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ANTHROPOCENE REVIEW

Environmental Degradation by Invasive Alien Plants in the Anthropocene: Challenges and Prospects for Sustainable Restoration

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Abstract

Biodiversity, soil, air, and water are the vital life-supporting systems of this planet Earth. However, the deliberate and accidental introduction of invasive alien plants (IAPs) in the Anthropocene majorly due to the global international trade perturbed the homeostasis of our biosphere. IAPs are considered as one of the major drivers of biodiversity loss and ecosystem degradation. The pervasive threats of IAPs to environmental sustainability and biosecurity are further exacerbated under the COVID-19 pandemic. The environmental disturbances resulting from IAPs can be attributed to several mechanisms/hypothesis (e.g., novel weapon (NW), enemy release (ER), and evolution of increased competitive ability (EICA), efficient reproductive attributes, and phenotypic plasticity, etc.) deployed by IAPs. Nevertheless, the interrelationship of IAPs with environmental degradation and restoration remain elusive especially in terms of ecological sustainability. Moreover, there is a dearth of studies which empirically assess the synergies of IAPs spread with other anthropogenic disturbances such as climate and land-use change. In this context, the present review is aimed to depict the impacts of IAPs on environment and also to assess their role as drivers of ecosystem degradation. The restoration prospects targeted to revitalize the associated abiotic (soil and water) and biotic environment (biodiversity) are also discussed in detail. Furthermore, the effects of IAPs on socio-economy, livelihood, and plant-soil microbe interactions are emphasized. On the other hand, the ecosystem services of IAPs such as associated bioresource co-benefits (e.g., bioenergy, phytoremediation, biopolymers, and ethnomedicines) can also be vital in sustainable management prospects. Nevertheless, IAPs-ecological restoration interrelationship needs long-term pragmatic evaluation in terms of ecological economics and ecosystem resilience. The incorporation of 'hybrid technologies', integrating modern scientific information (e.g., 'biorefinery': conversion of IAPs feedstock to produce bioenergy/biopolymers) with traditional ecological knowledge (TEK) can safeguard the environmental sustainability in the Anthropocene. Importantly, the management of IAPs in concert with circular economy principles can remarkably help achieving the target of UN Sustainable Development Goals and UN-Decade on Ecosystem Restoration.

Keywords Biotic invaders · Climate change · Ecosystem restoration · Ecological resilience · Forest biodiversity · Invasive alien plants · Plant-soil-microbe interactions · Sustainability · Traditional ecological knowledge

1 Introduction

The Anthropocene (i.e., human-dominated geological epoch) witnessed a rapid pace of industrialization and urbanization, transmogrifying the global land-use pattern (Lewis and Muslin 2015; Bauer and Reynolds 2016; Gornish and dos Santos 2016; Reynolds 2021). Environmental resources are finite in nature and form the very basis of life on this planet Earth. Therefore, the natural resources and biodiversity need to be protected from the multiple anthropocene risks (Edrsi et al. 2020; Díaz et al. 2020; Abhilash et al. 2021). Further, biotic/abiotic components of the environment provide a multitude of ecosystem services such as food, fiber, fuel, timber, carbon sequestration, nutrient cycling, and human well-being (Fig. 1). Unfortunately, environmental pollution caused by anthropogenic activities escalated the concentrations of hazardous heavy metals, organic chemicals,

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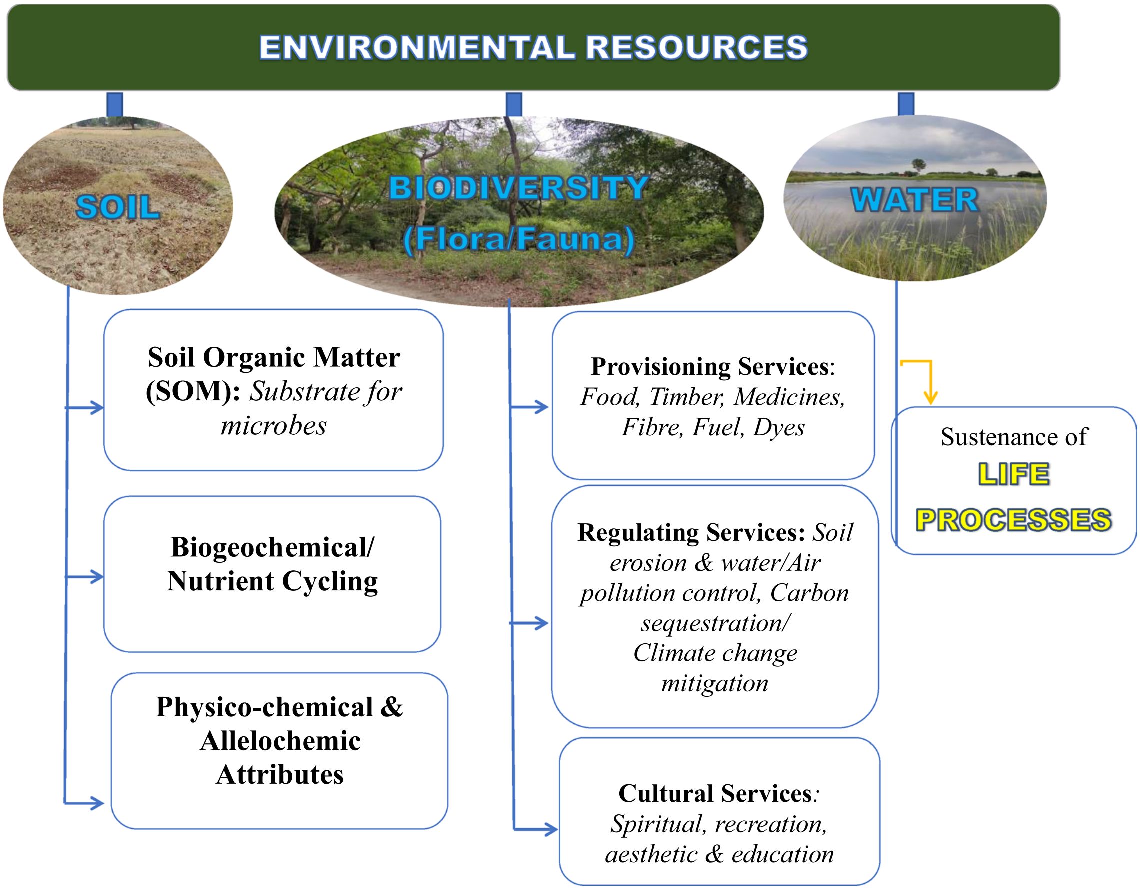

Fig. 1 The multitude of ecosystem services associated with abiotic/biotic complexities of environment, essential for the sustenance of human life, well-being, and livelihood in the Anthropocene

and emerging contaminants such as micro/-nanoplastics in multiple environmental matrices diminished the ecosystem services (Lewis and Muslin 2015; Rai et al. 2021). In this context, though the native biodiversity is considered to be safety-net against the environmental pollution and ecological invasions to safeguard the human health (Kennedy et al. 2002; Swaminathan 2003; Bawa et al. 2021; Crisp 2021), however, its continuous depletion also aroused concern about the loss of its associated ecosystem services, socio-cultural attributes, and socio-economic or livelihood aspects. Further, land-use and climate change in conjunction with nitrogen deposition and biotic exchange acted as major drivers of future changes in biodiversity, thereby impacting the global ecosystem services (Sala et al. 2000; IPCC 2013; Pyšek et al. 2020). The recent coronavirus (SARS-Cov-2) upsurge remarkably influenced the IAPs, biodiversity, indigenous agricultural food systems, livelihood of low-income population, and environmental footprint (McElwee 2020; Zavaleta-Cortijo et al. 2020). Incidentally, the anthropogenic pressure on biodiversity is likely to be escalated during post COVID-19 pandemic scenario which warrants sustainable solutions (Bouman et al. 2021).

In addition to environmental pollution, the alteration of ecological complexity and soil resources through invasive alien plants (IAPs) is a pervasive threat to native biodiversity while accelerating the overall process of environmental degradation (Stanek et al. 2020; Allen et al. 2021; Qu et al. 2021). International trade through several global routes was considered to be the prime drivers in the spread of biotic invaders (Hulme 2021). Biological invasions since its inception in ecological studies were considered as a sort of 'ecological explosions' (Elton 1958). In the present scenario, global estimates of 21 countries suggested that the number of biotic invaders per country have risen by about 70% since 1970 (IPBES 2019a, b). Further, the International Union for Conservation of Nature (IUCN)-Red List database assessed that IAPs contributed to 25% of global plant extinctions (IUCN 2017). Globally, the rapid spread of IAPs in the heterogeneous environment can be ascribed to several adaptive mechanisms or hypothesis [e.g. Novel Weapon (NW), Enemy Release (ER), and evolution of increased competitive ability (EICA)], efficient reproductive attributes (e.g., perfection of pollination and vigorous seed output), rapid biomass allocation, herbivore-IAP interactions, and phenotypic plasticity (Blumenthal 2006; Blumenthal et al. 2016; Pinzone et al. 2018; Pyšek et al. 2020; Wang et al. 2020; Rathee et al. 2021; Allen et al. 2021). Nonetheless, these mechanisms may be species/habitat specific in triggering the IAPs spread and environmental degradation.

The rapid pace of IAPs infestation in the Anthropocene perturbed the biotic and abiotic components of the environment (El-Barougy et al. 2021; Rathee et al. 2021). To this end, the IAPs have driven the environmental degradation by changing nutrient and pollutant cycling, habitat structure, microbial diversity; hydro-morphology, soil chemistry, water and disturbance regimes (Pyšek et al. 2020; Qu et al. 2021). In contrast, Gao et al. (2020) studied the effects of soil attributes on IAPs and revealed that soil nutrient heterogeneity has driven the growth of plant invaders. Hence, IAPs act as passengers as well drivers of environmental degradation in Anthropocene (Bolpagni 2021). In addition, it has been demonstrated that IAPs possess high phenotypic plasticity and better soil resource utilization in disturbed environment which gives them a competitive advantage over natives, especially under the changing global climate (Funk 2008; Ravi et al. 2009; Hulme 2012; Parepa et al. 2013; Gong et al. 2020). Further, the disturbed landscapes such as landfills/dumps can also act as IAPs epicentres or hotspots which can adversely affect the other environmental matrices and human health through the release of pollen and toxins (Plaza et al. 2018; El-Barougy et al. 2021).

