Plant Invasion in an Aquatic Ecosystem: A New Frontier Under Climate Change

9

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Abstract

Climate change and invasive species impose severe threats to biodiversity, ecosystem, and economy; however, the impact on human well-being and livelihood is not much known. The interaction between these is complex and intensifying, and there is increasing evidence that climate change is amplifying the deleterious effects caused by invasive species. Worldwide, the damage resulting from invasive species accounts for 5% of the global economy and has an impact on a large number of sectors such as forestry, agriculture, aquaculture, trade, recreation, etc. Variations in climatic conditions are more likely to interrupt the existing populations of native as well as aquatic invasive species and also increase the susceptibility of the aquatic ecosystem by creating favourable conditions for invasive species as they are more adaptable to disturbances and varied environmental conditions. Climate change is anticipated to cause warmer water temperatures, minimize ice cover, change the pattern of streamflow, increase salinization, etc., which would modify the pathways through which invasive species infiltrate the aquatic bodies. In addition, climate change will transform the ecological effects of invasive species by increasing their predatory and competitive effect on indigenous species and by enhancing the harmfulness of certain diseases. The impact of invasive species is anticipated to be more deleterious as they proliferate both in numbers and degree; can considerably change the composition, chemistry, structure, and function of aquatic systems. However, a clear insight into how climate change upsets invasive species growth

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and a study of their combined effects on the ecosystems is still required. Further to minimize the compounding impact of climate change on the devastating effect of invasive species, various preventive and control measures are required to regulate the invasive species that presently possess moderate effects and are restricted by seasonally adverse conditions. The present chapter focuses on how climate change affects plant invasion in the aquatic system and their complex interactions. This chapter also discusses various methods used for the management and restoration of the invaded ecosystem.

Keywords

Aquatic · Climate change · Ecosystem · Invasive aquatic species · Invasive plant species · Management · Restoration

Abbreviations

AIP	Aquatic invasive plants
AIS	Aquatic invasive species
IAAPS	Invasive aquatic alien plants species
IAPS	Invasive alien plants species
IAS	Invasive alien species
IPS	Invasive plant species

9.1 Introduction

An invasive species is a non-native species that enters a new area, becomes overpopulated, and alters the ecosystems that it colonizes. It is also termed as an alien, introduced, or exotic species. They impose a severe threat to the health, productivity, and sustainability of native ecosystems and cause huge economic loss. They exhibit a high dispersal rate, fast growth, a small lifespan, and increased tolerance to a wide range of environmental conditions that helps them to acclimatize to the new environment (Pimentel et al. 2005; Rai and Singh 2020). The impacts of invasive species are more severe as they flourish both in numbers and in degree. They extensively modify the structure and function of native aquatic systems through direct and indirect interactions (Wootton and Emmerson 2005; Burgiel and Muir 2010; Poland et al. 2021). The estimated damage from invasive species accounts for 5% of the world economy affecting various sectors such as forestry, agriculture, aquaculture, terrestrial habitat, waterways, trade, and recreation (Pimentel et al. 2001).

Freshwater habitats are more vulnerable to invasive species than terrestrial habitats (Moorhouse and Macdonald 2015). The susceptibility of aquatic bodies to invasion depends on various physical and chemical properties like their trophic state, depth, sediment, and flow rate. Thus, the degree and extent of destruction by invasive plants can be successfully controlled and it depends on various parameters like conditions of the site, recognition and response times, and management selection. Examples of submerged exotic aquatic plants, including *Brachiaria brizantha*, *Brachiaria mutica, Hydrocotyle vulgaris, Hydrilla verticillata, Myriophyllum aquaticum*, *Myriophyllum heterophyllum*, *Nitellopsis obtusa*, *Potamogeton crispus*, *Spartina alterniflora, Trapa natans*, etc.

Climate change intensifies the deleterious effect of invasive species. Both drivers (climate change and invasive species) are linked together in various manners (Walther et al. 2009; Smith et al. 2012). It increases the susceptibility of the aquatic ecosystem by creating conditions favourable for the invasive species.

Climate change effects like increased global temperature and CO_2 levels, severe weather events, changes in precipitation patterns and stream flow, increase in water temperature and salinization, decreased ice cover, etc. will result in transformation of pathways through which invasive species penetrate the aquatic systems. They favour these invasive species by increasing their chances to cross geographic barriers, spreading and establishing in new areas as they exhibit high adaptability to varied conditions (Walther et al. 2009; Burgiel and Muir 2010; Dai et al. 2022).

Detection at primary stages and eradication are regarded as the most efficient and cost-effective way to evade and regulate the introduction and establishment of invasive species. This also ensures long-term success in comparison to maintenance at post-entry stages. The outcome of invasive species is anticipated to further intensify with the change in climatic conditions; however, a clear insight into how climate change affects the growth of invasive species and their combined effects on the ecosystems still needs to be investigated. This chapter focuses on the impact of climate change on aquatic invasive species (AIS), how climate change affects plant invasion in the aquatic system and their complex interactions. This chapter also highlights various approaches used for the management and restoration of the invaded ecosystem.

