Plant Invasion and Climate Change: A Global Overview

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Abstract

The phenomenon of plant invasion is a consequence of invading plants' exceptional range expansion into new geographic areas. Even though older naturalists were aware of the problem of plant invasion, research on the subject has intensified mainly in the last two decades. The attributes of migrated alien plants, as well as the biotic and abiotic aspects of the introduced environment—which may be investigated with the aid of numerous hypotheses—are what lead to successful plant invasions. After going through an introduction-naturalization-invasion continuum, these species dominate the invaded ecosystem, homogenize the floristic composition, jeopardize rare and unique species, disturb ecosystem stability, and incur high social and financial losses. In the future, it is anticipated that the range of these species will increase significantly, in part due to the expansion of global trade, agriculture, and other human activities, and somewhat due to anthropogenically induced climate change. Most of the invasive plant species respond positively to various consequences of climate change, viz. rising temperatures, augmented nitrogen accumulation, enhanced CO_2 levels, erratic precipitation regimes, etc. With the growing fierceness of the recognized invaders and the continuous appearance of novel invaders, the threats and difficulties pertaining to the invasive aliens are continuously increasing. Furthermore, biological invasions and climate change may act concomitantly and magnify each other's effect, which makes it important to study both phenomena

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collectively to devise a better approach to mitigate their effects. This chapter offers a general framework for understanding plant invasion, including the fundamental background, the process of invasion, key hypotheses, consequences, and future of plant invasion in the global climate change scenario.

Keywords

Climate change · Ecological impacts · Invasion hypotheses · Invasive species · Socio-economic impacts

1.1 Introduction

The dissolution of biogeographic boundaries and the improvement of global trade, transportation, and tourism have increased the cross-border migration of non-indigenous plant species, giving rise to the global environmental challenge of plant invasion (Bonnamour et al. 2021; Byrne et al. 2022). The term *plant invasion* refers to the unusual range expansion of species into new geographical areas, whereas the term *invasive plant species* refers to the tiny percentage of migratory plant species introduced purposely or accidentally outside their natural range which are able to acclimate the novel environments, establish self-sustainable populations, and have a negative ecological and socio-economic influence on the introduced habitat (Kaur et al. 2019; Shackleton et al. 2019). Richardson et al. (2000) provided a general overview of the plant invasion as a complex multistage process (Fig. 1.1), the major steps of which are explained hereunder:

Introduction: A plant or its propagule must be transported via any agency across the primary intercontinental and/or intracontinental geographic barriers to begin the invasion process. It is mostly mediated by humans, but other elements may also be responsible. At this stage, the species could be described as "alien", "exotic", "non-native", "non-indigenous", or "introduced".

Acclimatization: The primary obstacle an alien plant species faces when it is introduced in a novel habitat is the environmental barriers composed of biotic and abiotic components. An invasive alien species must learn to adapt to such environmental variations to survive in the new habitat.

Naturalization: After establishment, a species must get past any obstacles preventing it from reproducing continuously. At this stage of invasion, a species is classified as "casual" or "naturalized". Casuals are characterized as imported species that can persist and occasionally breed but are unable to create populations that can replace themselves. As a result, they are dependent on frequent introductions for their survival within novel non-native bounds. Contrarily, plants capable of reproducing on their own, independently, and for numerous generations are called as naturalized.

Invasion: The term "invasive" is referred to a naturalized organism, which produces enormous off-springs through vegetative and/or generative mechanisms and