The present status of environmental perturbation can be realised by the fact that about 33% of the global land is degraded in nature due to multiple disturbances (Parepa et al. 2013; Nkonya et al. 2016). Further, according to United Nations Development Program (UNDP), 52% of global agricultural lands are degraded to varying extent, impacting the livelihood of 2.6 billion agrarian people and farmers (Abhilash 2021). Nevertheless, IAPs successfully colonized the marginal lands and depauperate ecosystems, not suited for growing other agricultural crops (Rai and Kim 2020). Past studies have also noted that the integral components of environment such as vegetation dynamics, forest community composition, litter decomposition, and soil nutrient status in protected landscapes are significantly influenced by the spread of IAPs (Aragón et al. 2014; Uddin and Robinson 2018; El-Barougy et al. 2021). It has been well known that almost 99% of the selected IAPs are used globally as food crops (e.g., wheat, maize, cassava, rice, potato, barley, soyabean, sugarcane, and oats) (Pejchar and Mooney 2009). Interestingly, 70% of global dietary need is secured by raising these alien food crops (Prescott-Allen and Prescott-Allen 1990; Pejchar and Mooney 2009; Kariyawasam et al. 2021). However, unsustainable practices such as monoculture plantations in agro-forestry/agro-ecosystems facilitated the IAPs spread and concomitantly increased susceptibility towards pathogenic microbes (Chazdon 2008). Several IAPs such as *Eichhornia crassipes* and *Salvinia molesta* can adversely influence the productivity of paddy fields (Kariyawasam et al. 2021). Allelochemic compounds released from IAPs (e.g., *Rhus typhina*) adversely influenced the growth of cultivated plant such as *Tagetes erecta* (Qu et al. 2021). Furthermore, IAPs in concert with climate change have remarkably affected the global agricultural systems (Ziska et al. 2011; Paini et al. 2016) and hence impose adverse implications on food security. The adverse effects of IAPs on agriculture systems under the event of climate change (e.g., abrupt increase/decrease in temperature and rainfall variables influencing the phenology and soil attributes) are being studied through climatic suitability heat maps, ecological niche and species distribution models (SDMs) (Gong et al. 2020; El-Barougy et al. 2021; Kariyawasam et al. 2021).

Restoration of degraded environment can rejuvenate the forestry/agro-forestry and agroecosystem biodiversity with the revitalization of ecosystem services which can assist in attaining the UN-Sustainable Development Goals (SDGs) (Leclere et al. 2020; Edrsi et al. 2020) (Fig. 2). Further, Fig. 2 lists the environmental challenges in Anthropocene, especially in relation to IAPs and elucidates their interrelationship with several targets of SDGs. In this sense, restoration of degraded environment encompasses a broad range of pursuits such as (a) reclamation of degraded abiotic environment due to mining and hazardous environmental contaminants, (b) revitalization of ecosystem services, and (c) rehabilitation of rare, endangered, and indigenous biodiversity through management of IAPs. Furthermore, explicit studies on plant-soil and plant-soil microbe interactions can be a vital foundation for formulating sustainable ecosystem restoration strategies (Eviner and Hawkes 2008). In Anthropocene, the sustainable restoration of biodiversity (SDG 15) can safeguard the human health under the event of future pandemics (SDG 3) (Bawa et al. 2021). Further, the biodiversity restoration is considered to be the sustainable way of mitigating the effects of climate change (SDG 13). In addition, several Institutions such as convention on biological diversity (CBD), United Nations Convention to Combat Desertification (UNCCD), and Kyoto Protocol widely identified the rapid pace of IAPs lead environmental degradation in Anthropocene as a major challenge for restoration ecologists (Waruru 2018).

The complex interactions among global environmental disturbances in Anthropocene have complicated the task of restoration ecologists (Hobbs and Cramer 2008; Walther et al. 2009; Rai 2015; Early et al. 2016). Concomitantly, these perturbations resulted in paradigm shift in ecological resilience, rehabilitation, self-regeneration, and restoration mechanisms of degraded environment. Several studies have been performed to analyse the impact of IAPs on biodiversity (in terms of 'autecology'/ vegetation ecology) whereas, the study on soil attributes are of paramount

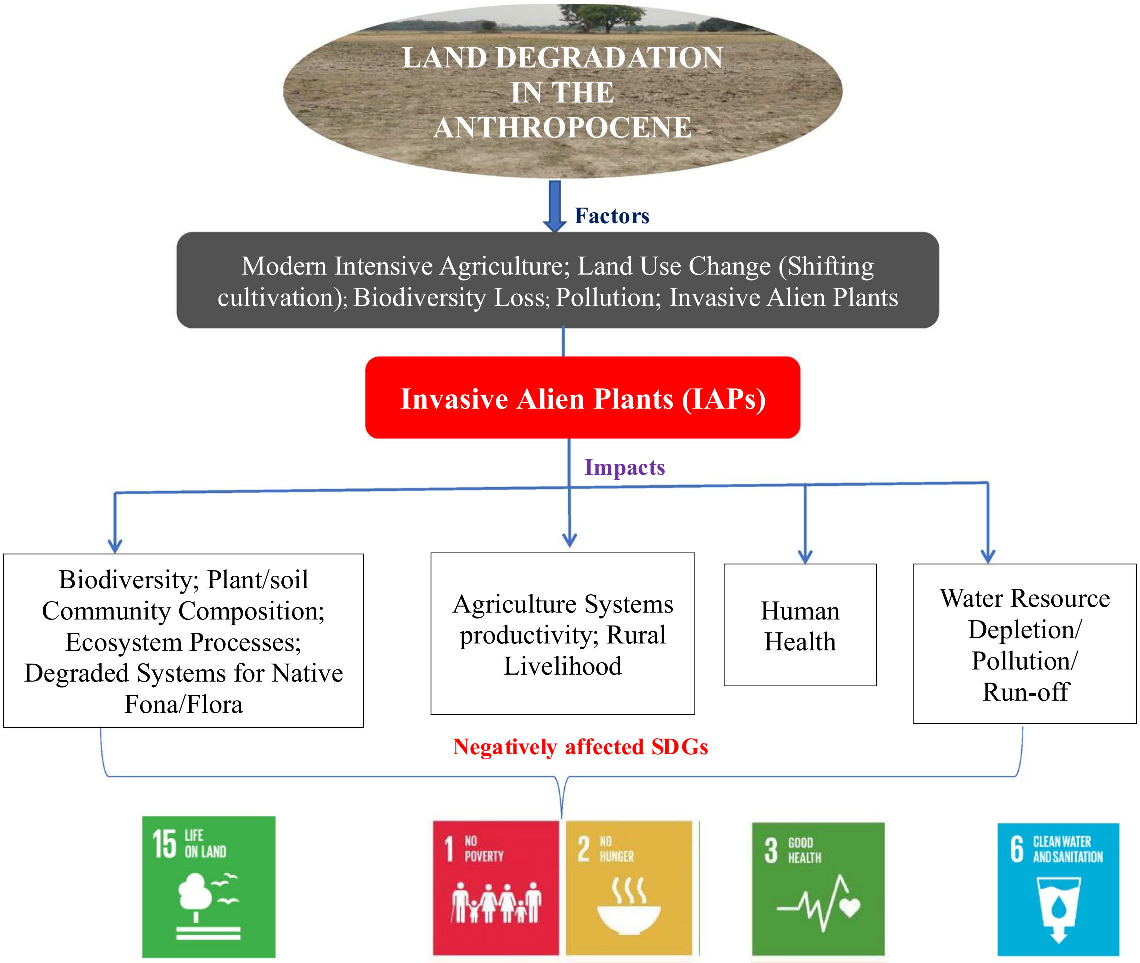

Fig. 2 Drivers of environmental degradation in the Anthropocene with special reference to plant invaders which are interrelated with multiple SDGs; The IAPs can influence the attainment of various SDG targets (1, 3, 6, and 15) and hence inextricably linked with the environmental sustainability

importance in understanding plant invasion ecology. In this respect, several search engines such as SCOPUS, Web of Science, Science Direct, and Google Scholar were visited in quest of the existing voids in subject knowledge. In studying the subject both academic and grey literature were covered. To this end, several keywords such as "Plant invasion and ecosystem degradation", "Invasive alien plants and soil properties", "Invasive alien plants and soil microbes", "Invasive alien plants and restoration" and Plant invasion climate change and land-use" were searched in literature selection methodology to provide a systematic review of the subject. In previous studies, the multifaceted impacts of IAPs are widely documented, however; there is a dearth of studies which describes the environmental degradation and sustainable restoration strategies in an interrelated framework. Henceforth, this review addresses the impacts of IAPs on multiple environmental matrices to assess their holistic effect. To this end, the effects of IAPs on biodiversity, soil, and water are discussed in this review. These environmental impacts of IAPs were observed to reverberate up to the level of ecosystem degradation. Importantly, in this review, IAPs driven environmental degradation and restoration are discussed critically in terms of positive and negative implications. In addition, the restoration strategies, capitalizing the role of traditional ecological knowledge (TEK) are described to attain environmental sustainability. The present discussion advocated the use of 'hybrid technologies' (i.e., integrating scientific knowledge, TEK, and scientific co-benefits in terms of environmental remediation and 'bio refinery') for IAPs management and sustainable ecosystem restoration. The implementation of hybrid technologies in ecosystem restoration can be of wider community acceptance and can concomitantly augment in help achieving the target of SDGs and rural livelihood.

2 Impacts of Invasive Alien Plants on Environmental Resources

2.1 Biodiversity

The landscape spread of IAPs is widely accepted as pervasive threat to native biodiversity (Pyšek et al. 2020; El-Barougy et al. 2021). On contrary, the rich native biodiversity is considered to be a line of the defence against IAPs infestation in accordance with ‘diversity resistance hypothesis’ (Kennedy et al. 2002). However, the increased colonization of IAPs in novel ecosystems can adversely influence the native biodiversity and carbon storage (Jackson et al. 2002; Leclere et al. 2020). Globally, it has been estimated that about 17% of the biodiversity is highly vulnerable to biotic invasions (Early et al. 2016). Further, the geographical landscapes of 15% of the low Human Development Index (HDI) countries and 16% of global biodiversity hotspots are highly threatened due to biotic invasions (Early et al. 2016). Adaptability to grow in an environment with spatio-temporal heterogeneity, strong clonal ability, and efficient utilization of resources (e.g., nutrients) can facilitate the IAPs success over the native biodiversity (Wang et al. 2021). In this aspect, study on *Parthenium hysterophorus* in Himalayan mountain ecosystems revealed the role of phenotypic plasticity, reproductive fitness (e.g., large number of heavier but small-sized seeds), and biomass allocation in the spread of this IAP (Rathee et al. 2021). Further, the adverse effects of IAPs on indigenous or native biodiversity are further exacerbated under the event of high global deforestation rate i.e., 13 million ha^{-1} (Chazdon 2008) and climate change (Pyšek et al. 2020). Climate change in concert with other environmental perturbations influenced the diversity of soil microbes (Young and Larson 2011). In addition, it has been estimated that about 500 million hectares of tropical forests have been lost due to intensive land-use changes which can potentially facilitate the colonization of IAPs (Lamb et al. 2005; Pyšek et al. 2020). In addition to extensive deforestation, IAPs spread is encouraged through practicing unsustainable traditional/modern intensive agricultural practices (Chazdon 2008). Accordingly, multiple anthropogenic disturbances encouraged IAPs spread in forested landscapes. These synergistic interactions of IAPs resulted in an adverse influence on stochastic process of forest succession which eventually turned them into degraded secondary forests (Chazdon 2008; Rai 2009). Anthropogenic activities such as mining can drastically remove the vegetation cover and top-soil and has been estimated to impact an area of 2 million hectares/year worldwide (FAO 2006**).** In this sense, biodiversity loss through forest degradation alone is predicted to influence the well-being of about 1.6 billion people among which about 74% are rural people with low livelihood opportunities (Abhilash 2021).