9.2 Impact of Climate Change on Aquatic Ecosystem and Aquatic Invasive Plants

Rapidly increasing aquatic invaders pose a great risk to aquatic ecosystems. They can thrive in new surroundings and harm local ecosystems. Invasive species displaces native species, reduces ecological services, and also causes economic loss. Non-native species invasion is the primary source of biodiversity loss globally, especially in freshwater systems, which have more number of species in comparison to any ecosystem (Ricciardi and MacIsaac 2011; Thomaz et al. 2012). In freshwater ecosystems, invasion causes considerable harm by affecting the functional and structural integrity. The loss of species is more than that in terrestrial and marine habitats. These species spread to new locations through a variety of channels (Olden et al. 2006; Strecker et al. 2011). Human activity related to global trade has accelerated the spread of species to new locations and is the primary cause of most recent invasions (Levine and Antonio 2003). Freshwater systems, especially lakes, are vulnerable to invasion due to trophic linkages (Gallardo et al. 2016). Aquatic incursions influence ecosystem populations, communities, and processes (Ehrenfeld 2010). Once an invasion establishes itself, the species completely takes the place of the native species, consequently resulting in their elimination (Getsinger et al. 2014; Brundu 2015).

Effects of invasive species include shifts in the structure, composition, and even function of ecosystems (Lloret et al. 2004; Bobeldyk et al. 2015). It is well known that invasive species may alter the food webs of freshwater ecosystems (Vander Zanden et al. 1999). Invasive plant species (IPS) have negative societal effects as well. The IPS provides a lower-quality food supply for macroinvertebrates as well as higher-level consumers (Madsen et al. 1991).

Species abundance and richness, food web structure (Villamagna and Murphy 2010; Stiers et al. 2011), macrophyte composition (Hussner 2014), and even oxygen levels are all impacted by aquatic invasions (Shillinglaw 1981). IPS has the ability to reproduce clonally and spread quickly. Since clonal integration and invasion of alien plants are strongly connected, clonal plants reproduce rapidly and disperse to new areas (Maurer and Zedler 2002). Thus, due to their rapid proliferation, AIS poses a great danger to ecosystems and displays adverse effects on the environment as well as the economy (Brundu 2015).

Non-native plants proliferate in excess and create monospecific stands that block water flow. This affects water quality by reducing oxygen levels and odour. The extensive growth of aquatic weeds can impede water flow and block inlet pathways, which can result in floods (Hassan and Nawchoo 2020). The development, spread, and effects of IS may be exacerbated by increased nutrient levels, elimination of top predators, and altered flow regimes caused by increased overharvesting (Gherardi 2007). Floating aquatic plants may minimize freshwater extraction and navigation, fish harvesting, and water cycling and chemistry (MacDougall and Turkington 2005). Invasion effects are undoubtedly a reason for worry given the high level of biodiversity and susceptibility of freshwater ecosystems to biotic exchange (Sala et al. 2000). Invasive species affect ecosystems and the economy, which are responsible for several socio-ecological issues, and also impact people's health and livelihoods (Perrings et al. 2002). Management of foreign invasive species requires an understanding of invasive plant dispersion tactics, perpetuation time, and manner of invasion (Hassan and Nawchoo 2020).

9.2.1 Effect of Climatic Change on the Aquatic System

Global warming and climate change, which have forced ecological systems, biodiversity, and human existence to face the worst issue in history, have started to influence aquatic ecosystems, from plankton to mammals (Hoegh-Guldberg et al.

2019). Due to their size and diversity, oceans and seas are majorly impacted by the transformation brought on by global warming. In addition to the rising temperature of vast water bodies including oceans, seas, lakes, and ponds, an increase in atmospheric temperature also triggers hydrological processes that alter physical as well as chemical properties of water. Sea level rise, an increase in ocean temperature, and changes to current precipitation, wind, and water circulation patterns are all possible impacts of climate change (Scavia et al. 2002; Roessig et al. 2004).

Climatic changes are the most extreme component of global development. As a result of global warming, thermal stratification increases, glaciers melt, sea levels rise, coastal erosion increases, lakes evaporate more quickly, greenhouse effects are exacerbated, ocean acidity rises, carbonate concentration decreases, biological invasion increases, and biodiversity declines (Sivaramanan 2015). Climate change is not a national concern; it spans continents. The sudden spike in catastrophic climatic effects was caused by hydrologic shifts in worldwide water that migrated towards land. This makes aquatic species the most afflicted animals (Eissa and Zaki 2011).