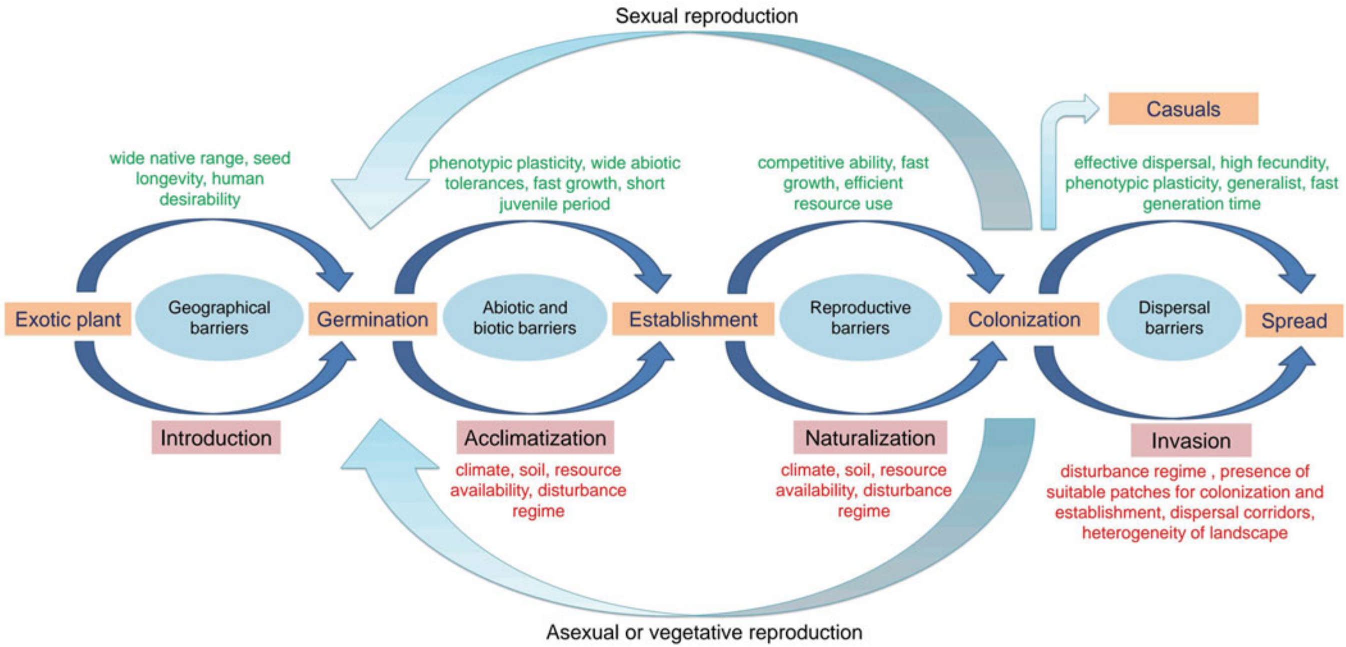

Fig. 1.1 Scheme of the plant invasion process summarizing significant stages, barriers, and plant and habitat attributes facilitating the process. (After Richardson et al. 2000; Theoharides and Dukes 2007)

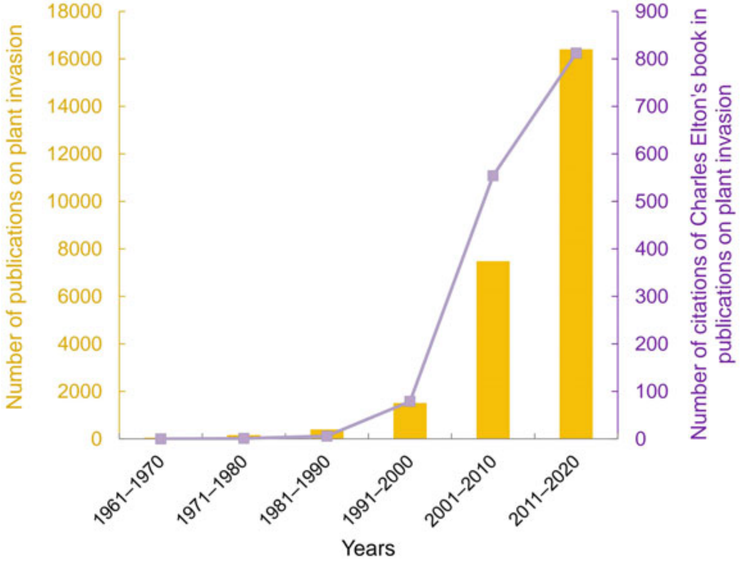

Fig. 1.2 Rate of publications on plant invasion and citations of Charles Elton's book "The Ecology of Invasions by Animals and Plants" (Elton 1958) in those publications over the years

overcomes local/regional dispersal obstacles, thereby spreading far from the parent plants. At this stage, the species begins to interfere with the native vegetation of the introduced region, leading to severe consequences.

Since ancient times, naturalists have studied the phenomenon of invasion, and various nineteenth and twentieth century scientists have mentioned such terms and/or descriptions in their writings. Yet the notion did not perceive much significance until Charles Elton, a British naturalist from the twentieth century, described the precise idea of biological invasion in his book "The Ecology of Invasions by Animals and Plants" (Elton 1958). Elton introduced the concept of invasion and emphasized the unnatural distribution of invasive species, their impacts on biodiversity, and the reasons for their spread. Even today, the hypotheses put forward by him with limited experimental evidence are duly considered and proven from time to time (Richardson and Pyšek 2008). Both, the number of publications on plant invasion and the acknowledgement of Elton's book in those publications have readily increased over time (Fig. 1.2). Later it was also established that biological invasion is the second most important ecological disturbance that endangers global biodiversity (Bellard et al. 2016) and is the primary factor responsible for island ecosystems' loss of species (Tershy et al. 2002).

Lately, invasion dynamics are changing unprecedently due to global climate change. Invasive plant species respond positively to various components of climate change, viz. global warming, augmented nitrogen accumulation, enhanced CO_2 levels, erratic precipitation regimes, etc. (Gao et al. 2018; Johnson and Hartley

2018; Howell et al. 2020; Ren et al. 2022). With the growing aggressiveness of the established invasive species and the ongoing appearance of novel invaders, the threats and difficulties pertaining to plant invasion are continuously increasing. Furthermore, biological invasions and climate change may act concomitantly and magnify each other's effects (Sage 2020), which makes it important to study both phenomena collectively to devise a better approach to mitigate their effects.

The present chapter discusses the background and concepts of plant invasion. This discussion aims to improve understanding of the phenomenon of plant invasion by outlining the key factors responsible for the establishment of an alien plant species in a new geographic range. The subsequent presentation of the global status of invasive plant species along with their negative effects at ecological and socio-economic levels and their response toward global climate change emphasizes the current and futuristic issues pertaining to plant invasion.