The ‘invasion windows’ generated by anthropogenic disturbances allow IAPs to act as passenger along with the potential plant traits such as; prolific seed production, efficient seed dispersal, greater propagules mobility, and allelochemic attributes (Sakachep and Rai 2021). Interestingly, these traits associated with IAPs can help them to establish in novel habitats and threaten the native biodiversity (Rai and Singh 2021). Accordingly, IAPs act as carriers along with the anthropogenic disturbances such as habitat destruction through deforestation. In view of this arrested forest development and infested IAPs, Food and Agriculture Organization (FAO) estimated that secondary degraded forests constitute about 60% of global forest area (FAO 2005). In addition, United Nation’s (UN) Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES) predicted that about one fifth of the Earth’s land surface is at risk due to biotic invaders therefore, considered them as major driver of biodiversity loss (IPBES 2019a, b). Accordingly, Earth Summit in Rio de Janeiro, 1992, therefore, delineated the IAPs spread in the forestry/agroforestry systems as one of the main causes in impacting the environment, biodiversity, human health, and ecosystem services. Henceforth, the threat of IAPs to global biodiversity hotspots and associated environmental degradation is of concern to conservation and restoration ecologists. The IUCN Invasive Species Specialist Group (ISSG) developed two global databases i.e., the Global Invasive Species Database, which provides explicit details of specific biotic invaders and the Global Register of Introduced and Aliens (Pyšek et al. 2020). Further, Delivering Alien Species Inventories for Europe (DAISIE) and North European and Baltic Network on Invasive Alien Species (NOBANIS) projects aimed to monitor the biodiversity and health effects of IAPs. In addition, other global efforts to minimize the effects of IAPs and strengthen biodiversity conservation were channelized through institutional and regulatory organizations such as Global Biodiversity Information Facility (GBIF), World Database on Protected Areas (WDPA), Global Register of Introduced and Invasive Species (GRIIS), Invasive Species Compendium (CABI), and Environmental Impact Classification for Alien Taxa (EICAT) (McGeoch and Jetz 2019; Leclere et al. 2020).

2.2 Soil

The adverse impacts of IAPs on soil and associated ecosystem processes can remarkably facilitate the environmental degradation. The different steps involved in ecological succession and spread of IAPs are inextricably associated with plant-soil/plant-soil-microbe interactions

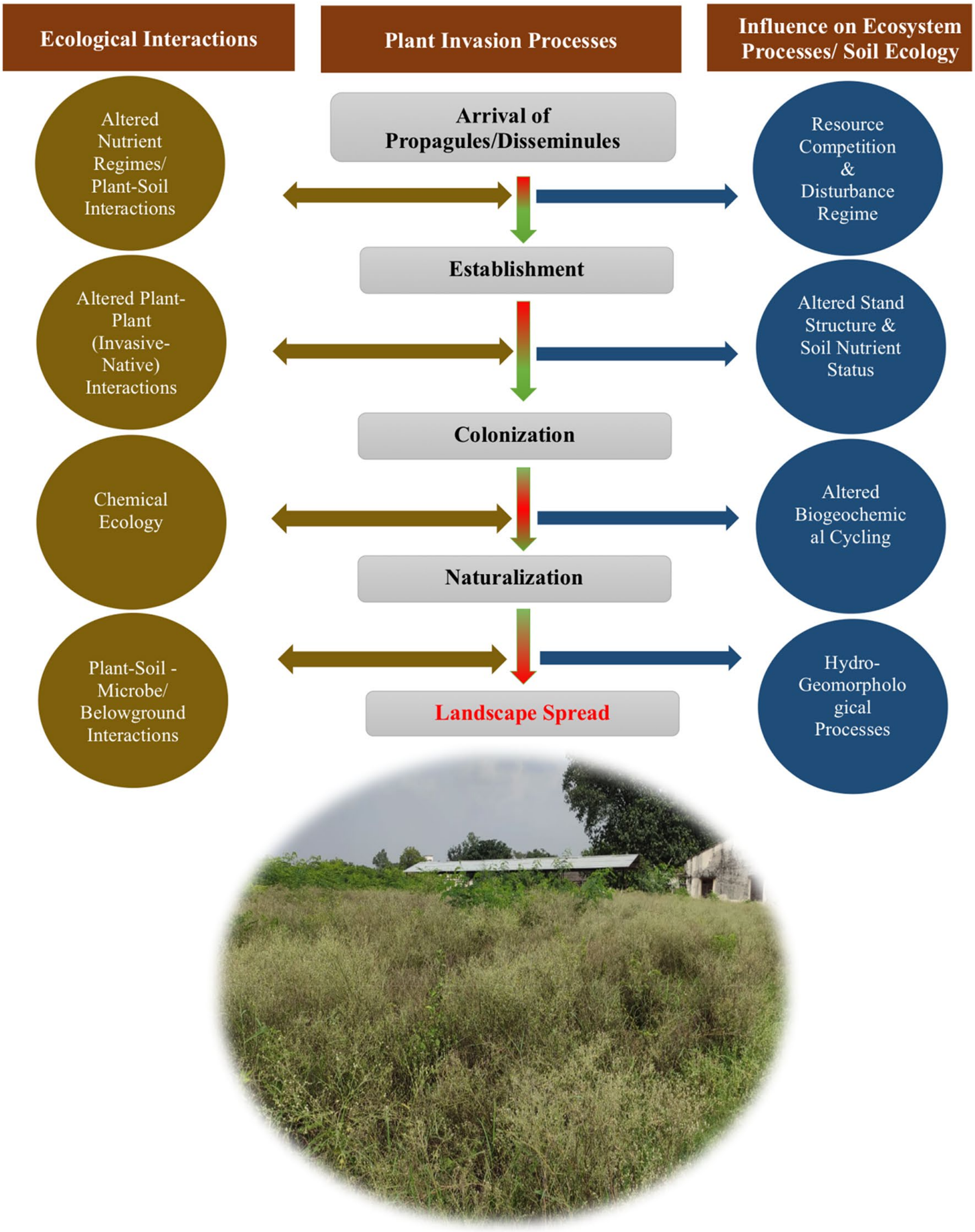

Fig. 3 The interrelationship of plant invasion ecology /their ecological succession mechanisms/hypotheses with plant-soil-microbe interactions, influencing the soil physic-chemical/biological characteristics and ecosystem processes

(Fig. 3). The changes in soil physic–chemical attributes, biogeochemical cycling, and hydrogeomorphological processes are tightly linked with different steps (propagules arrival, establishment, colonization, and landscape spread) in IAP succession (Fig. 3). The successful colonization of IAPs such as *Rhus typhina* can adversely impact the soil physico–chemical and microbial attributes (Qu et al. 2021).

2.3 Impact of IAPs on Soil Physicochemical Properties

The effects of IAPs on soil physico–chemical characteristics can be variable in different ecosystems. In this respect, the effects of *Chromolaena odorata* on soil attributes were noted higher in savannah when compared with forest ecosystems (Koné et al. 2021). In the context of soil physico–chemical characteristics, certain IAPs (e.g., *Bromus tectorum*, *Eucalyptus tereticornis*, and *Phragmites australis*) positively altered the physical properties of soil or associated micro-topography (Bargali et al. 1993; Windham and Lathrop 1999; Kumar et al. 2021). Such influences of IAPs on soil attributes were attributed to increased soil porosity due to the presence of shallow fine roots. Further, in the case of multiple IAPs-natives interactions, multidirectional effects can result in a considerable divergence in soil physico-chemical attributes (Stefanowicz et al. 2018). In this aspect, colonization of IAPs (e.g., *Lantana camara* and *Ageratina adenophora*) in chir pine forests of Central Himalayan region increased soil physico–chemical parameters such as soil moisture, porosity, nitrogen (N), potassium (K), and organic C while there was noted a decrease in bulk density (Kumar et al. 2021). Herein, the increased nutrient status in enriched soil substratum of chir pine forests was predicted to facilitate the spread of *L. camara* and *A.adenophora*. Conversely, certain IAPs such as *E. tereticornis* reduced the organic matter, water holding capacity, and nutrient levels, thereby degrade the soil physico–chemical parameters (Bargali 1993; Parepa et al. 2013; Qu et al. 2021). In another study, the infestation *of Prosopis juliflora* was observed to increase the soil pH but decreased exchangeable sodium, calcium, and magnesium when compared with un-invaded lands (Shiferaw 2021). In addition, the long term colonization *H. mantegazzianum* impacted the physical, chemical, and biological attributes of soil (Jandova et al. 2014). Therefore, depending on specific IAPs, their impacts on soil physico–chemical characteristics can be positive and negative. Several studies investigated the strong interrelationship between IAPs success and soil attributes. In this sense, the infestation of IAPs [e.g., *Solidago gigantea*, *Fallopia japonica, Impatiens glandulifera* (Himalayan Balsam), and *Heracleum mantegazzianum*] increased the nutrient stock and aboveground biomass when compared with un-invaded vegetation (Dassonville et al. 2008). Thus, the comparative ecological investigation of invaded and un-invaded sites displayed divergent soil chemistry and plant community composition (Dassonville et al. 2008).