The ongoing rise in sea level will, to some extent, put a large number of aquatic species in danger. Warming changes species ranges, fundamental metabolic processes, and the timing (or phenology) of critical biological events. Acidification limits the development of calcifying organisms and produces physiological stress in sensitive marine species (Waldbusser and Salisbury 2014; Asch 2015). Aquatic species distribution, range of aerobic conditions, and chances of survival can be affected by ocean deoxygenation and hypoxia conditions (Breitburg et al. 2018; Griffith and Gobler 2020). Many aquatic birds, including warblers, flamingos, aquatic swan geese, and pelicans as well as migratory fish species such as eels and mullet, other species like coral reefs, turtles, and some aquatic crustaceans are among those that are susceptible to such severe effects (Newson et al. 2009). According to Stocker et al. (2013), emissions of greenhouse gas by human activities have a significant role in climate change and ocean acidification, which has an effect on marine ecosystems and their products and services (Gattuso et al. 2015; Weatherdon et al. 2016). Climate change directly affects organisms' development, and their ability to reproduce. Thus indirectly, it results in a change in the structure, composition, function, and productivity of aquatic ecosystems (Ghosh et al. 2020).

9.2.2 Impact of Aquatic Invasive Plants (AIP) in Response to Global Climatic Change

In contrast to native species that cannot adapt to climate change, many alien species are anticipated to benefit from climate change and expand their range. IAS and climate change may progressively interact in a positive feedback loop, with the former creating new habitats for the latter and making ecosystems more vulnerable to the latter (McNeely 2000, 2001). According to the UN's Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES), biotic invaders threaten 1/5th of surface of the Earth, including biodiversity hotspots (IPBES 2019). Through several unusual physiological traits (such as large biomass, long roots, and increased transpiration), the IPS may enter aquatic systems and obstruct water flow, rendering it unfit for drinking and irrigation (Pejchar and Mooney 2009). Climate change and AIS pose a range of threats to ecosystems, biodiversity, human health, and socio-economic situations through a variety of methods (Bartz and Kowarik 2019; Rai and Singh 2020). In addition to having an impact on human health, invasive alien plant species (IAPS) also increase the frequency of floods by narrowing stream channels and changing the soil properties (such as decreasing its ability to retain water and increasing soil erosion) (Rai and Singh 2020). Ground and surface water supplies are also known to be impacted by IAPS (Shackleton et al. 2019). IAPS is known to interfere with water transportation regularly, which has a detrimental impact on recreation and tourism activities (Eiswerth 2005). Biologists who study invasions have recently concluded that not all invasions are harmful to ecosystems (Young and Larson 2011). Numerous IAPs are recognized for the positive effect they have on ecosystem services, which might include things like providing aesthetic value and entertainment, preserving cultural traditions, and enforcing laws and policies (Pejchar and Mooney 2009). It has been proposed that use of IAPS like *Phragmites* sp. and *Eichhornia crassipes* to create bioenergy might serve dual goals, i.e. to make renewable energy that won't run out and to get rid of weeds simultaneously (Rai et al. 2018; Stabenau et al. 2018). Effective phosphorus recycling by *Elodea nuttallii* may result in nutrient enrichment (eutrophication), which would be bad for aquatic habitats. Producing biogas and phosphorus-rich compost from this aquatic IAPS biomass is beneficial (Stabenau et al. 2018).

Several AIS have been discovered to have a detrimental effect on the Benthic Quality Index (BQI) in marine environments (Zaiko and Daunys 2015). Therefore, coastal invasive species may be used as a general indicator of the health of the marine ecosystem. Many foreign aquatic plants are intentionally introduced as they offer commercial, aesthetic, or environmental benefits; however, they also pose a negative impact on aquatic ecosystems by obstructing rivers, limiting aquatic life by lowering dissolved oxygen levels and reducing native biodiversity. They also offer a variety of ecosystem services like food, fodder, decorative use, ecological restoration, landscaping, and green manure (Wang et al. 2016). Aquatic alien plants, in particular, can induce oxygen deprivation, decrease native biodiversity, degrade water quality, and even disrupt food web structures in freshwater habitats once they have effectively invaded (Hussner 2014). These ecological consequences, whether favourable or unfavourable, might be amplified by global warming. Inputs of phosphorus and nitrogen may potentially change the status of some alien organisms. Additionally, the relationships between alien aquatic plants and herbivores have changed as an outcome of change in climatic conditions, which will affect how far they spread in the future (Wu and Ding 2019). The species makeup of plant communities may vary due to global change, and further affecting the ecological and physiological characteristics of alien plants in water habitats (Henriksen et al. 2018). Tabular representation of aquatic invasive plants that have been reported to expand under changing climatic conditions has been provided in Table 9.1.

Table 9.1 Tabular representation of list of aquatic invasive plants and effect of changing climatic conditions on the spread and invasiveness of these plants