1.2 Factors Affecting the Success of Invasive Alien Plants

The introduction-naturalization-invasion continuum relies heavily on the functional traits of the introduced species as well as those of the invaded habitat (Roiloa et al. 2020; Ibáñez et al. 2021). Additionally, it is acknowledged that invasion is governed by a variety of factors and is not dependent on a single theory or hypothesis (Dai et al. 2020). For example, three factors, including climatic conditions, habitat resistance, and vigour of the invasive species, are used in the Invasion Factor Framework presented by Young et al. (2022) to elucidate the establishment of invasive plant species. Likewise, the combined outcome of species introduction and plantation record, changes in the introduced regions, and dispersal passages, all contribute to the species richness of alien taxa in the natural forest ecosystems (Wagner et al. 2021). Further, Liao et al. (2021) stated that different functional characteristics account for different aspects of the process. For instance, the characteristics linked to population growth and evolutionary adaptation may determine the breadth of invasion, whereas traits associated with relative competitiveness define the severity of invasion impact (Ni et al. 2021). Fuentes-Lillo et al. (2021), on the contrary, believe that the anthropogenic influences may outweigh the abiotic factors in being the most significant driver of the distribution of alien plant species in certain cases (Fuentes-Lillo et al. 2021). Similar frameworks and hypotheses have been put forth by researchers from time to time explaining the mechanisms underlying the invasion process, and some of those express opposing viewpoints (Enders et al. 2018).

1.2.1 Hypotheses Ascertaining the Influence of Habitat Characteristics on Invasion

Community ecologists have long recognized the importance of habitat characteristics in the success of alien plant invasion. It is becoming more widely acknowledged that community ecology's ideas and experimental methods could significantly advance our knowledge of plant invasions and ability to control them (Huston 2004). Certain well-accepted hypotheses that are proven to enhance the invasibility of an ecosystem are explained hereunder:

Disturbance: The hypothesis states that compared to the ecosystems have not been disturbed, perturbed ecosystems are more likely to be the target of alien species invasions (Elton 1958; Hobbs and Huenneke 1992). Disturbance facilitates greater seedling recruitment for many invasive species, thus, having an essential role in their success (Pearson et al. 2022). Guo et al. (2022) demonstrated that even among different habitat types, disturbance-related factors affected the invasibility of a species more than phylogenetic and native plant diversity.

Empty Niche or opportunity windows: Invaders are drawn to establish and reproduce when there are resources or unfilled niches available (MacArthur 1970). Holzmueller and Jose (2011) reported that the patches of *Imperata cylindrica* (L.) P.Beauv. quickly increase in size and density to fill vacant niches that emerged after a disturbance, such as a fire or a hurricane.

Fluctuating resource: Any natural or anthropogenic disturbance increases or decreases resource availability, and hence, impacts the vegetation patterns causing dominance of invaders (Davis et al. 2000). Ibáñez et al. (2021) observed that fluctuation of resources is strongly linked with the performance of alien invasive plants, particularly in case of decreasing water availability and/or increasing light and nutrient availability.

Diversity-invasibility or biotic resistance: The hypothesis states that biodiverse communities are more capable of fending off the invasion by alien species in comparison to ecosystems with lesser diversity (Elton 1958). The shreds of experimental evidence collected at small geographical scales support the hypothesis contending that biologically diverse communities are fiercely competitive (Ernst et al. 2022). Li et al. (2022a) demonstrated a negative association between resident species diversity and grassland invasion by *Ambrosia artemisiifolia* L., which remained constant even after the nutrient addition. Likewise, in various community types and ecoregions of the United States, Beaury et al. (2020) showed a negative association between native richness and alien occurrence.

Biotic acceptance: In contrary to the biotic resistance hypothesis, certain researchers state that the presence of rich and diverse native populations supports invasion by non-native species (Stohlgren et al. 2006). In the riparian forests of the Warta River Valley (Poland), Dyderski et al. (2015) discovered an affirmative association between the richness of alien and indigenous woody perennials, which indicates that diverse ecosystems readily attract exotic invaders.

Enemy release: According to this hypothesis, the lack of native foes (pests, diseases, and predators) in the invaded zone encourages the unrestrained spread of the alien species (Elton 1958; Keane and Crawley 2002). Native habitats have greater control over plant populations via natural enemies than non-native habitats (Lucero et al. 2019). For instance, the establishment of *Ambrosia trifida* L. in the alien range was influenced by the release from both above- and below-ground enemies, which used to attack the weed at different life stages (Zhao et al. 2020).

Specialist–generalist: Ecosystems that have specialized local pests/predators and generalist local mutualists are more vulnerable to invasion (Callaway et al. 2004). A study by Eschtruth and Battles (2009) examined the role of the white-tailed deer (*Odocoileus virginianus* Zimmermann), a generalist herbivore, in the invasion of three exotic plant species (*Microstegium vimineum* (Trin.) A.Camus, *Alliaria petiolata* (M.Bieb.) Cavara and Grande, and *Berberis thunbergii* DC.) in American forest ecosystems, and the findings of the study showed that herbivory patterns exhibited by the deer can hasten the spread of exotic plants.