In general, the colonization of IAPs in specific landscape can contribute towards homogenisation of soil conditions (Qu et al. 2021). The multiple soil attributes (such as litter dynamics, soil carbon (C), N mineralisation, phosphorus (P) content, allelochemic concentrations, enzymatic activity, and microbial diversity) can be significantly influenced by the colonization of IAPs (Ni et al. 2020) (Table 1). These IAPs induced changes in soil pools impose persistent effect on soil structure or processes which can extend to landscape level, thereby altering the geomorphology (Fig. 4). In this context, Fig. 4 represents the interrelationship between IAPs and native traits. The interrelationship of plant traits such as litter chemistry, mineralization, soil organic matter, cation exchange, root exudates, and phenology with soil physical–chemical attributes (e.g., soil-temperature, pH, water holding capacity, and microbial biomass) can influence the IAP dynamics. The alterations in soil nutrient pool can potentially impact the plant community dynamics. In this sense, increased soil N facilitated the colonization of an IAP *Flaveria bidentis,* which caused elimination of another plant invader i.e., *Bidens* sp. (Huangfu and Li 2019). Another study revealed that an enhanced level of nutrients such as soil N was demonstrated to facilitate the landscape spread of *B. tectorum*, (annual cheat grass) by out-competing the native plants (Morris et al. 2016).

2.3.1 Impact of IAPs on Soil Biochemical Properties

Plant invaders remarkably influence the biochemical properties of soil (Qu et al. 2021; Shiferaw 2021). In general, IAPs enhance soil enzymatic activities greater than natives and differential enzyme levels can act as proxy for N-mineralization (Ehrenfeld 2003; Shiferaw 2021). Interestingly, allelochemicals in soil released from IAPs can exert immediate harmful effects and also potentially persist as allelopathic legacy to influence the native biodiversity, in long-term (Fabbro and Prati 2015). Interestingly, IAPs spread is also impacted by release of allelochemicals (e.g., phenolic/sesqui-terpenoid compounds) and their influence on soil chemistry (Qu et al. 2021). The allelochemic compounds or secondary metabolites emitted from IAPs can also influence the litter decomposition, root exudates chemistry, and subsequent release of nutrients (Ehrenfeld 2003; Qu et al. 2021). Individual plant-based simulation model (e.g., ECOTONE) revealed that soil texture, in concert with allelopathy influenced the landscape spread of a C_3 IAP *Acroptilon repens* which on long-term infestation increased the extent of soil erosion (Goslee et al. 2001; Qu et al. 2021).

Plant invaders such as *Casurina equisetifolia* are considered to produce more litter with slow decomposition than natives (e.g., *Melaleuca quinqenervia*) (Greenway 1994). Further, IAPs influence litter persistence their quantity and quality thereby, impacting the litter dynamics of infested landscape (Qu et al. 2021). The IAPs litter (e.g., those of *Lantana camara*, *Myrica faya*, and *P. australis*) also differ in tissue chemistry owing to high N content, allelochemic potential, and decomposition rate, when compared with natives (Raizada et al. 2008). Therefore, variability in litter

Table 1 Impacts of invasive alien plants (IAPs) on soil nutrients and microbial diversity

S. no	Invasive alien plant	Invaded region or landscape	Effects (structural and functional)	References
Soil nutrients				
1	*Bromus tectorum* (cheatgrass)	National Park in Southeastern Utah	Reduce the Nitrogen (N) mineralisation and adversely impacting native i.e., *Hieracium* spp. and other plants	Belnap and Phillips (2001); Morris et al. (2016); McLeod et al. (2016); Kumar et al. (2021)
2	*Prosopis juliflora*	Lucknow, India	Influence soil physical–chemical attributes; Elevated soil nutrient levels compared to un-invaded sites; Groundwater depletion	Dzikiti et al. (2017); Edrisi et al. (2020); Shiferaw (2021)
3	*Eucalyptus* sp.	Central Himalaya	IAP induced decline in proportion of finer particles, Water holding capacity, organic matter and nutrient concentration	Baragali et al. (1993); El-Barougy et al. (2021)
4	*Lantana camara, Mikania mikrantha*, and *Chromolaena odorata*	Hailakandi District, Assam, North East India	Decline in soil organic carbon (SOC) and the soil organic matter (SOM) content at invaded or disturbed site; control of particulate matter pollution	Rai and Singh (2015); Sakachep and Rai (2021)
5	*Impatiens glandulifera* (Himalayan Balsam)	River/riparian systems of UK and Switzerland	Increased soil erosion due to alterations in geochemistry	Greenwood et al. (2018); Stefanowicz et al. (2019)
Microbial diversity				
6	*Solidago gigantea*	Zurich, Switzerland	Reduced bacterial biomass, increased fungal biomass and fungal to bacterial ratio	Dassonville et al. (2008); Rai and Singh (2020a, b)
7	*Alliaria petiolata* (garlic mustard)	Oak–hickory forest, Illinois	Decrease in Arbuscular Mycorhhizal Fungi (AMF) abundance and diversity of native species	Roberts andAnderson (2001); Van der Putten (2007); Qu et al. (2021)
8	*Typha angustifolia*	Calcareous fen (wetland), New York State	IAP decreased the AMF colonization in natives of the invaded landscapes	Wolfe and Klironomos (2005)
9	*Bromus tectorum* (cheatgrass)	National Park in Southeastern Utah	Increase in species richness of fungi and abundance of active bacteria; decrease in specialist pathogenic fungi; shifts in composition of AMF and bacteria	Belnap and Phillips (2001); Kumar et al. (2021)
10	*Phragmites australis* (common reed)	Brackish marshes, New Jersey	Significant alterations in composition of microbial communities at disturbed or IAP invaded sites; potential phytoremediation bioresource	Ravit et al. (2003); Rai (2021)

Fig. 4 Mutual intricate interrelationship between plant traits and soil health (physico–chemical and biological parameters) with significant ecosystem restoration implications

persistence can exert a profound impact on soil nutrient status, stand structure, biogeochemical cycles, and hydrogeomorphological processes (Jandova et al. 2014; Wang et al. 2021).

Certain IAPs such as *L. camara* and *P. australis* demonstrate higher N-use efficiency than natives; thereby influence the mineralization and N-dynamics of invaded landscapes (Wang et al. 2021). In addition, IAPs such as *Lepidium latifolium* influence the carbon dynamics of invaded regions due to their higher biomass, net CO_2 assimilation rate, clonal spread, and lower leaf construction costs (Ehrenfeld 2003). Moreover, the long-term infestation of IAPs such as *C. equisetifolia* can competitively eliminate the soil stabilizing grasses, causing steepening of slopes, and resulting in shoreline erosion, which eventually influence the geomorphology of the infested landscape (Raizada et al. 2008). An IAP *Melaleuca quinquenervia* owing to its phenological attributes and timing of litter deposition can impact the soil, micro-topography, and geomorphology in shallow wetlands (Boon 1997; Wang et al. 2021). Table 1 lists the impacts of IAPs on soil nutrients and microbial diversity.

2.3.2 Impact of IAPs on Soil Microorganisms and Plant–Microbe Interactions

The effects of IAPs on plant-soil microbe interactions can remarkably influence the soil biogeochemistry and competitive dynamics of native plant community (Qu et al. 2021). In this respect, IAP s such as *Impatiens glandulifera* can remarkably influence the soil microbial diversity, thereby enabling the niche construction to encourage the spread of IAPs (Stefanowicz et al. 2019). The adverse effects of IAPs can also contribute to environmental degradation (Wolfe and Klironomos 2005; Eviner and Hawkes 2008; Qu et al. 2021). In this sense, Kumar et al. (2021) observed a significant increase in microbial biomass C and N in chir pine forest invaded with *L. camara* and *A.adenophora,* with explicit seasonal variation trends (i.e., rainy > summer > winter). Conversely, soil microbial biomass C declined in forest ecosystems which were invaded with *C. odorata* (Koné et al. 2021). In addition, the species-specific allelochemic extracts released from IAPs can influence the plant-soil-microbe interactions (Qu et al. 2021).

Microbial communities are considered to act as soil health indicators which can be vital parameter in the restoration of degraded environment (Li et al. 2015). Accordingly, plant-soil-microbe interactions are considered to be at the heart of revitalizing the degraded environment (Qu et al. 2021). Microbial diversity can influence the plant-soil interactions by increasing the vegetation establishment, soil organic matter, efficient mobilization of nutrients, and soil aggregation (Eviner and Hawkes 2008). The use of molecular tools such as 16S rDNA sequencing revealed that invasion of *Bidens alba* (formerely *B. pilosa*) remarkably altered the soil bacterial community composition when compared with uninvaded site (Wang et al. 2020). In this respect, the diversity of native arbuscular mycorrhizal fungi (AMF) was noted as a better tool in environmental restoration than allocthonous species (Caravaca et al. 2003). However, the IAPs can shift about 80% of the AMF diversity from with natives towards their side and get tightly associated (Callaway et al. 2004). The AMF association with IAPs potentially facilitate their colonization and landscape spread (Hawkes et al. 2006).

Plant soil feedback (above and belowground interactions) and herbivory in disturbed ecosystems play a vital role in the success of IAPs (Fukano et al. 2013; Allen et al. 2021). The association of microbes, especially those of mycorrhizal fungal diversity is extremely vital in sustenance of plant diversity and ecosystem resilience (Van der Heijden 1998; Koné et al. 2021). These secondary metabolites impact the belowground microbial diversity as demonstrated in the case of *Alliaria petiolata,* which pertub the AMF association with natives (Van der Putten 2007; Qu et al. 2021). Such adverse impact of IAPs in disrupting microbial association became the basis for the 'Mycorrhizal Degradation Hypothesis' (Vogelsang et al. 2004). Henceforth, the below ground community significantly influence the aboveground plant composition and hence colonization of IAPs.

Molecular tools (16S rRNA gene sequencing) also revealed that the invasive spread of IAPs such as *A. adenophora* (formerly *Eupatorium adenophorum*) was ascribed to their close association with the microbial diversity and the increased levels of nitrate in soils of invaded landscape (Kong et al. 2017). Conversely, the plant invaders can also enrich the soil microbial diversity in in novel landscapes (Qu et al. 2021). In this aspect, *I. glandulifera* increased the diversity of soil fungal and bacterial populations in newly colonized land surfaces (Gaggini et al. 2018). Similarly, several IAPs (e.g., *Centaurea stoebe* and *B. tectorum*) facilitate the colonization of nutrient (e.g., N) cycling bacteria, thereby linked to ecosystem functioning (McLeod et al. 2016). Therefore, unravelling the plant-soil-microbe interactions is necessary in elucidating the IAPs spread and restoration mechanisms.