S. No.	Plant species	Factors	Effects	References
1.	*Hydrilla verticillata*	Increased water temperature and carbon dioxide	The plants are more adaptable to warmer temperature. Increased in CO_2 level enhances the biomass under precise conditions	Chen et al. (1994), McFarland and Barko (1999), Williams et al. (2005), EPPO (2008)
2.	*Mimosa pigra*	Flooding and Rainfall	In Australia, flooding and rainfall assisted in seed dispersal by flotation	Lonsdale (1993)
3.	*Phragmites australis*	Increase in ambient air temperature	It is abundant on the Atlantic Coast and is quickly expanding to westward and northward	Wilcox et al. (2003)
4.	*Ranunculus trichophyllus*	Decreased length of ice cover	It has spread to non-vegetated lakes in the Himalayas	Lacoul and Freedman (2006)
5.	*Eichhornia crassipes* and *Typha angustifolia*	Storm, in case of after Tsunami occurred in southeast Asia in 2004	It spread to lagoon and estuaries. Storms resulted in increased disturbance in habitats and thus favoured the establishment and expansion of already existing invasive species	Bambaradeniya et al. (2006)
6.	*Posidonia oceanica*	Warming of water temperature	Warming was found to induce flowering	Diaz-Almela et al. (2007)
7.	*Arundo donax*	Climatic warming	It is native to riparian habitats of eastern Asia. It was introduced to South Africa and has expanded to riparian habitats of rivers and streams. They can withstand broad range of environment conditions and are suitable to South Africa's climatic conditions. Rooting of stem fragments was found	Milton (2004), Nel et al. (2004), Mgidi (2004), Wijte et al. (2005), Quinn and Holt (2008)

(continued)

Table 9.1 (continued)

S. No.	Plant species	Factors	Effects	References
			to be 100% at temperature 17.5 °C or greater than it. Thus, has increased its likelihood to expand and invade under changing climatic conditions	
8.	*Thalia dealbata*	Climate warming	It is predominant in China and has spread to upper altitude as result of warming	Chen and Ding (2011)
9.	*Eichhornia crassipes*	Warming, extreme rainfall	It is native to South America and has spread to Lake Victoria (Kenya), Tanzania, and Uganda. It is presently established in regions of southern Europe but is likely to expand to remaining parts of Mediterranean Basin and further to northward into Europe due to warming. It was introduced in China but later turned into invasive and has spread across 16 provinces. In addition to China, it has also expanded to Central America, Central Africa, Western Africa, Southeast Asia and South-eastern United States. These plants overcome winter as they possess floating vegetative tissues. The warm temperature of water avoids the root and leaves from being destroyed from frost	EPPO (2008), You et al. (2014), Wu and Ding (2019)

(continued)

Table 9.1 (continued)

S. No.	Plant species	Factors	Effects	References
			condition during winter. Their vegetative biomass (overwintering) also responds fast to increase in temperature and thus enhances their invasiveness. Extreme rainfall supports the transport of propagules across China	
10.	*Pistia stratiotes, Azolla filiculoides, Cabomba caroliniana,* and *Egeria densa*	Climatic warming, elevated rainfall	It was introduced in China and then turned into invasive. *P. stratiotes* is widely distributed in China and is found in more than 9 provinces. It is also reported to have spread in Germany. *A. filiculoides* is introduced in Spain and China, *and C. caroliniana* in China, *E. densa* in United states. In China, warming has resulted in transformation of these plants into invaders and thus has led to their expansion to new areas particularly to upper latitudes. Warming induces overwintering and their invasiveness. Increased rainfall has enhanced the survival and adaptation of these plants. It also assisted in propagules transport of these free-floating plants across China. Created favourable	Santos et al. (2011), Hussner (2014), Espinar et al. (2015), Gao et al. (2015), Vojtkó et al. (2017), Wu and Ding (2019)

(continued)

Table 9.1 (continued)

S. No.	Plant species	Factors	Effects	References
			conditions by providing more appropriate aquatic environments that helped in their spread and establishment at greater latitudes	
11.	*Nymphaea rubra*	Warming	Warming increases adaption	Hussner and Lösch (2005), Vojtkó et al. (2017)
12.	*Myriophyllum aquaticum*	High rainfall or water level variations	It was introduced in China and then turned into invasive. It is widely distributed in China and is found in more than 9 provinces. High rainfall or water level variations enhance clonal integration, number of branches and length of stolon	Chen et al. (2016), Wu and Ding (2019)
13.	*Myriophyllum spicatum*	Climatic warming	It is native to Europe, Asia and has invaded to North America. Warming has extended its growing season and thus has increased its abundance in freshwater and also improved its carbon stock as well as biomass	Velthuis et al. (2018)
14.	*Alternanthera philoxeroides*	Warming, Increased precipitation and variation in water level	It was introduced in China and then turned into invasive. It has spread to higher latitudes in North China and South America. Reported to have spread across 18 provinces in China. The fluctuation in water level increases length of shoot length and reduces	Yu (2011), You et al. (2013a, b), Lu et al. (2015), Chen et al. (2016), Wu et al. (2017a), Wu et al. (2017b), Wu and Ding (2019)

(continued)

Table 9.1 (continued)

S. No.	Plant species	Factors	Effects	References
			intraspecific competition. Warming induces increase in net rate of photosynthesis and morphological plasticity	

9.3 Climate Change and Aquatic Invasive Species Interactions

Invasive plant species (IPS) typically have a higher degree of environmental tolerance, faster rates of growth and dissemination, and shorter generation times, which make them more resilient to abrupt climate changes. Species interactions play a vital role in configuring different communities and these interactions are majorly influenced by climate. Tylianakis et al. (2008) in their review analysed the probable effect of global climate change on the terrestrial ecosystem and proposed that climate change might influence almost every species interaction. It can weaken the positive interactions (mutualism), can affect the food web, richness of taxa, intensity of predation, etc. Aquatic ecosystems are similarly vulnerable to these changes. Climate change might alter the competitive species interactions due to which the native communities may become more or less vulnerable to novel invasions or it can also lead to the establishment of already existing invaders. Alternatively, climate change might reduce the competitive capacity of primary invaders to the point that they are no longer deemed as invasive and this could enhance the abundance of secondary invaders (Bellard et al. 2013; Pearson et al. 2016). Predicting the future dispersal and species interaction of IPS in response to changes in climatic conditions is a challenging endeavour since many variables affect the local and transient invasion trends (Mainali et al. 2015). The impact of climate change on AIS introduction, establishment, spread, and dispersal is discussed in the following section.