Island susceptibility: Compared to continental ecosystems, islands are additionally vulnerable to the onslaught and effects of invaders (Jeschke 2008). Gimeno et al. (2006) examined the comparative susceptibility of islands to the invasion of *Oxalis pes-caprae* L. in comparison to the neighbouring mainland regions of Spain and found that the islands occupy a larger share of habitats preferred by the weed.

1.2.2 Hypotheses Ascertaining the Influence of Plant Characteristics on Invasion

Ecologists have also long sought to predict which species are likely to invade new habitats, and recently, quantitative studies have been employed to do so. In this context, the suggested hypothesis and investigations, despite being limited to a small number of taxa, provide valuable insights into the establishment and dissemination of invaders (Kolar and Lodge 2001). Some of these hypotheses are listed hereunder:

Ideal weed: Certain characteristics of an invasive plant species determine the chances of its successful establishment in the introduced habitat (Elton 1958; Rejmánek and Richardson 1996). Functional traits such as the ability to germinate under diverse conditions, fast nutrient acquisition, high growth and reproduction rate, quick life cycle, etc. play a significant role during the introduction phase of the invasion process, making it easier for the introduced plants to survive and colonize new ranges (Dai et al. 2020; Montesinos 2022).

Limiting similarity: The likelihood of invasion by a species will increase as the disparity between native and foreign species grows (MacArthur and Levins 1967). The concept of limiting similarity is built on the idea that antagonism within species would be the highest amongst phylogenetically closer species and for species to coexist, they need to be functionally distinct (Price and Pärtel 2013).

Darwin's naturalization conundrum: Charles Darwin presented two opposing hypotheses related to plant invasion: the "pre-adaptation hypothesis" stating that pre-adapted traits in an exotic species would be crucial for environmental filtering and its survival in a particular habitat and the "naturalization hypothesis" stating that trait disparities in an exotic species allow it to successfully establish via niche differentiation and competitive exclusion (Park et al. 2020). A recent study by Omer et al. (2022) demonstrates that the correlation between phylogenetic remoteness to the indigenous vegetation and the successful establishment of a non-native plant species shifts from one step of the invasion process to the next one, thus proving both hypotheses.

Evolution of increased competitive ability: When herbivory is reduced as a result of the dearth of usual foes in the novel habitat, invaders choose higher growth rates and improved competitiveness over defense (Blossey and Nötzold 1995). According to Feng et al. (2011), *Ageratina adenophora* (Spreng.) R.M.King & H.Rob. populations from non-native ranges (China and India) allocate more nitrogen to photosynthesis and less to cell walls than native populations, indicating a shift away from defense and towards growth and development. Likewise, invasive plants change the composition of secondary metabolites to produce fewer compounds that are used to protect them from herbivores and more chemicals that are used to help them adapt to their abiotic environment (Xiao et al. 2020).

Phenotypic plasticity: Invasive species can function superior in a variety of new localities by altering their phenotypic traits in response to environmental conditions (Williams et al. 1995). According to Rathee et al. (2021), phenotypic alterations in reproductive traits assisted *Parthenium hysterophorus* L. to invade and spread well in mountainous ecosystems.

Propagule pressure: An invasive species has a competitive advantage over native species if it can produce long-lasting, viable seeds (Lockwood et al. 2013). For example, high propagule pressure considerably increases the dry weight and dominance index of *Solidago canadensis* L. (Liu et al. 2022).

Invasional meltdown: Ecosystem disruption caused by invaders allows other alien species to establish themselves (Simberloff and von Holle 1999; Sax et al. 2007). Fruit preferences and foraging strategies of an invasive fruit-eating mammal, *Macaca fascicularis* Raffles enhance the seed dispersal of invasive plants in remnant forests of Mauritius (Reinegger et al. 2022). Likewise, in China, *A. philoxeroides* (Mart.) Griseb. has been noted to act as a wintertime insulator for an alien mosquitofish (*Gambusia affinis* S. F. Baird & Girard), which allows the spread of the fish as farther as the plant is expanding with climate change (Xiong et al. 2019).

Novel weapon: Phytochemicals (known as allelochemicals) generated by an invading plant species mediate novel interactions among plants and between plants and microbes (known as allelopathy), changing how the ecosystem functions (Callaway and Ridenour 2004). Invasive plants such as *P. hysterophorus*, *Verbesina encelioides* (Cav.) A.Gray, *Calyptocarpus vialis* Less., etc. exhibit phytotoxicity against various crop and weed species by releasing toxic chemical compounds via leachation, root exudation, and residual decomposition (Lal et al. 2021; Mehal et al. 2023a; Kaur et al. 2022a). The latest investigation indicated that allelopathy is present in 72% of the 524 invasive species studied, suggesting it to be a ubiquitous mechanism of invasion (Kalisz et al. 2021).