2.3.3 Invasive Alien Plants Induce Soil Erosion and Desertification

Plant invaders can perturb the soil attributes which result in soil erosion to exacerbate the environmental degradation. In this respect, Pejchar and Mooney (2009) reported that IAPs can alter the soil stability through alterations in physico–chemical and biological characteristics, thereby causing soil erosion. Invasions by noxious IAPs, such as spotted knapweed (*C. stoebe*), leafy spurge (*Euphorbia esula*) and cheat grass (*B. tectorum*) may have profound impact on the soil quality of the grassland ecosystems (Gibbons et al. 2017), which may induce environmental degradation. Likewise, another IAP of Mediterranean ecosystem i.e., *Acacia dealbata* reduced the native plant diversity by adversely affecting the soil chemistry and microbial functioning (Lazzaro et al. 2014). In addition, the infestation of certain IAPs such as *I. glandulifera* increased the rate of soil erosion, as compared to un-invaded landscapes (Greenwood et al. 2018).

The IAPs can guide the conversion of perennial grasslands into desert scrublands (Jackson et al. 2002; Ravi et al. 2009). This land-use change can impact the global climate, biodiversity, biogeochemical cycles, and food security. IAPs infestation in grasslands can remarkably influence the fire regime, soil nutrient status, and soil-erosion rates (Schlesinger et al. 1990; Kumar et al. 2021). These IAPs induced alterations in grassland community perturb the heterogeneity of soil resources and convert them to exotic annual degraded grasslands which can further pave the way for desertification. Furthermore, the spread of biotic invaders can be facilitated under the event of climate change which remarkably accelerates the process of environmental degradation (Rai and Singh 2020a, b). The continuous connected patches of exotic grasslands can enhance the fire cycles; alter the soil attributes, wind erosion rates, and soil erodibility, which facilitate the process of land degradation (Ravi and D'Odorico 2008). Interestingly, after the invasion-fire interactive cycle, certain organic compounds are emitted which induce varying levels of soil water repellency, depending on the soil attributes, duration of fire, intensity of fire, and vegetation type (Doerr et al. 2000; Allen et al. 2021). The characteristic soil water repellency is demonstrated to impact the soil moisture (both adsorption and retention) which remarkably attenuate the inter-particle bonding forces, thereby increasing the susceptibility of soil towards wind/water erosion (Ravi et al. 2006; Acharya et al. 2018; Bolpagni 2021). Therefore, IAPs induced redistribution of soil resources and plant community composition in long-term can result in soil erosion, desertification, and eventually environmental degradation.

2.4 Water

Plant invaders can exert a profound impact on global water resources. IAPs can perturb the aquatic ecosystem health and diminish the ecosystem services of Ramsar wetlands (Pathak et al. 2021). In freshwater ecosystems, the aggressive IAPs can transmogrify the aquatic ecology (Bolpagni, 2021). Global aquatic invaders are predicted to impose an economic loss of US$345 billion (Cuthbert et al. 2021). Interestingly, IAPs of aquatic systems are equipped with certain specific traits (e.g., high biomass, deep roots, and high evapo-transpiration) which can reduce water flow, water holding capacity, and other soil-physico–chemical attributes. These IAP traits induced alterations in soil–water systems which can increase the flood frequency, soil erosion, and land degradation (Pejchar and Mooney 2009). Several IAPs such as *M. quinquenervia* and Eucalyptus species are equipped with extensive deep tap roots systems which enable them to exploit an enormous quantity of the ground water (Schmitz et al. 1997). Further, several IAPs such as *B. tectorum*, and *Tamarix ramosissima,* owing to their functional traits (greater leaf area, high water demand, and higher evapotranspiration), tends to exploit the water resources better than natives and thus influence the hydro-dynamics, fluvial processes, and habitat ecology of the invaded site (Graf 1978; Melgoza et al. 1990; Bolpagni, 2021). In this respect, *Prosopis* spp. was demonstrated to exploit more groundwater than co-occurring neighbouring native tree (*Vachellia karroo*) (Dzikiti et al. 2017). Accordingly, removal of *Prosopis* spp. resulted in groundwater recovery. In this aspect, geochemical and modelling studies revealed that alien trees (e.g., *Acacia mellifera, Dichrostachys cinerea, Eucalyptus camaldulensis, Prosopis glandulosa,* and *Tamarix ramosissima*) adversely influenced the groundwater recharge of invaded landscapes (Acharya et al. 2018). Thus, biotic invaders tend to use an enormous amount of water, which caused remarkable shift in the water table and socio-ecological regimes (Gaertner et al. 2014). It has been exemplified through a study on *Prosopis pallida* (N-fixing IAP in arid regions of Hawaii Island) which intensively exploited groundwater resources eventually perturbing the integrity of soil structure (Dudley et al. 2014).

Food and Agriculture Organization (FAO) Database on Introductions of Aquatic Species (DIAS) comprises the biotic invaders in freshwater and marine environment (FAO 2019). Several countries such as South Africa are widely recognised as ‘dark continent’ in terms of severe IAPs infestation, especially in Riparian habitats (Holmes et al. 2005; Richardson et al. 2007). Riparian habitats are of particular socio-ecological/socio-economic relevance as they act as ‘critical transition zones’ between aquatic and terrestrial ecosystems (Ewel et al. 2001; Richardson et al. 2007). In riparian habitats of South Africa, the widely distributed woody IAPs are *Melia azedarach* and *Salix babylonica* while *Arundo donax* is non-woody (Foxcroft et al. 2003), Further, IAPs such as *C. odorata* and *L. camara* are identified as potential shrubs in South Africa (Foxcroft et al. 2003). These IAP trees are observed as driving factors for the Riparian habitat degradation (Hood and Naiman 2000). In this context, other factors disrupting Riparian habitat ecology are conversion of forested landscapes to agriculture systems (Kentula 1997), frequent floods with deposition of silt (Holmes et al. 2005), and release of hazardous pollutants in the surrounding catchment (Richardson et al. 2007; Singh and Rai 2016; Rai et al. 2019; Rai and Singh 2020a). In addition to the direct influence of IAPs on water, indirect impacts can also be observed by altering the soil attributes and fire regimes. For example, the extensive infestation of tree IAPs can drastically influenced the soil stability and fire regimes and therefore exerting adverse impacts on river geomorphology (Holmes et al. 2005). Plant invaders can also influence the quantity of surface and ground water, which are in interface with the soil (Shackleton et al. 2019).

The adverse effects of IAPs in water resources can also result in loss of aesthetic and economic values. In this sense, IAP such as Tamarisk invasion in aquatics caused an economic loss around US$52 million annually (Zavaleta 2000). Another IAP, *Castor canadensis* imposed adverse impact on water quality and increased the flood risk (Lizarralde 1993). In addition, *Acacia mangium* exerted a profound impact on environment, socio-economy, and rural livelihood through alteration of the water quality (Souza et al. 2018; Pathak et al. 2021). Therefore, there exists an urgent need to formulate the sustainable restoration strategies to mitigate the water, soil, and biotic resource degradation.

3 Restoration of IAPs Invaded Ecosystems

Restoration of the degraded environment is quite challenging in Anthropocene due to complex synergistic interactions among IAPs, climatic variables, land-use change, and other human-mediated disturbances (Gong et al. 2020). Restoration ecologists adopted a plethora of strategies to maintain the biodiversity and resilience of the global ecosystems under the event of IAPs infestation (McGeoch and Jetz 2019; Bawa et al. 2021; Leclere et al. 2020). These complex interdisciplinary interactions need to be studied for formulating sustainable restoration strategies, as was observed in a case study on the highly invasive Fynbos plant species of South Africa (Gaertner et al. 2012). However, several restoration strategies such as physical removal or eradication of IAPs were observed to exert adverse effects on the holistic ecosystem health in several case studies (Zavaleta et al. 2001; Bauer and Reynolds 2016; Gornish and dos Santos 2016; Reynolds 2021). Therefore, for attaining sustainability paradigm in environmental restoration, long-term restoration/rehabilitation efforts should go in tandem to conserve the ecosystem benefits and services while managing the IAPs (Montoy et al. 2012; Pathak et al. 2021).

In the management of biological invasions, the explicit assessment of bidirectional feedbacks of soil on plant community dynamics and plant diversity on soil attributes are extremely vital foundation for formulating sustainable ecosystem restoration strategies (Eviner and Hawkes 2008; Koné et al. 2021**)**. In addition, the site conditions [(competitive, stressful and disturbed as per Grime (2001); high fertility and low fertility as per Chapin (2003)] can also influence the plant community dynamics, and hence, the ecosystem restoration process (Eviner and Hawkes 2008; Kumar et al. 2021). The colonization of IAPs can impede the ecosystem restoration processes through specific traits and influencing the soil attributes (Stefanowicz et al. 2019; Gao et al. 2020; Kumar et al. 2021). In this aspect, the colonization of invasive red oak (*Quercus rubra*) tree produced litter of high C/N ratio with low decomposition (Stanek et al. 2020). Here, in addition to influencing the soil attributes, invasive red oak also negatively influenced species richness and cover of understory vegetation. Therefore, by modifying the soil attributes and understory plant community dynamics, invasive red oak can changed the structure and function of ecosystems. Thus, there is an intricate association among soil health, plant diversity, and eco-restoration process.

Importantly, in relation to plant a trait there exists a trade-offs among the highly variable soil conditions which need to be elucidated in context of formulating sustainable restoration strategies (El-Barougy et al. 2021; García-díaz et al. 2021). Explicit evaluation of trade-offs will assist in planting suitable trees in multiple soil conditions (Eviner 2004; El-Barougy et al. 2021). Among various plant traits, litter persistence in terms of its chemistry and structure is the most important parameter to influence soil moisture, temperature, pH, available inorganic N, Available inorganic P, microbial biomass (C, N, P), and soil aggregation (Eviner and Chapin 2003; Stanek et al. 2020; Kumar et al. 2021; Wang et al. 2021).

The restoration and rehabilitation strategies of IAP invaded sites should be formulated in a manner so that that they revitalize different biophysical complexities of environment, ecosystem functioning, and ecological services (Lamb et al. 2005; Pathak et al. 2021). In addition, forest ecosystem restoration, rehabilitation, and regeneration are urgently required for maintaining the sustainable ecosystem services as well as rural livelihoods which are threatened with IAPs colonization (Chazdon 2008; Stanek et al. 2020). Importantly, the restoration strategies (in terms of revitalizing the biodiversity and ecosystem services) of invaded sites should be implemented after explicitly studying the extent of ecosystem degradation (Fig. 5). As shown in Fig. 5, for attaining a sustainable restoration approach different steps (reclamation, rehabilitation, agroforestry/native tree plantation, and assisted/natural regeneration) can be formulated depending on the extent of site/IAP-specific impact on environmental degradation. Accordingly, at particular sites where land-use changes are less intensive, the pollinating/dispersal agents can also aid in restoration by ensuring seed rains between interconnected forest and agricultural patches (Lamb et al. 2005; García-díaz et al. 2020). In this aspect, Lamb et al. (2005) also emphasized that such restoration strategies are cost-effective way of reclaiming environmental degradation and concomitantly, contributing to sustainable rural livelihood. In contrast, the sites of intermediate land degradation with intact soil surfaces, but devoid of pollinators can opt for reforestation programme (Lamb et al. 2005). In this context, the plantation of potential native or agroforestry species (Fig. 5) can be useful in terms of restoring ecosystem services and rural livelihood (Chazdon 2008; Banerjee et al. 2021).