9.3.1 Altered Mechanism of Invasive Species Introductions

It is predicted that climate change can increase the temperature of the water, decrease the thickness of the ice, influence the pattern of stream flow, and enhance salinization. Such changes might alter the pathways of invasive species introduction, growth, their spread and their dispersal (Rahel and Olden 2008; Kariyawasam et al. 2021). Studies have shown that the melting of ice has facilitated the migration of aquatic birds and mammals among the Atlantic and Pacific Ocean basins (McKeon et al. 2016). Plants have long been introduced for decorative and agricultural purposes. The majority of newly introduced plants have physiological characteristics that enable them to thrive in a variety of climatic situations and hasten their establishment and expansion (Bradley et al. 2010). The quest for plants that can withstand a variety of stress and are resistant to abiotic stress may increase due to climate change (Bradley et al. 2012). Many invasive species majorly spread to new sites as contaminants via human-assisted transport like cargo ships and as contaminants of agricultural products (Hulme 2009). Climate changes could modify human travel and connect previously disconnected locations. Such travel alterations could indirectly affect the invasive species' ability to propagate and establish itself in newer aquatic regions (Hellmann et al. 2008). According to Corlett and Westcott (2013), native plants possibly will face 'Migration lag' due to climate variation and such place when invaded by invasive species might change the community structure (Bernard-Verdier and Hulme 2015). In a nutshell, fluctuations in climate have the ability to modify the entry points and growth conditions that are favourable for invasive species in aquatic systems.

9.3.2 Influence of Climate Change on Establishment of Aquatic Invasive Species (AIS)

The establishment of AIS could be influenced by climate change negatively or positively. For many invasive species, phenotypic plasticity is thought to be a key factor in determining their establishment and growth. Acquired genetic variations may also regulate germination which in turn is crucial for the establishment of invasive species (Richards et al. 2006). Davis et al. (2000) suggested that instabilities in aquatic habitats due to eutrophication and other stresses can enhance plant invasions by raising their 'invasibility'. Wainwright et al. (2012) predicted that climate change will favour the establishment of species that have germination flexibility under a wide range of environmental variations. Information about the germination phenology of native and invasive species are very important for foreseeing the identification of species that may establish efficiently under varied climatic conditions (Gioria et al. 2018). Orbán et al. (2021) through their experiments on four invasive species suggested that disturbance parameters should also be considered while assessing the consequence of climate change on the growth and establishment of invasive species. It can be hypothesized that invasive species with flexible germinations will be able to establish successfully under variable climatic conditions in aquatic habitats.

9.3.3 Influence on Spread and Distribution Change of AIS

Climate change can significantly regulate the distribution and spread of AIS. The most significant factors in determining the geographic range of invasive species are the temperature and precipitation (Finch et al. 2021). In addition to enhancing survivability, milder winters in temperate regions due to enhanced temperature would lengthen the growing season, which could enhance reproductive productivity

(Hellmann et al. 2008). Species that can quickly shift their ranges may have an edge over other species. Water hyacinth, also known as *E. crassipes*, is one of the most troublesome species of tropical aquatic plant, and has invaded a number of other nations. You et al. (2013a, b) analysed the effect of temperature on the growth of water hyacinth and observed enhanced growth with the increase in temperature. From their experiments, they concluded that climate warming may increase the invasiveness of water hyacinth by increasing its distribution and spread (You et al. 2013a, b). Adhikari et al. (2019) studied the possible repercussions of climate change on the spread of IPS in the Republic of Korea (ROK). From their study, they predicted that climate change can enhance the IS richness and dispersion in the northern and eastern provinces of ROK. According to the findings of their research, Kariyawasam et al. (2021) concluded that climate variability will lead to the growth of AIP in the locations (different regions of Sri Lanka) that they studied. The dispersal of species has also been considerably enhanced by humans (Havel et al. 2015). Most research on the impact of climate on invasive species has been piloted on terrestrial systems; however, such research can aid in the design of experiments for AIS.