Community ecology: Invasive alien species with evolved phenologies become easily acclimated to the non-native ranges, particularly under climate change scenarios (Wolkovich and Cleland 2011). *P. hysterophorus*' varied phenology in response to shifting temperature and humidity conditions, as described by Kaur et al. (2017), explains the weed's ability to adapt and invade a variety of non-native habitats.

The invasion aspect of a species may be affected by one of these or several additional elements that have not been taken into account by these hypotheses. Although we have a solid grasp of the principles underlying successful plant invasions, yet there is much more to investigate and learn considering the complexity of ecological components and functions and the constantly increasing frequency of invasions.

1.3 Statistics of Invasive Alien Plants

It is anticipated that about one-sixth of the earth's landmass, which also constitutes 16% of the world's biodiversity hotspots, is vulnerable to invasion (Early et al. 2016). In the world's 843 continental and island locations, 13,168 naturalized vascular plant species have been reported that account for nearly 3.9% of the global extant flora (van Kleunen et al. 2015). According to recent estimates, non-native species currently make up more than one-fourth of island floras (Brock and Daehler 2022). The scientists also claimed that while the Pacific Islands had the highest accretion rate of naturalized flora, North America had the maximum naturalized flora (van Kleunen et al. 2015). This study was supported by a second investigation on the naturalized alien flora of the world, which identified California, North America as having the most diverse naturalized alien flora with 1753 species of alien plants (Pyšek et al. 2017). Likewise, more than 2677 naturalized exotics are recorded from various countries in South America (Zenni et al. 2022). South Africa, with 1139 species, constitutes the maximum number of naturalized non-natives among African countries (Richardson et al. 2022). In Europe, the maximum naturalized flora is reported from England (1379 species), followed by Sweden (874 species), Scotland (861 species), Wales (835 species), France (716 species), the European part of Russia (649 species), Ukraine (626 species), and Norway (595 species), showing that northern Europe is the most heavily invaded (Pyšek et al. 2022). An inventory of global plant invaders is presented in Table 1.1 (Global Invasive Species Database 2023).

A comparatively limited number of families and genera contain the majority of global invaders (Mack et al. 2000). Asteraceae, which includes 1343 species, has contributed the most to the world's naturalized flora, trailed by 1267 species of Poaceae and 1189 species of Fabaceae (1189 species) (Pyšek et al. 2017). Global representative genera of naturalized alien plants are *Solanum*, *Euphorbia*, and *Carex* with 112, 108, and 106 species, respectively (Pyšek et al. 2017). It has also been determined that transportation and naive possessions contribute to the majority of

Table 1.1 List of the global invasive alien plant species as provided by Global Invasive Species Database (2023)

Family	Plant species
Acanthaceae	*Acanthus mollis*; *Asystasia gangetica*; *Hygrophila polysperma*; *Ruellia brevifolia*; *Thunbergia grandiflora*
Aceraceae	*Acer ginnaal*, *A. platanoides*
Agavaceae	*Agave americana*, *A. sisalana*; *Furcraea foetida*; *Phormium tenax*
Aizoaceae	*Carpobrotus edulis*
Araliaceae	*Hedera helix*
Alismataceae	*Sagittaria platyphylla*, *S. sagittifolia*
Amaranthaceae	*Alternanthera philoxeroides*, *A. sessilis*
Anacardiaceae	*Cotinus coggygria*; *Rhus longipes*; *Schinus terebinthifolius*
Annonaceae	*Annona glabra*, *A. squamosa*
Apiaceae	*Heracleum mantegazzianum*
Apocynaceae	*Funtumia elastica*; *Thevetia peruviana*; *Vinca major*
Araceae	*Epipremnum pinnatum*; *Pistia stratiotes*; *Syngonium podophyllum*; *Zantedeschia aethiopica*
Araliaceae	*Schefflera actinophylla*
Arecaceae	*Archontophoenix cunninghamiana*; *Elaeis guineensis*; *Livistona chinensis*; *Phoenix canariensis*; *Trachycarpus fortunei*
Asclepiadaceae	*Cryptostegia grandiflora*, *C. madagascariensis*; *Cynanchum rossicum*
Asteraceae	*Ageratina adenophora*, *A. riparia*; *Ageratum conyzoides*; *Ambrosia artemisiifolia*; *Austroeupatorium inulifolium*; *Bellis perennis*; *Bidens pilosa*; *Carduus nutans*; *Centaurea biebersteinii*, *C. diffusa*, *C. melitensis*, *C. solstitialis*; *Chromolaena odorata*; *Chrysanthemoides monilifera*; *Cirsium arvense*, *C. vulgare*; *Conyza floribunda*; *Cynara cardunculus*; *Delairea odorata*; *Dyssodia tenuiloba*; *Elephantopus mollis*; *Erigeron karvinskianus*; *Eupatorium cannabinum*; *Euryops multifidus*; *Gymnocoronis spilanthoides*; *Hieracium aurantiacum*, *H. floribundum*, *H. pilosella*; *Hypochaeris radicata*; *Launaea intybacea*; *Mikania micrantha*; *Nypa fruticans*; *Onopordum acanthium*; *Parthenium hysterophorus*; *Pluchea carolinensis*, *P. indica*; *Senecio angulatus*, *S. inaequidens*, *S. jacobaea*, *S. squalidus*, *S. viscosus*, *S. vulgaris*; *Sonchus asper*, *S. oleraceus*; *Sphagneticola trilobata*; *Taraxacum officinale*; *Tithonia diversifolia*; *Tussilago farfara*; *Xanthium spinosum*
Balsaminaceae	*Impatiens glandulifera*, *I. walleriana*
Basellaceae	*Anredera cordifolia*
Begoniaceae	*Begonia cucullata*
Berberidaceae	*Berberis buxifolia*, *B. darwinii*, *B. thunbergii*
Betulaceae	*Alnus glutinosa*
Bignoniaceae	*Macfadyena unguis-cati*; *Spathodea campanulata*; *Tabebuia heterophylla*; *Tecoma capensis*, *T. stans*
Boraginaceae	*Cynoglossum officinale*; *Heliotropium curassavicum*
Brassicaceae	*Alliaria petiolata*; *Brassica elongata*, *B. tournefortii*; *Camelina sativa*; *Cardamine flexuosa*, *C. glacialis*; *Lepidium latifolium*, *L. virginicum*
Buddlejaceae	*Buddleja davidii*, *B. madagascariensis*
Butomaceae	*Butomus umbellatus*
Cabombaceae	*Cabomba caroliniana*