For sustainable ecosystem restoration, the scientific or experimental researches can be conducted to explicitly optimize the implementation of specific strategies. In some degraded ecosystems, passive restoration strategies were found to be more effective in terms of cost and environmental sustainability (Prach et al. 2007), than intensive mechanical approaches (Sampaio et al. 2007; Banerjee et al. 2021). Therefore, at the sites with self-regenerating degraded lands, the application of intensive strategies such as mechanical plantation, grass removal, and ploughing can impede the natural un-assisted sustainable restoration (Sampaio et al. 2007). Further, the tree plantations though enhance the carbon sequestration potential of disturbed landscapes, however; such emerging forests can also make the site ripe for infestation with potential stress-tolerant IAPs (Laurance et al. 2006).

In addition to biodiversity, restoration of the water system can also assist in mitigating the environmental degradation. In this respect, the identification of ecological indicators can be useful to assess the extent of ecosystem degradation and formulating sustainable restoration strategies in aquatic ecosystems (Rai and Singh 2020a, b). Especially, restoration of IAPs invaded riparian habitats being at soil–water interface is given considerable attention in view of immense ecological/economic values (Pattison et al. 2017). The plant invaders such as *I. glandulifera* and *F. japonica* were observed as ecological indicators of riparian habitats (Pattison et al. 2017). In this aspect, Smith et al. (2007) also noted that IAPs acted as the ecological indicators of riparian habitat quality. Further, IAPs in conjunction with land-use change can remarkably impacted the functional plant traits, aquatic biodiversity, and biogeochemical cycling in the wetland systems (Roy et al. 2019). In riparian habitats the restoration through re-introduction of native trees plantation should be

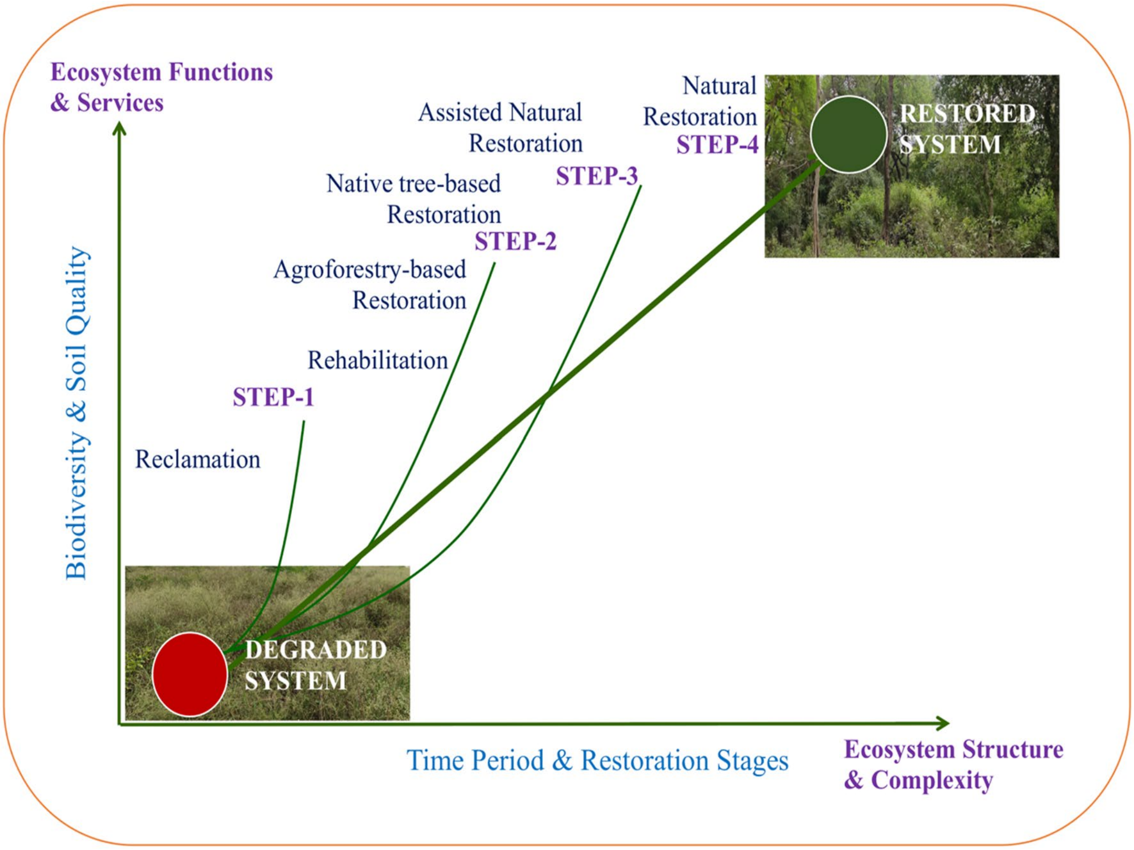

Fig. 5 The underlying ecological processes to transform the degraded ecosystems to restored systems; The judicial options for adequately formulating the ecosystem restoration strategies (e.g., reclamation, rehabilitation, agroforestry/native tree plantations, and assisted/natural regeneration), based on the state of environmental degradation (low to high-X axes), need of revitalizing the biodiversity/ecosystem services (Y axes-left), and time/cost-effectiveness (Y axes-right) of implemented strategies (Redrawn and amodified after Chazdon, 2008)

mediated through hydrological and geomorphological attributes (Holmes et al. 2005; Richardson et al. 2007). However, restoration efforts in riparian habitat invaded with IAPs are faced with several challenges. The abiotic- biotic thresholds, pervasive anthropogenic disturbances (e.g., water extraction), land-use changes (e.g., cultivation of food crops lead eutrophication/sediment deposition), floods induced IAPs transport, and decreased ecosystem resilience are the challenges in the restoration of riparian habitats (Richardson et al. 2007; Pathak et al. 2021). In this aspect, certain IAPs such as *Acacia mearnsii*, *Solanum mauritianum*, and *C. odorata* are having persistent seed banks as invasion legacy, which impose serious challenge to restoration ecologists (Pieterse and Boucher 1997; Holmes et al. 2005; Rai and Kim 2020). The persistent seed banks remaining at the site can rejuvenate, thereby resulting in the failure of the restoration efforts. Henceforth, Holmes et al. (2005) recommended an explicit study on recruitment of native vegetation, dispersal, and seed bank dynamics to augment the sustainable restoration efforts in riparian habitats. The persistent seed bank is vital legacy which can potentially modulate the regenerative potential and predict future community dynamics (Gioria and Pyšek 2016). Interestingly, the alterations in seed bank dynamics can act as an indicator of IAPs induced environmental degradation and driver of secondary invasion (Gioria and Pyšek 2016). Therefore, the future studies should explicitly study the seed bank legacy of IAPs to prevent the secondary invasion, thereby facilitate sustainable management.

In a nutshell, restoration of IAPs induced degraded environment can be attained through the recovery of its biotic/abiotic components (such as soil, water, and biodiversity) and diminished ecosystem services. Forest biodiversity restoration can make the ecosystems resilient which can withstand anthropogenic stressors such as IAPs, environmental pollution, N-deposition, habitat fragmentation, and climate change (Chazdon 2008; Kariyawasam et al. 2021). Moreover, the forest restoration is inextricably associated with levels of land or soil degradation, biodiversity erosion, residual vegetation, and desired restoration outcomes (Fig. 5). Henceforth, all these factors should be taken into consideration for achieving sustainable ecosystem restoration. Especially, in perspective of growing or the lower-middle income economies such as India the National Mission on Biodiversity and Human Well-Being (NMBHWB) aimed to preserve as well as restore biodiversity (Bawa et al. 2021; Banerjee et al. 2021). Elucidating the future distribution of IAPs such as *Cecropia peltata* and *Ulex europaeus* through ecological niche models can be vital in their containment as well as environmental restoration (Gong et al. 2020). In this context, the effects of climate change on IAPs can be dependent on environmental scenario and IAP-specific attributes (Gong et al. 2020). Henceforth, under the umbrella of biodiversity conservation multiple aspects (e.g., livelihood, human well-being, ecosystem services, climate change, agriculture, health, and bio-/circular economy) need to be addressed in an integrated framework for sustainably managing the plant invaders.

4 Ecosystem Services and Socio-Economic/Livelihood Impacts of IAPs Invasion

Certain IAPs may be useful in terms of ecosystem services and associated socio-economic or livelihood co-benefits. Several IAPs can also modulate the nutrient levels and hence augment the soil fertility in agroecosystems, as evidenced through colonization of cheatgrass (*B. tectorum*) in association with cyanobacterial consortium (Ferrenberg et al. 2018). Further, soil amendment with *L. camara* biomass was demonstrated to improve soil hydraulic properties which increased the wheat productivity in a rice–wheat cropping sequence (Bhushan and Sharma 2005). Another IAP, *F. japonica* (Japanese knotweed) has shown its adaptability to survive in habitat stressed with salinity, thus can be used in short-term land rehabilitation strategies (Rouifed et al. 2012). It has been well known that mutualistic association of microbial diversity (e.g. of AMF) with higher plants can assists in the sustenance of healthy forest ecosystems (Kumar et al. 2021). In this sense, a few plant invaders have also been reported to promote the diversity of AMF in Hawaii forests (Gomes et al. 2018). In this respect, IAPs such as *C. stoebe* and *E. esula* enhanced the colonization of mycorrhizal fungi which can find implications in ecosystem restoration (Lekberg et al. 2013). Also invasive alien plants regulate biogeochemical nutrient cycling (by enriching the soil with better nutrient allocation and carbon sequestration) and food webs (by their role as food crops/medicinal importance) (Rai 2017a). Some IAP such as *A. adenophora* acted as invasion corridor to facilitate the entry of other IAPs such as Eucalyptus in agroecosystems, which is actually mediated through alterations of soil physico–chemical characteristics (Yu et al. 2014). Conversely, certain IAPs (e.g., *Mesembryanthemum crystallinum*, and *Tamarix* spp.) prevented the entry of other IAPs by enhancing the soil salinity (El-Ghareeb 1991; Zavaleta et al. 2001). Therefore, the option of IAPs in restoration projects can be species and site-specific to help maintain the environmental sustainability.

