz et al. 2018). The wise application of remote sensing can monitor the invasion patterns, impacts, and dynamics. Thus, effective monitoring facilitates eradication of the IAPs at early invasion stages, thereby, preventing their landscape spread (Vaz et al. 2018). In brief, before implementing the specific management strategies in mountain regions, the judicial cost–benefit analysis, ecosystem-based responses and public acceptance need to be evaluated (McDougall et al. 2011).

Future prospects in Indian Himalayan and North East region

In the previous sections, we highlighted several ecological investigations that have been done on multiple aspects of IAPs in PAs, IHR and NE India. Nonetheless, the majority of studies on invasion ecology in biodiversity rich Indian regions are rather incomplete in context of habitat invasibility, latitudinal/ altitudinal ranges and socio-economic implications of IAPs, which need to be explicitly elucidated for their sustainable management (Khuroo et al. 2011). Likewise, there is scanty research in these regions which integrate the soil biology, landscape features, disturbances, climatic/environmental factors and species richness in relation to IAPs. Therefore, ecological investigation of dominant IAPs in tropical forests of IHR/NE India is pertinent in order to device the sustainable management strategy.

Study on invasion science in PAs and forest divisions of NE India (lying in an Indo-Burma Hot spot region) may also assist in their sustainable management. To this end, PAs in Mountains (Murlen National Park, Tawi and Lengteng wild life sanctuary of Mizoram can be investigated further. Study of invasion ecology as well as eco-management in protected areas and forested landscapes, especially lying in global biodiversity hotspots may also pave the way to biotechnological innovations (Rai and Singh 2020a, b).

Also, study on interrelationship of plant invasion with climate change, and anthropogenic disturbance induced spatial heterogeneity is required in future to fill-up the knowledge gap. Drastic/abrupt climatic changes and anthropogenic disturbances in forested landscapes of these PAs may be