(continued)

Table 1.1 (continued)

Family	Plant species
Cactaceae	*Acanthocereus tetragonus*; *Opuntia cochenillifera*, *O. ficus-indica*, *O. monacantha*, *O. stricta*
Cannaceae	*Canna indica*
Caprifoliaceae	*Lonicera japonica*, *L. maackii*
Caryophyllaceae	*Cerastium fontanum*; *Sagina procumbens*; *Stellaria alsine*, *S. media*
Casuarinaceae	*Casuarina equisetifolia*
Cecropiaceae	*Cecropia peltata*, *C. schreberiana*
Celastraceae	*Celastrus orbiculatus*; *Euonymus alata*, *E. fortunei*
Ceratophyllaceae	*Ceratophyllum demersum*
Chenopodiaceae	*Salsola tragus*
Chrysobalanaceae	*Chrysobalanus icaco*
Clusiaceae	*Hypericum perforatum*
Combretaceae	*Terminalia catappa*
Commelinaceae	*Commelina benghalensis*; *Tradescantia fluminensis*, *T. spathacea*
Convolvulaceae	*Ipomoea aquatic*, *I. cairica*, *I. setosa* ssp. *pavonii*; *Merremia peltata*, *M. tuberosa*
Crassulaceae	*Crassula helmsii*; *Kalanchoe pinnata*
Cucurbitaceae	*Coccinia grandis*; *Sechium edule*
Cyperaceae	*Cyperus rotundus; Oxycaryum cubense*
Dioscoreaceae	*Dioscorea bulbifera*, *D. oppositifolia*
Elaeagnaceae	*Elaeagnus angustifolia*, *E. pungens*, *E. umbellata*
Ericaceae	*Calluna vulgaris*; *Rhododendron ponticum*
Euphorbiaceae	*Aleurites moluccana*; *Antidesma bunius*; *Euphorbia esula*; *Jatropha gossypiifolia*; *Ricinus communis*; *Triadica sebifera*
Fabaceae	*Abrus precatorius*; *Acacia concinna*, *A. confuse*, *A. farnesiana*, *A. longifolia*, *A. mangium*, *A. mearnsii*, *A. melanoxylon*, *A. nilotica*, *A. pycnantha*, *A. retinodes*, *A. saligna*; *Adenanthera pavonina*; *Albizia julibrissin*, *A. lebbeck*; *Caesalpinia decapetala*; *Coronilla varia*; *Cytisus scoparius*, *C. striatus*; *Dalbergia sissoo*; *Dichrostachys cinerea*; *Dipogon lignosus*; *Falcataria moluccana*; *Flemingia strobilifera*; *Genista monspessulana*; *Haematoxylum campechianum*; *Lespedeza cuneata*; *Leucaena leucocephala*; *Lotus corniculatus*; *Melilotus alba*; *Mimosa diplotricha*, *M. pigra*, *M. pudica*; *Prosopis glandulosa*, *P. juliflora*; *Psoralea pinnata*; *Pueraria montana* var. *lobata*; *Robinia pseudoacacia*; *Samanea saman*; *Senegalia catechu*; *Sesbania punicea*; *Trifolium dubium*, *T. repens*; *Ulex europaeus*; *Vachellia drepanolobium*; *Wisteria floribunda*, *W. sinensis*
Flacourtiaceae	*Flacourtia indica*
Geraniaceae	*Erodium cicutarium*
Goodeniaceae	*Scaevola sericea*
Gunneraceae	*Gunnera manicata*, *G. tinctoria*
Haloragaceae	*Myriophyllum aquaticum*, *M. heterophyllum*, *M. spicatum*
Hydrocharitaceae	*Egeria densa*; *Elodea canadensis*; *Halophila stipulacea*; *Hydrilla verticillata*; *Hydrocharis morsus-ranae*; *Lagarosiphon major*; *Vallisneria nana*, *V. spiralis*