Aquatic IAP such as *Phragmites* sp. (Giant reed), rated among 100 worst global invaders (Lowe et al. 2000), has got applications in the polymer industry owing to its rich lignocellulosic biomass (Fiore et al. 2014). Another study noted that the use of Giant reed in soil/sludge amendment which can enhance the agricultural productivity (Pelegrín et al. 2018). Several IAPs augment to the sustainable ecosystem restoration by offering several co-benefits such as bio-energy, animal feed, bio-polymers, and in augmenting the green economy (Edrisi and Abhilash 2015; Rai and Kim 2020). In this aspect Edrisi et al. (2020) also described various community livelihood benefits, ecosystem services, and co-benefits in the form of bioenergy of an IAP *Prosopis juliflora*. Nevertheless, Edrisi et al. (2020) opined the judicial use of multi-purpose IAPs in ecosystem restoration due to their possible adverse impacts on native diversity, soil microbial community, and livelihood uses of native fodder/food crops.

Several attribute of IAPs can be treated as vital ecosystem services. In this aspect, 'Nurse Plant' (shielding the plantations against heat and solar radiation), providing the physical structure (perches) for pollinators (e.g., birds and bats) which are useful in seed recruitment, acting as provision fuel for controlled fire to reshape vegetation, safeguarding or securing the site against further biotic invasions, maintaining healthy trophic relationships, biogeochemical services, and bio-agents for phytoremediation (Ewel and Putz 2004; Rai et al. 2020) are beneficial prospects of IAPs. Nonetheless, there are several challanges (e.g., issue of ecological economics, long-term effects, and reversibility aspects) which complicate the utility of IAPs in restoration. In highly disturbed ecosystems, where IAP acted as 'transformer species'/drivers (Richardson et al. 2000), the traditional weed management strategies can be impractical and may end up in an un-sustainable restoration (MacDougall and Turkington 2005; Hastings et al. 2007). Therefore, Reid et al. (2009) opined that IAPs management strategies for eco-restoration can be sustainable only in moderately disturbed landscapes. There has been great debate on the use or role of IAPs in ecosystem restoration. The divided opinion on the utilization of IAPs in the restoration of degraded environment are either in terms of threat (adverse effects) or utility (IAPs associated positive co-benefits). The origin of this different school of thought lies in the fact that a group of restoration ecologists advocated that all IAPs should not be considered as a nuisance in totality (Ewel and Putz 2004). This IAPs advocacy was based on fact that in certain cases the IAPs management strategies for the restoration of degraded environment were either reversible or economically infeasible.

This was exemplified in a case study on IAPs *M. quinquenervia* (melaleuca tree; 3–6 million USD) and *Hydrilla verticillata* (hydrilla; 14.5 million USD) (Pimentel et al. 2005; Reid et al. 2009). Accordingly, Ewel and Putz (2004) therefore countered the blanked condemnation of IAPs in restoration strategies and advocated their judicial use in view of their co-benefits in terms of ecological and socio-economic payoffs.

Several studies revealed that the long-term use of IAPs in restoration projects can be hazardous to the environment. The use of IAPs (e.g., *M. mikrantha* and *C. odorata*) in restoration of degraded jhumlands initially played a vital role in preventing the soil as well as nutrients run-off (Toky and Ramakrishnan 1983). Considering the traditional practice of un-regulated shifting cultivation, *M. mikrantha* was able to enrich nutrients, especially potassium (K) in aboveground biomass, thereby assisting in restoration of degraded environment (Saxena and Ramakrishnan 1983; Swamy and Ramakrishnan 1987; Rai 2017b). Nevertheless, in shortened jhum cycle, the ‘arrested forest succession’ and incomplete restoration of soil fertility was noted to reduce the agricultural productivity (Toky and Ramakrishnan 1983; Rai 2017b). Concomitantly, the long-term heavy infestation of *M. mikrantha* can reduce the native biodiversity and soil fertility which can eventually lead to desertification of invaded site (Ramakrishnan 2017). Another study by Li et al. (2015) revealed that indigenous native plants (*Cupressus torulosa* and *Pinus yunnanensis*) were more effective in restoration of soil N/microbial biomass when compared with an IAP (*Eucalyptus globulus*). In addition, *Mikania mikrantha* (mile a minute weed) was introduced as cover crop in an Indo-Burma hotspot region (NE India) to mitigate the soil erosion in tea gardens however, several socio-ecological concerns aroused after its landscape spread (Ramakrishnan 2017). Likewise, Edrisi et al. (2020) also noted a decrease in belowground microbial biomass and number of native plants in *Prosopis juliflora* invaded degraded land, when compared with non-invaded patches. Hence, a group of ecologists demonstrated the adverse effects of IAPs in restoration of degraded environment.

5 Traditional Ecological Knowledge (TEK) in IAPs Management and Ecosystem Restoration

In restoration programmes of IAPs, the local community participation and judicially utilizing their indigenous or traditional ecological knowledge (TEK) on the ecological/economic aspects of planted trees or food crops can be of paramount importance (Chokkalingam et al. 2005; Zavaleta-Cortijo et al. 2020). In restoration perspectives of plant invaders, incorporation of TEK in biodiversity rich regions can help in achieving environmental sustainability and rural livelihood. Nevertheless, the recent Coronavirus pandemic adversely influenced the IAP risks assessment studies, TEK, and livelihood /food security options of poor people (Zavaleta-Cortijo et al. 2020).

In past studies, TEK was successfully implemented in the restoration of several IAP invaded global landscapes such as Amazon River basin, Indonesia, Peru, Indo Burma hotspot region, and Philippines (Chokkalingam et al. 2005; Rai and Singh 2021). Further, the implementation of traditional pastoralist practice under HASHI (Hifadhi Ardhi Shinyanga as Swahili acronym which denotes Shinyanga Soil Conservation programme in northwest Tanzania, operated during 1986–2004) remarkably assisted in restoration of 350,000 ha of Acacia and Miombo woodland which benefitted local people from 833 villages, in moderate time interval of 18 years (Monela 2004). Shifting cultivation *Jhoom* is an ethnoagricuture practice in certain regions, closely linked with TEK, socio-cultural life and livelihood of the traditional indigenous people (Ramakrishnan 1993; Ramakrishnan 2017; Rai 2017b). During past decades shifting cultivation (with jhum cycle of 20–30 years) was supposed to be a sustainable use of forest ecosystems as cultivators had plenty of forest areas available (Ramakrishnan 2001). However, in recent times, this ethnoagriculture practice accounted for about 61% of total tropical forest destruction, decline in faunal diversity, and makes the degraded land surface ripe for IAPs infestation (Raman 2001; Rai 2012). Furthermore, due to expanding population, the area under forested landscapes rapidly declined, therefore fallow period became drastically reduced to 4–5 years, resulting in serious soil erosion and decline in the soil’s fertility and productivity (Ramakrishnan 2001). The tropical forests which are extremely fragile due to its highly leached soil and tight nutrient cycling (via a surface root mat) are particularly sensitive to unregulated shifting cultivation and IAPs colonization (Ramakrishnan 2017; Rai and Singh 2021).

The reduced fallow period of 4–5 years in shifting cultivation was observed to be more prone to infestation of IAPs such as *M. mikrantha* and *C. odorata,* than those following regulated time frame of 30 years (Ramakrishnan 2017). Herein, IAPs acted as passengers along with the environmental disturbances imposed through unregulated shifting cultivation. To elucidate the geographical horizon of this ethnoagricuture practice in NE India, Landsat-8 data (2014–2018) revealed that Manipur state had highest shifting cultivated land with a fallow area of 1528.5 km^2 while Tripura recorded lowest i.e., 178.3 km^2 (Pasha et al. 2020). To this end, Pasha et al. (2020) noted the dominance of four IAPs (*M. micrantha, Ageratum houstonianum, and C. odorata* and *A. adenophora*) in fallow lands under shifting cultivation. Furthermore, shifting cultivation fallow hotspot map was designed to delineate the repetitive patches in NE India and such patches were noted highest in Arunachal Pradesh (24.9%) while lowest in Tripura (3.6%) (Pasha et al. 2020). These disturbed patches can pave the way to introduction and successful colonization of plant invaders.

Several studies in traditional landscapes noted that IAPs initially acted as passengers along the disturbance gradients and later became the drivers of environmental degradation (Saxena and Ramakrishnan 1983; Sakachep and Rai 2021; Vanlalruati and Rai 2021). The population dynamics of IAP like *M. micrantha* (Swamy and Ramakrishnan 1987) and *Eupatorium odoratum* (now *C. odorata*) (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) (Rai 2017b). In this sense, Swamy and Ramakrishnan (1987) observed that invasive spread of *M. mikrantha* in short-cycled jhum systems was remarkably facilitated by burning or fire. As discussed earlier in the present article, *M. micrantha* and *C. odorata* can be associated with several pros as well as cons in ecosystem restoration perspective of jhumlands (Fig. 6). Figure 6 represents the patch of degraded land invaded with *Parthenium hysterophorus* (Fig. 6A) and heavy infestation of *M. micrantha* (Fig. 6B) in Mizoram, NE India.

Unregulated shifting cultivation has therefore perturbed the pristine ecology, forest diversity, and caused IAPs induced environmental degradation in in traditional landscapes (Ramakrishnan 2017). Shifting cultivation and deforestation are major constraints in developing sustainable food-production systems in the traditional landscapes (Rai 2012; Bawa et al. 2021). Moreover, in urban areas of high demographic growth and increasing land shortages, intensification of slash and burn system can be highly detrimental and make the sites prone to infestation of IAPs (Rai and Singh 2020a, b). Intensified land use under shifting cultivation not only increase IAPs infestation but also shift in the species composition, as demonstrated through the dominance of bamboo species (Rai 2009; Banerjee et al. 2021). Therefore, Food and Agricultural Organisation (FAO) in 1957 officially condemned shifting cultivation due to major cause of IAPs infestation, soil erosion, land degradation, and deforestation (Rai 2017b).

In biodiversity-rich countries, traditional landscapes, and global protected areas, the concept of ‘hybrid technologies’ can be incorporated in the implementation of IAPs restoration strategies to help attain the holistic environmental sustainability (Ramakrishnan 2017). Herein, hybrid technologies can be pragmatic integration of formal science or knowledge-based technologies (e.g., biorefinery) with TEK practiced by indigenous community. In this context, TEK can be further segregated into (a) Economic TEK related to the use of traditional wild crop varieties and ethno- medicinal plants (Rai and Lalramnghinghlova 2011a, b; Rai 2017a; Feng et al. 2021); (b) ecological/social TEK involves judicial use of biodiversity for enhancing the environmental reliance towards various environmental disturbances and restoring soil fertility, and (c) ethical TEK aims to revitalize the socio-cultural, religious, and spiritual aspects through the evolution of sacred species and landscapes (Ramakrishnan 2017).