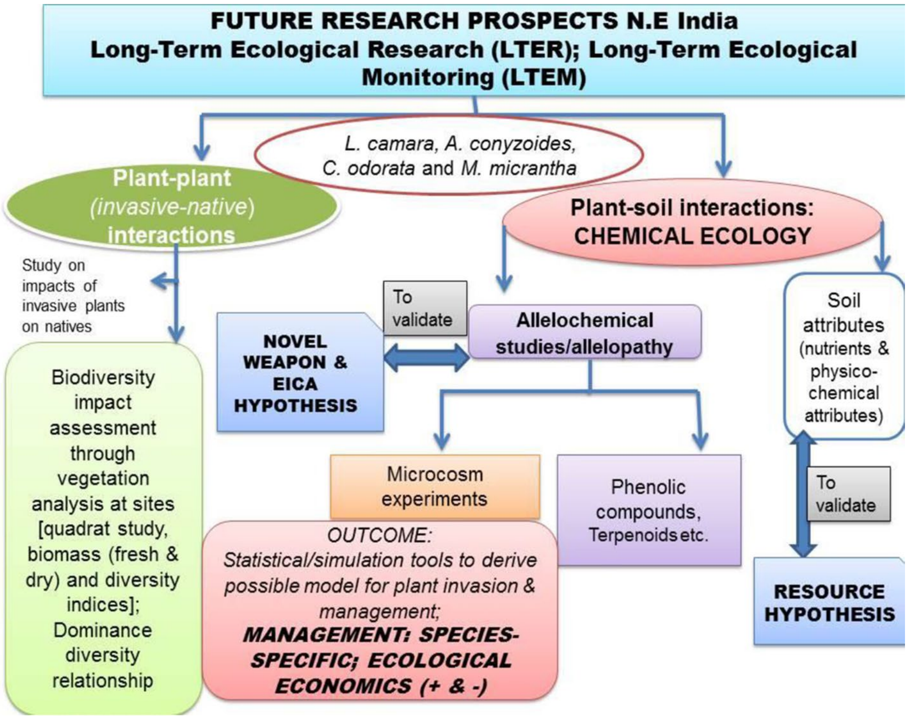


Fig. 4 Future research prospects in NE India and Indian Himalayan region *w.r.t.* plant invasion ecology; The IAPs-natives (plant–plant interactions) can be studied through vegetation analysis (e.g., phytosociological methods and diversity indices) while plant–soil interactions can be investigated through chemical ecology (e.g., study on allelochemic interactions and microcosm growth experiments to detect the allelopathic impacts of IAPs on natives); The plant–soil interactive approach is associated with evolution of increased competitive ability (EICA) novel weapon and resource hypothesis (NWH/RH); The outcome of plant–plant/plant–soil interactions can be statistically validated for formulating the holistic management strategies of IAPs; In restoration policies of IAPs, the ecological economics/indicator perspectives should also be considered for sustainable management of plant invaders

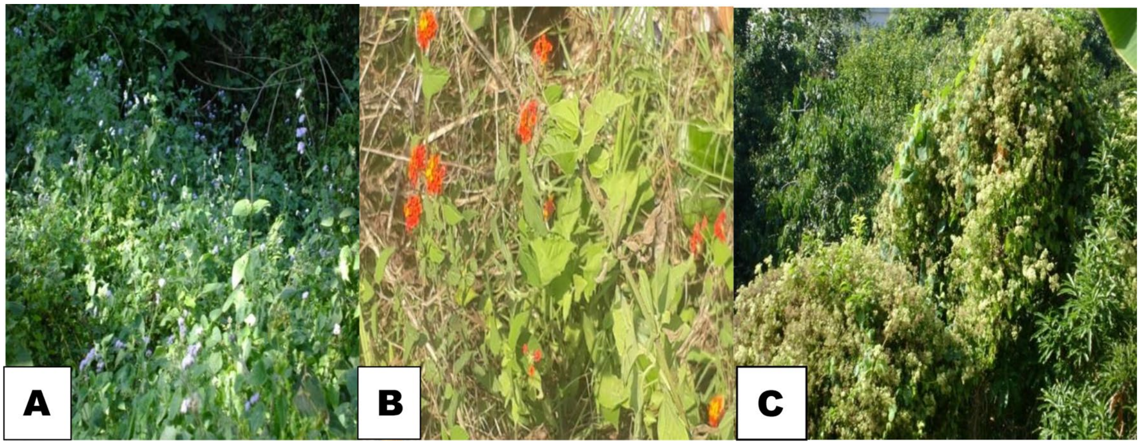


Fig. 5 Dominant plant invaders observed in Aizawl, Mizoram, North East India during the case study on studying the plant invasion ecology through quantitative method—**a** *Ageratum conyzoides* (billy goat weed); **b** *Lantana camara*; **c** *Mikania micrantha* (mile a minute weed)

intimately linked with plant invasion ecology which must be investigated. Thus, there may be immense research opportunities in future for invasion science research on mountain biodiversity (especially in Indian PAs, IHR and NE India) under the scenario of global climate change and habitat fragmentation.

Plant invasion ecology should also be linked with ecological informatics/databases, simulation/modelling and long-term ecological research (LTERs)/LTEM for assessing the linkage with other environmental perturbations e.g., global climate change (Bakker et al. 1996; Singh, 2011; Negi et al. 2019). The future prospects in N.E. India (especially, Mizoram and Adjoining Bark Valley region of Assam can be to study the plant-plant (i.e., invasive-native) and plant-soil interactions in invaded/non-invaded regions through the adoption of LTER or LTEM strategies (Fig. 4). In this aspect, the plant-plant interactions could be studied through vegetation analysis using various diversity indices to assess the impact of IAP on native biodiversity. In this respect, the species specific impacts (e.g., dominant IAPs observed in present case study like *M. micrantha, L. camara*, and *A.conyzoides* (Fig. 5) can also be unravelled in perturbation of biodiversity.