(continued)

Table 1.1 (continued)

Family	Plant species
Iridaceae	*Iris pseudacorus*
Juncaceae	*Juncus tenuis*; *Luzula campestris*
Lamiaceae	*Ocimum gratissimum*
Lardizabalaceae	*Akebia quinata*
Lauraceae	*Cinnamomum camphora*, *C. verum*; *Litsea glutinosa*
Lemnaceae	*Landoltia punctata*
Lentibulariaceae	*Utricularia gibba*
Liliaceae	*Agapanthus praecox*; *Asparagus densiflorus*, *A. officinalis*; *Sansevieria hyacinthoides*, *S. trifasciata*
Limnocharitaceae	*Limnocharis flava*
Lythraceae	*Cuphea ignea*; *Lythrum salicaria*; *Trapa natans*
Malpighiaceae	*Hiptage benghalensis*
Malvaceae	*Abelmoschus moschatus*
Melastomataceae	*Clidemia hirta*; *Melastoma candidum*; *Miconia calvescens*; *Tibouchina urvilleana*
Meliaceae	*Cedrela odorata*; *Melia azedarach*
Menyanthaceae	*Nymphoides peltata*
Moraceae	*Castilla elastica*; *Ficus microcarpus, F. rubiginosa*; *Morus alba*
Myricaceae	*Morella faya*
Myrsinaceae	*Ardisia acuminata, A. crenata, A. elliptica*
Myrtaceae	*Eugenia uniflora*; *Kunzea ericoides*; *Melaleuca quinquenervia*; *Pimenta dioica*; *Psidium cattleianum*, *P. guajava*; *Rhodomyrtus tomentosa*; *Syzygium cumini*, *S. jambos*; *Waterhousea floribunda*
Najadaceae	*Najas minor*
Nymphaeaceae	*Nymphaea odorata*
Oleaceae	*Fraxinus floribunda*; *Ligustrum lucidum*, *L. robustum*, *L. sinense, L. vulgare*; *Olea europaea*
Onagraceae	*Fuchsia boliviana*, *F. magellanica*; *Ludwigia peruviana*
Orchidaceae	*Oeceoclades maculata*
Oxalidaceae	*Oxalis corniculata*, *O. latifolia*, *O. pes-caprae*
Passifloraceae	*Passiflora edulis*, *P. foetida*, *P. maliformis*, *P. suberosa*, *P. tarminiana*
Piperaceae	*Piper aduncum*
Pittosporaceae	*Pittosporum tenuifolium*, *P. undulatum*, *P. viridiflorum*
Plantaginaceae	*Veronica serpyllifolia* ssp. *humifusa*
Poaceae	*Aegilops triuncialis*; *Agrostis capillaries*, *A. gigantean*; *Ammophila arenaria*; *Andropogon virginicus*; *Arundo donax*; *Bambusa vulgaris*; *Bothriochloa pertusa*; *Bromus inermis*, *B. rubens*, *B. tectorum*; *Cenchrus ciliaris*, *C. clandestinus*, *C. echinatus*, *C. macrourus*, *C. polystachios*, *C. setaceus*; *Cortaderia jubata*, *C. selloana*; *Cynodon dactylon*; *Dactylis glomerata*; *Glyceria maxima*; *Heteropogon contortus*; *Holcus lanatus*; *Imperata cylindrica*; *Ischaemum polystachyum*; *Melinis minutiflora*; *Microstegium vimineum*; *Miscanthus sinensis*; *Nassella neesiana*, *N. tenuissima*; *Neyraudia reynaudiana*; *Oplismenus undulatifolius*; *Panicum repens*; *Paspalum scrobiculatum*, *P. urvillei*, *P. vaginatum*; *Phalaris arundinacea*; *Phragmites australis*; *Phyllostachys flexuosa*; *Poa*

(continued)

Table 1.1 (continued)