The modern scientific approaches (e.g., biorefinery, biopharmacy, phytoremediation, phytochemistry, eco-friendly innovations in agro-biotechnologies, nano-science, carbon dioxide removal technologies, solar geoengineering, in situ genetically modified organisms, gene drive organisms, de-extinction, and high-tech ecosystem restoration) are advocated to address the problem of biodiversity depletion and climate change (Rai et al. 2018; Rai 2019; Reynolds 2021). The TEK (e.g. Sacred groves based on religious sentiments, Apatanis agricultural practice of integrated wet rice cultivation in an Indo–Burma hot spot region, indigenous water harvesting eco-technologies, ethno-medicinal plants in primary health care, and sustainable agroforestry with keystone species of socio-economic importance) can also assist in ecosystem restoration of invaded landscapes (Ramakrishnan 2001; Rai 2012; Reynolds 2021). Incorporating TEK-based technologies in the restoration of IAPs invaded regions can assist in selection of plantation species which are of socio-cultural, ecological, environmental, and socio-economic importance (Rai, 2012, 2013; Feng et al. 2021). In this aspect, Ramakrishnan (2017) identified several ecological keystone plants such as *Alnus nepalensis* (Nepalese alder), *Quercus* spp. (Oaks), *Ficus* spp, and several bamboo species which were of paramount importance in restoring the degraded shifting cultivated lands. Among these plants, Nepalese alder can potentially conserve 125 kg N/ha annually in degraded *jhumlands* and thus can be used in restoration projects (Ramakrishnan 1993). Therefore potential screening of appropriate plants with respect to the TEK, biorefinery co-benefits, and socio-cultural/socio-economic aspects of local people can aid in sustainable ecosystem restoration of IAPs invaded landscapes (Rai 2012, 2021; Feng et al. 2021; Syed et al. 2021). Thus, judicial adoption of IAPs management strategies can be practiced in cultural landscapes, to help attain the sustainable restoration of IAPs and rural livelihood.

6 Sustainability Considerations in the Restoration of IAPs Invaded Ecosystem: Future Prospects

In IAPs management and ecosystem restoration, sustainability paradigm can be driven by multiple factors (e.g., the soil-type/cover, habitat fragmentation, and dispersal) (Bauer and Reynolds 2016; Gornish and dos Santos 2016;

Fig. 6 Environmental degradation and potential IAPs induced ecosystem/land degradation in the infested region. (A) *Parthenium hysterophorus* L. menace in Varanasi, a sacred Indian landscape (Photo courtesy: Mr. Krishna Kumar Pandey, IESD, BHU, Varanasi) and (B) Heavy infestation of *Mikania micrantha* Kunth in fallow lands of Mizoram, NE India (Photo courtesy: PK Rai)

Gao et al. 2020; Shiferaw 2021; García-díaz et al. 2021). In this sense, Priyadarshini and Abhilash (2020) opined that implementation of environmental restoration strategies in concert with the incorporation of circularity practices, such as biorefinery co-benefits (e.g., bioenergy/bio-fuel production) to provide an impetus in achieving the several targets of SDGs. Furthermore, the clean energy production through potential bioenergy non-food crops (e.g., *Panicum virgatum* and *Brassica carinata*) on degraded or marginal non-arable lands can enhance the C-sequestration, energy security, provisioning services, rural livelihood, and, assist in climate change mitigation without compromising the food security (Priyadarshini and Abhilash 2020; Abhilash 2021; Feng et al. 2021).

Circular bioeconomy emphasizes the use of renewable bioresources for the human needs such as materials, food, and energy (Woźniak et al. 2021). In this sense, several IAPs act as potential bioresource and can contribute to circular economy (Feng et al. 2021). The basic principles of circular economy (e.g., reduction, recycling, recovery, and resource efficiency) are inextricably linked with ecosystem services. The judicial application of the circularity in replenishing the ecosystem services (e.g., provisioning, regulating, and cultural services) can help achieving the SDG 2, 6, 7, 8, 10, 12, 13, and 15 (Priyadarshini and Abhilash 2020). To this end, several IAPs such as *Spartina alterniflora* can engineer the soil attributes with concomitant applications to biorefinery prospects and circular economy (Syed et al. 2021). In addition, the pyrolysis of IAP feedstocks for biochar production is a potential biorefinery approach to augment the circular economy (Feng et al. 2021). These approaches in totality address the economic considerations and financial incentives involved in restoration projects of IAPs invaded regions. However, the on-going COVID-19 pandemic also impeded the global progress in the use of IAPs in circular bioeconomy and biorefinery prospects (Zavaleta-Cortijo et al. 2020; Woźniak et al. 2021).

In respect of sustainable IAPs mitigation, several global Institutions such as Scientific Committee on Problems of the Environment (SCOPE), GISP (Global Invasive Species Program), CABI (Centre for Agriculture and Bioscience International), and UN-IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) are enforcing legal regulatory measures for biodiversity restoration. In this respect, UN-IPBES-global indicators target (i.e., 15.8) aimed to achieve SDGs through implementation of effective management strategies to control the IAPs by 2020 (IPBES 2019a, b; McGeoch and Jetz 2019; Rai and Singh 2021). Especially, in relation to IAPs management, CBD adopted Aichi Biodiversity Target 9 to effectively restore and revitalize the ecosystem services (Egoh et al. 2020). In this aspect, UNCCD advocated the adoption of land degradation neutrality (LDN) as a solution to stop further environmental degradation and concomitantly revitalize various ecosystem services and livelihood prospects. In additon, LDN was also intimately linked with the attainment SDG 15.3 target (Chapman and Tsuji 2020). Conversely, IAPs were considered to be a major challenge in achieving SDG targets, especially in the context of lands (Paulvon et al. 2019) (Fig. 2). Furthermore, the environmentally sustainable land restoration strategies are an integral doctrine of United Nations Decade of Ecosystem Restoration (UN-DER, 2021–2030) which was adapted and resolved in 73rd session of UN Assembly. Nonetheless, the COVID-19 pandemic further impeded the prospects of attaining the SDGs in the given time framework (Chapman and Tsuji 2020).

Under the existing regulatory measures of IAPs, UN-SDG 15.8 (to "reduce the impact of IAPs on land and water ecosystems and control or eradicate the priority species.") emphasize their management to sustain the land biodiversity. Further, the CBD also prioritized to mitigate the adverse effects of IAPs (e.g., through "Zero Draft of the Post-2020 Global Biodiversity Framework") (CBD 2020). Notably, the action target 3 of CBD states to "control IAPs to eliminate or reduce their impacts by 2030 in at least (50%) of priority sites". Therefore, the past research studies and regulatory measures of IAPs prioritized the need for impact-based long-term management (García-díaz et al. 2021). In this sense, efforts to mitigate the adverse impacts of biotic invaders are prioritized as sustainable strategy in long-term which can be difficult to attain with species-specific approach. In addition, protected areas and global biodiversity hotspots should be given special attention to minimize the adverse impacts of IAPs on environment and ecosystem services (Rai and Singh 2021). Due to the high risks of IAPs, biosecurity regulations should be tightly regulated at a global scale as 'National biosecurity programs' such as Australia and New Zealand (Pyšek et al. 2020). In relation to environment and biodiversity restoration, strict trading regulations with concrete biosecurity framework and implementing focused holistic legal measures in perspective of IAPs are required (Banerjee et al. 2021). In addition, classical control can be abridged with recent biotechnological advances (e.g., CRISPR-Cas9 (clustered regularly interspaced short palindromic repeats), gene-editing technology, and omics) in quest of effective IAPs management (Rai et al. 2020).

In biodiversity-rich nations with a growing economy, the IAPs management is faced with several challenges such as poor decision support systems/response capacities, inadequate collaboration among stakeholders, huge dependency on bioresources, and lack of people participation (Banerjee et al. 2021). There exists a dearth of studies which empirically investigate the synergies of IAPs spread with other anthropogenic disturbances under the event of climate change (Pyšek et al. 2020). Henceforth, the ecological investigation of this synergy in IAPs success can provide an impetus to their sustainable management. In assessing the effects of IAPs (e.g., *Salvia rosmarinus, Eucalyptus globulus,* and *Acacia saligna*) on environment the trait-environment modelling approach can inventory the high-risk plant invaders, whereas SDMs can assist in the prioritization of habitats prone to infestation (El-Barougy et al. 2021). Hulme (2021) opined that the current scientific studies and institutional/legislative measures to manage the global biotic invaders are inadequate and warrant empirical researches in a future perspective. Moreover, the lockdowns during COVID-19 pandemic revealed both positive and negative short-term effects on the spread of biotic invaders (Parrino et al. 2021). These effects were ascribed to decreased human disturbances and altered Man-Environment interactions. However, long-term effects of COVID-19 induced lockdowns need to be assessed in future studies with sustainable action for IAPs management and possible environmental amelioration (Bouman et al. 2021; Parrino et al. 2021).

7 Conclusions

In the Anthropocene, IAPs acted as passengers along with the multiple environmental disturbances. The adverse impacts of IAPs on biodiversity, water, and soil resources acted as drivers of environmental degradation. In the present scenario, the COVID-19 pandemic has remarkably influenced the IAPs research and environmental sustainability. The IAPs driven effects on soil physico–chemical and biological characteristics remarkably jeopardized the health of global ecosystems. For sustainable restoration of IAPs invaded environment, abiotic/biotic components need to be revitalized in totality. In addition, the restoration of IAPs infested ecosystems needs to be prioritized as inextricably linked with attainment of various SDGs (e.g., SDG 2, 6, 7, 8, 10, 12, 13, and 15). Though blanket condemnation of IAPs in ecosystem restoration is not advised in several studies due to multiple co-benefits however, the use of IAPs in ecological restoration needs pragmatic evaluation of ecological economics and long-term ecosystem effects. To this end, the incorporation of hybrid technologies (which integrate acquired scientific information and TEK) in restoration efforts can augment the environmental sustainability and rural livelihood prospects of indigenous people. The success stories of hybrid technologies and sustainable restoration strategies in the containment of IAPs should be extrapolated in other landscapes to mitigate the environmental degradation. Last, the holistic approach in the restoration of the degraded environment in concert with the circular economy can remarkably influence in attaining the target of UN-SDGs and UN-DER (2021-30).

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Declarations

Conflict of interest Author declares that there is no conflict of interest in relation to contents of this article.

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