The second approach of plant–soil interactions represented in Fig. 4 aims to assess the IAPs spread impacted by soil attributes (physico-chemical characteristics), especially, through the lens of allelochemicals (e.g., phenolic/sesquiterpenoid compounds). The researches on plants invasion mostly focused on plant-plant interactions (vegetation ecology), whereas, the study on soil attributes impacted by IAPs were largely ignored. The soil attributes (such as litter dynamics, soil carbon, nitrogen mineralisation, phosphorus content, allelochemic concentrations, enzymatic activity and microbial diversity) can be significantly impacted by IAPs, therefore, deserve focused future research to elucidate the plant invasion ecology (Raizada et al. 2008; Min and Suseela 2020; Ni et al. 2020).

The phenomenon of allelopathy can play a vital role in IAPs spread through release of certain chemicals which are toxic and thus suppressive to the diversity of native plants. Thus, allelochemic interaction approach can validate the existing Novel Weapon Hypothesis-NWH/Evolution of Increased Competitive Ability – EICA, responsible in IAP success (Fig. 4). Thus, both plant–plant/plant–soil interactions can assist in understanding of eco-system based mechanisms behind the IAPs success in this region, thereby, assisting in the formulation of their management or biodiversity restoration through ecological informatics/modelling approach.

In future researches, the IAP ecology and management should be directed towards attaining sustainability paradigm in long-term biodiversity restoration programmes (Rai and Kim 2020). In fact each and every plant invader cannot be nuisance in all aspects, rather few terrestrial like *L. camara* (in timber industry) (Kannan et al. 2014, 2016) and aquatic IAPs [*E. crassipes, A. donax, Phragmites australis* etc. in phytoremediation of pollutants (Rai et al. 2020), polymer industry and bioenergy (Rai and Kim 2020)] have environmental/socio-ecological/socio-economic beneficial prospects. Therefore, adequate cost–benefit analysis with well-defined indicators should be done before the implementation of ecological restoration strategies.

In the context of IAPs management, since it has been observed that several eco-restoration/rehabilitation efforts turned reversible and unsustainable, therefore, judicial site/IAP-specific ecological economics need to be studied wisely. Henceforth, abridging the IAP-ecological sciences with sustainability science is need of the hour (Clark and Dickson 2003; Palmer et al. 2005; Singh 2011; Rai and Kim 2020) in N.E. Indian/Indian Himalayan prospects. In respect of IAPs mitigation, SCOPE, GISP, CABI, and UN-IPBES

(Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) are enforcing legal regulatory measures for biodiversity restoration. UN-IPBES-global indicators target (i.e., 15.8) aims to achieve SDGs by effective management strategies to control the IAPs by 2020. However, the institutional, legal, and regulatory measures should be strongly enforced to mitigate the IAPs induced risks. Moreover, the risk assessment protocols, indicator perspectives and biosecurity implications should be adequately strengthened through interdisciplinary future researches for IAPs containment.

Conclusions

The spread of IAPs in protected areas, IHR, and the NE India impoverish their native biodiversity and diminish the socioeconomic, socio-ecological prospects, in addition to ecosystem services. Sustained biodiversity assessment is essential in Himalayan biodiversity hotspots to assess the loss of native species owing to IAPs spread. In this respect, the database on the number of native plants which have become endangered or have the potential to become endangered due to IAPs spread can also be useful for biodiversity conservation and restoration programmes. In studying plants invasion ecology, integration of modern geo-spatial tools is required for a state of art comprehensive account of the IAPs in Himalayan biodiversity hotspots and PAs. Further, geospatial technologies (remote sensing and GIS) should be applied more extensively in tough terrains to explicitly correlate them with ground based or field datasets. The spatial heterogeneity can also remarkably facilitate the IAPs success, as revealed through the small case study in Aizawl, Mizoram NE India. However, adequate methodological approaches can be used in delineating the disturbance gradient in a specific spatial heterogeneity landscape set-up. Also, quantitative and qualitative ecological methods can be wisely used for assessing the impacts and spread of IAPs. Among mitigation or containment measures, detection of IAPs at early successional stages, adequate mitigation response, people participation, and regulatory policy measures can lead to their sustainable management.

Acknowledgements Authors thank DBT for financial assistance vide Project No. BT/PR24917/NER/95/907/2017; Professor J.S. Singh thanks BHU and INSA for support.

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