9.4 Management of Aquatic Species Vulnerable to Climate Change

Aquatic invasive species (AIS) is a threat to biodiversity loss and species extinction and is difficult to control. Reasons behind the invasion of species that are non-native are many; however, the main reason could be climate change. Wetlands are also vulnerable to invasive species and their impacts on the present diversity of the region, therefore, pose a major global concern (Zedler and Kercher 2004; Shackleton et al. 2018; Bolpagni et al. 2020; Adams et al. 2021; Lázaro-Lobo and Ervin 2021). Many attempts and also many efforts are made to restore ecosystems after an invasion explosion (Kettenring and Adams 2011; Prior et al. 2018). India due to its diverse environmental and varied climatic conditions is highly prone towards biological invasion and favours both accidental and intentional entry of plant species (Kohli et al. 2011). Plants in aquatic ecosystems are critical invasive species, namely *Alternanthera philoxeroides*, *E. crassipes*, *Lemna perpusilla, Marsilea quadrifolia*, *M. aquaticum*, *Salvinia molesta,* and *Ipomoea* spp. (Raghubanshi et al. 2005). *Eichhornia crassipes, A. philoxeroides, S. molesta,* and *Ipomoea* sp. invade aquatic ecosystems and cause much harm to the biodiversity of aquatic ecosystems (Reddy 2008). IPS is widely known for their harmful effects, and many nations are implementing strategies such as preventing the invasion of alien species, preventing its spread, detecting the invasions rapidly, eradicating it wherever possible, reducing the impact of consequences of invasive species and restoration of damaged ecosystems. Here, we review a few approaches to dealing with IPS. A schematic illustration of different stages of invasion, the successful establishment of invasive species in a region, and various management schemes that can be implemented at each stage is depicted in Fig. 9.1.

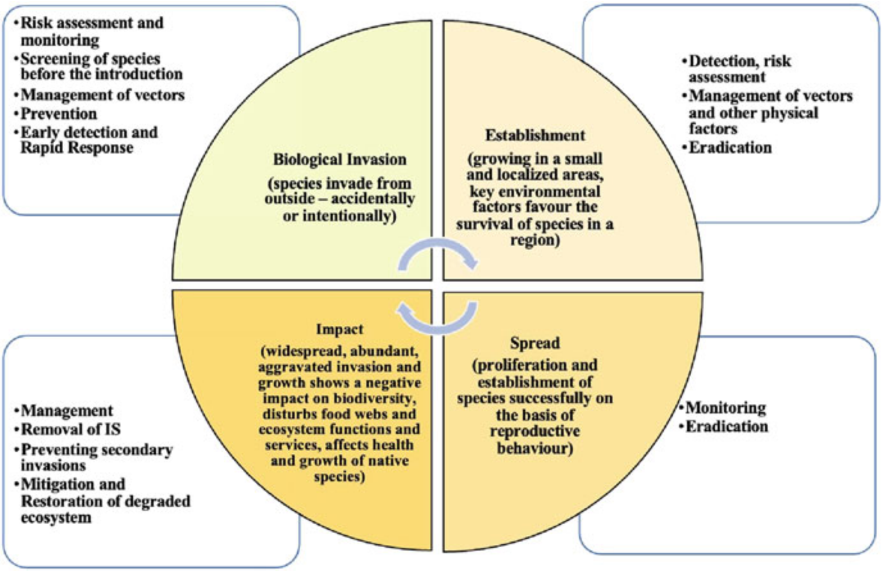

Fig. 9.1 Schematic representation of different stages of invasion and successful establishment of invasive species (IS) in a region and management strategies that are suggested to be implemented at each stage

9.4.1 Risk Assessment

It is a priority to assess the risk factors of establishment of alien species in aquatic systems and to consider the consequences that can arise upon the introduction. However, species are introduced for human welfare, and ornamental purposes and so humans are responsible for dispersal and establishment (Pyšek and Richardson 2010; Havel et al. 2015). The negative impact and consequences of invasion of aquatic alien plants can result in the change in the biodiversity of native species, aggravation of biological invasions, increases in non-target effects, disturbance in aquatic food webs, and accelerated water pollution, that change overall interspecific changes. Therefore, screening of species before introduction has to be done (Singh 2021). The history of species and the behaviour of growth and reproduction are crucial for screening. Also, weed risk assessment is significant for controlling high-risk species**.** Risk maps are to be created for determining invasive spread in fragmented areas and areas of higher risk, and therefore, remote sensing technology, computing, monitoring mechanisms, and modelling methods are being used nowadays (Bradley and Mustard 2006; Pyšek and Richardson 2010).

9.4.2 Management of Vectors

At various places, where climate change is the main problem, the management of vectors is necessary to reduce the invasion of alien species. In addition to the vectors and mechanisms of dispersal that are to be identified, other opportunities such as spread through garden escapes also make ornamental plant invasion and establishment easy. Therefore, there is an emergent need to find ways to control through the biological method, and measures of early detection of invasive species and alternatives to invasive species (Pyšek and Richardson 2010).

9.4.3 Early Detection and Rapid Response Strategy (EDRR)

Early detection and rapid response management strategy has a significant role in integrated techniques for the control of invasive species. Early detection of invaded species can aid in quick observation, thus, rapid responsiveness and safety regulation and control (Hulme et al. 2009). Sometimes, inconspicuous numbers and small sizes of invaders during the early stages of invasion escape early detection and mapping. Research and development are, therefore, focused on remote sensing (Koger et al. 2004) and mapping (Barnett et al. 2007). At places where species are introduced from many regions, their taxonomic identification can be difficult.

9.4.4 Eradication

Successful eradication of invasive species belonging to different taxons such as *Mytilopsis sallei* (marine mussel) from northern Australian harbour, *Caulerpa taxifolia* (seaweed) from a lagoon in California and *Bassia scoparia* (herb), and *Cenchrus echinatus* (grass) from a Hawaiian island, and Australia has been conducted and reported (Pyšek and Richardson 2010).

9.4.5 Difficulty in Controlling Key Environmental Factors

Degradation of ecosystems at accelerating rates due to multiple pressures of anthropogenic activities like urbanization, industrialization, and agriculture intensification leads to more frequent instances of species invasion (Kercher and Zedler 2004; Ervin et al. 2006). Though biological invasions also characterize degraded aquatic ecosystems. Therefore, an integrated approach of using effective control measures of preventing invasiveness and post-recovery mechanisms against various external factors and pressures is needed (Lavergne and Molofsky 2006). Botanists remain unaware of the spread and establishment of some invasive species, their mechanisms of propagation, and the dynamics of their growth and development, therefore, management is also tricky. Therefore, appropriate assessment of the risk of their potential invasiveness, early detection, forecasting and further rapid removal, education, raising awareness and legislation, and effective controls often require integrated long-term commitment techniques and approaches (Willby 2007).

9.4.6 Mitigation and Restoration

The strategies and approaches need to be focused on restoring ecosystems following degradation and their negative impacts. Also increasing incidences of 'secondary invasions', that is quick establishment of new invasive species in the place of earlier species in disturbed regions are reported that are favoured due to the various management strategies and interventions, control methods, and/or alteration of resources. Restoration involves the removal of invasive species. Though various control and restoration efforts were rather not appropriate, and therefore, exhibited consequences are not preferred in case to control the predator as this can cause further higher number of intermediate predators that affect trophic levels in food chains and food webs cascade through the ecosystem (Pyšek and Richardson 2010).

9.5 Restoration Methods for a Degraded Ecosystem

The methodology adopted for the restoration of aquatic systems is done through taking small steps towards stabilizing biodiversity with the constant increase in species count, using methods and approaches conserving habitats with their natural biodiversity and ecosystems. In general, habitat restoration can address the chemical properties of an ecosystem, such as re-oligotrophication or a decrease in the number of contaminants that are present in excess, as well as the rehabilitation of the physical-structural properties of an ecosystem, restoring connectivity, or any combination of these. In order to support ecosystem functioning, more emphasis is placed on the requirement to maintain habitat complexity and connectivity while focusing on biodiversity itself at the habitat, assemblage, or the individual species level (Dethier et al. 2003; Giller et al. 2004).

In order to create a balance in the ecosystem, the removal of IAS is frequently carried out via different restoration projects that have been approved to eradicate the alien species (Hobbs and Richardson 2011). A strong criticism was raised by ecologists due to the unrealistic methods of tackling with IAPS control (Richardson et al. 2004; Shaw et al. 2010). These studies utilized a restoration ecology approach that neglected the understanding of the basic cause of ecosystem damage. In order to improve restoration efforts, a common approach defining restoration ecology as well as invasion ecology together could bring clarity on the causes of invasion. This could further be supported via sharing and putting forward knowledge with supportive research, having application in the administration and restoration of the ecosystem. The main cause of the degradation of the ecosystem is competition because of IAPS and the most effective way is to eradicate them. However, the abrupt removal of invaders changes the natural habitat, which hinders the growth and re-establishment of native species or even results in the death of the native species that have been reintroduced into the ecosystem (Vila and Gimeno 2007; Beater et al. 2008; Bergstorm et al. 2009).

9.6 Ecological Restoration Practices

As per the Society of Ecological Restoration (SER), the main goal of restoration projects is to restore the ecosystem features that have been continuously destroyed, as a result of human interference (Ruiz-Jaen and Mitchell Aide 2005). According to reports by Benayas et al. (2009), ecological restoration benefits the recovery of native species and biodiversity. Based on meta-analyses research evaluating the impacts of restoration on various types of ecosystems across globe, ecological restoration projects raised the level of biodiversity present and also uplifted ecosystem benefits with 44% and 25%, respectively. This held true for additional ecological restoration meta-analyses carried out on more defined ecosystems, such as wetlands and forest reserves (Felton et al. 2010; Meli et al. 2014). Different passive or active strategies were used to implement ecological restoration for positive results. The removal of degrading elements is the first step in passive restoration, which is followed by the autogenic or natural regeneration of native species and their respective community. Active restoration (assisted regeneration) entails actions like adding desired plant species, amending the soil, and controlling fire regimes, which also drive secondary native succession (Holl and Aide 2011). It is difficult to reset the endpoint of ecological restoration, particularly for freshwater ecosystems, to that of the pre-invasion state because of changing environmental patterns such as climatic conditions, land use, and significant anthropogenic behaviour. As a result, the recovery of ecosystem processes and the regular operation of an ecosystem, which will produce ecosystem goods and services for society and wildlife, are the foundations for restoration success (Suding 2011). IAPS species management and restoration activities primarily use passive strategies in aquatic ecosystems, including herbicidal control, mechanical clearing, and the application of biological control measures (Coetzee et al. 2011; Stiers et al. 2011; Gaertner et al. 2012). In South Africa, passive restoration practices of alien invasive species resulted in the secondary invasion, according to Ruwanza et al. (2013). Their study noted following restoration management perspectives:

- Passive restoration alone is a slow and ineffective method that only permits the natural regeneration of native communities.
- Following catchment management strategies that constrained the discharge of nutrient-rich effluents, a freshwater lake in Scotland that was previously known to be highly eutrophic showed a significant reduction in its nutrient status. It demonstrated an autogenic recovery of the local species following a check on the lake's nutrient reduction (Carvalho et al. 2012).
- For successful ecosystem recovery, most eutrophic freshwater lake ecosystems require a combination of passive (reduction in nutrient input) and active restoration, using biological changes (Liu et al. 2018). This two-pronged approach to

restoration has enabled the recovery and re-establishment of native plant communities, followed by the distribution of related organisms, creating a balanced ecosystem with clear structure and function.

Even though active restoration can be expensive, it is justified for areas and regions with high conservation value, such as threatened or endangered biomes, biodiversity hotspots, and high-priority catchment areas for freshwater resources (Gaertner et al. 2012). In terms of the role that IAAP species invasion has played, biological control has been successful in reducing IAAP biomass and contributing to long-term benefits like water conservation and ecosystem recovery after control (Fraser et al. 2016; Martin et al. 2018). The South African Riparian invasion control proved to be an excellent example of dual restoration practice involving both passive and active methods. Implementation of a massive terrestrial and riparian invasive alien removal program leads to ecosystem balance/recovery studies showing complete establishment of introduced native species at those studied sites showing positive outcomes (Ruwanza et al. 2013; Nsikani et al. 2019).

Anthropogenic activities and landscape developments are the main reason behind the conversion of natural ecosystem to urban developments and agricultural space, which leads to natural habitat fragmentation, thus playing a significant role in compromising ecological recovery for freshwater ecosystems and limiting native gene pool flow (Kietzka et al. 2015). Elaborative studies and research practices on ecological restoration indicate the success and hardship in relation to the restoration of degraded ecosystems, with active long-term management studies providing evidence in order to develop knowledge and fulfill the bridge-gap of these approaches in understanding the complex variables. With regard to long-term post-IAAP species, management and restoration monitoring to give useful trajectories on restoration mechanisms within the aquatic environments was further supported by a number of researchers (Kettenring and Adams 2011; Suding 2011; Prior et al. 2018). These studies demonstrate the necessity and relevance of conducting additional IAAP species recovery studies following biological control, as the majority of meta-analyses and reports focus on restoration initiatives involving river channelization, urbanisation, deforestation, and mechanical removal of IAAP species (Miller et al. 2010; Kettenring and Adams 2011; Kail et al. 2015; Prior et al. 2018).

9.7 Conclusion and Future Prospects

Climate change and invasive species are two of the major threats to biodiversity and ecological services. There are evidence that invasive species has a greater impact on aquatic freshwaters in comparison to terrestrial ecosystems and is more susceptible to invasion. Moreover, climate change is intensifying the deleterious impact of invasive species. Global climate changes interfere with the population of native species and increase the vulnerability of the aquatic bodies to invasion by creating favourable conditions. Invasive species exerts a negative impact on the invaded habitat by modifying the structure and function of the native ecosystem via direct and indirect effects at various ecological levels. The primary intervention is a cost-effective method for controlling and managing invasive species. However, to ensure long-term success, restoration and rehabilitation should be aimed at attaining resilient ecosystem resistance to invasions. Further knowledge is required to:

- Understand as how and to what degree climate change is controlling the selection procedure on invasive species going through range extension that would aid in the effective management of invasive species. Insight into the relationship between climate change and genetic processes will be vital in predicting as how the invasive species adapts to climatic change.
- To gain insight into which species are more vulnerable including species that are tolerant to temperature and which systems are more susceptible to invasion in response to temperature change, water quality and quantity, nutrient availability, and changes in community compositions are required.
- The complexity created by the interaction between climatic variations and plant invasions can be resolved using a multidirectional approach. In order to apprehend the effect of biotic as well as abiotic interactions, transcriptomics along-with growth analyses are frequently utilized to locate and identify the genes involved in the IPS.
- By examining alien species at the population level in both native and invasive ranges and incorporating genomics and multi-omics approaches, we can learn more about the mechanisms underlying plant responses to climate change. Long-term experiments could help in gaining an in-depth understanding of how to target particular responsive genes by assessing the effects of environmental changes on invasions during each invasion stage.
- Need to find out the effect of mechanical, chemical, and biological controls under various climatic conditions and is also important to identify which control method is more robust, most adaptable, and healthy for the ecosystem.
- To develop integrated monitoring and information mechanism that syncs with new techniques for the management of aquatic IS.

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