Family	Plant species
	annua, *P. pratensis*; *Rottboellia cochinchinensis*; *Sacciolepis indica*; *Schismus barbatus*; *Setaria verticillata*; *Sorghum halepense*; *Spartina alterniflora*, *S. anglica*, *S. densiflora*; *Sporobolus africanus*; *Urochloa maxima*, *U. mutica*; *Vulpia bromoides*; *Zizania latifolia*
Polygalaceae	*Polygala paniculata*
Polygonaceae	*Persicaria perfoliata*; *Polygonum cuspidatum*; *Rumex acetosella*, *R. crispus*, *R. obtusifolius*
Pontederiaceae	*Antigonon leptopus*; *Eichhornia crassipes*
Portulacaceae	*Montia fontana*
Potamogetonaceae	*Potamogeton crispus*, *P. perfoliatus*
Proteaceae	*Grevillea robusta*
Ranunculaceae	*Clematis terniflora*, *C. vitalba*; *Ranunculus ficaria*
Rhamnaceae	*Colubrina asiatica*; *Frangula alnus*; *Rhamnus alaternus*, *R. cathartica*; *Ziziphus mauritiana*
Rhizophoraceae	*Rhizophora mangle*
Rosaceae	*Duchesnea indica*; *Eriobotrya japonica*; *Fragaria vesca*; *Prunus campanulata*; *Pyrus calleryana*; *Rosa bracteata*, *R. multiflora*; *Rubus discolor*, *R. ellipticus*, *R. moluccanus*, *R. niveus*, *R. pinnatus*, *R. rosifolius*; *Spiraea japonica*
Rubiaceae	*Cinchona pubescens*; *Paederia foetida*; *Spermacoce verticillata*
Rutaceae	*Triphasia trifolia*
Salicaceae	*Populus alba*; *Salix babylonica*, *S. cinerea*, *S. humboldtiana*
Sapindaceae	*Cardiospermum grandiflorum*; *Cupaniopsis anacardioides*
Saururaceae	*Houttuynia cordata*
Scrophulariaceae	*Bacopa monnieri*; *Limnophila sessiliflora*; *Linaria vulgaris*; *Paulownia tomentosa*; *Striga asiatica*; *Strobilanthes hamiltoniana*; *Verbascum thapsus*
Simaroubaceae	*Ailanthus altissima*
Solanaceae	*Cestrum nocturnum, C. parqui*; *Nicotiana glauca*; *Physalis peruviana*; *Solanum mauritianum*, *S. seaforthianum*, *S. sisymbriifolium*, *S. tampicense*, *S. torvum*, *S. viarum*
Tamaricaceae	*Tamarix aphylla*, *T. parviflora*, *T. ramosissima*
Typhaceae	*Typha latifolia*
Urticaceae	*Boehmeria penduliflora*
Verbenaceae	*Citharexylum spinosum*; *Lantana camara*; *Verbena brasiliensis*, *V. rigida*; *Vitex rotundifolia*
Vitaceae	*Ampelopsis brevipedunculata*
Zingiberaceae	*Alpinia zerumbet*; *Hedychium coccineum*, *H. coronarium*, *H. flavescens*, *H. gardnerianum*; *Elettaria cardamomum*
Zosteraceae	*Zostera japonica*, *Z. marina*

incidental plant introductions, whereas horticulture and nursery commerce are the primary conduits for purposeful introductions (Ward et al. 2020; Beaury et al. 2021). Additionally, a study of Natura 2000 habitats indicates that freshwater and grasslands were the most invaded habitats, followed by coastal dunes and forests (Lazzaro et al. 2020). After establishment, invasive species affect the area's varied ecological and socio-economic characteristics leading to unnatural environmental modifications.

1.4 Ecological and Socio-economic Impacts of Invasive Alien Plants

Invasive plant growth endangers key socio-economic resources in addition to endangering ecosystem processes and natural biodiversity (Lazzaro et al. 2020; Rai and Singh 2020). Ecologically sensitive ecosystems, biodiversity hotspots, and protected areas are more susceptible to invaders and their accompanying impacts as these regions are already facing threats due to habitat loss and global climate change (Bhatta et al. 2020; Fenouillas et al. 2021; Rai and Singh 2021; Brock and Daehler 2022). Similarly, on tropical coral islands, where ecosystems are relatively vulnerable with a high number of endemic species, invasive alien species are a significant component contributing to the deterioration of native flora (Cai et al. 2020). Though it is challenging to determine the exact extent of the harm that invasive plants have caused to the invaded habitat; nonetheless, financial losses due to the impairment of ecological and socio-economic services as well as the imposition of management measures can be calculated.

1.4.1 Ecological Impacts

It is evident that invasive plant species impact ecological processes such as soil chemical properties, biogeochemical cycling, water and fire regimes, climatic conditions, biotic/abiotic interactions, soil microbial assembly, vegetational diversity, and advanced trophic levels, both directly and indirectly (Livingstone et al. 2020; Reilly et al. 2020; Hansen et al. 2021; Sampaio et al. 2021; Torres et al. 2021; Yu et al. 2021; Faccenda and Daehler 2022; Litt and Pearson 2022; Maan et al. 2022; Nasto et al. 2022; Singh et al. 2022; Xu et al. 2022; Zhang et al. 2022; Mehal et al. 2023b; Sharma et al. 2023; Fig. 1.3). These also interfere with the mutualistic connections, such as those between plants and their pollinators or mycorrhiza (Parra-Tabla and Arceo-Gómez 2021; Řezáčová et al. 2021). Native liana and tree communities bear negative effects on their structure, network, and topological roles due to invasive tree species in the natural forests (Addo-Fordjour et al. 2022). Increased hybridization, disease transmission, and obstruction of forest regeneration are some other risks accentuated by invasive plants in woodlands (Langmaier and Lapin 2020).

Apart from these notable effects, ecosystem modifications by invasive species can also have auxiliary cascading impacts on plant and soil communities, which magnify the overall impacts of plant invasion (Carboni et al. 2021). Also, most of the invasive species alter one or more components of the inhabited ecosystem, thus creating novel

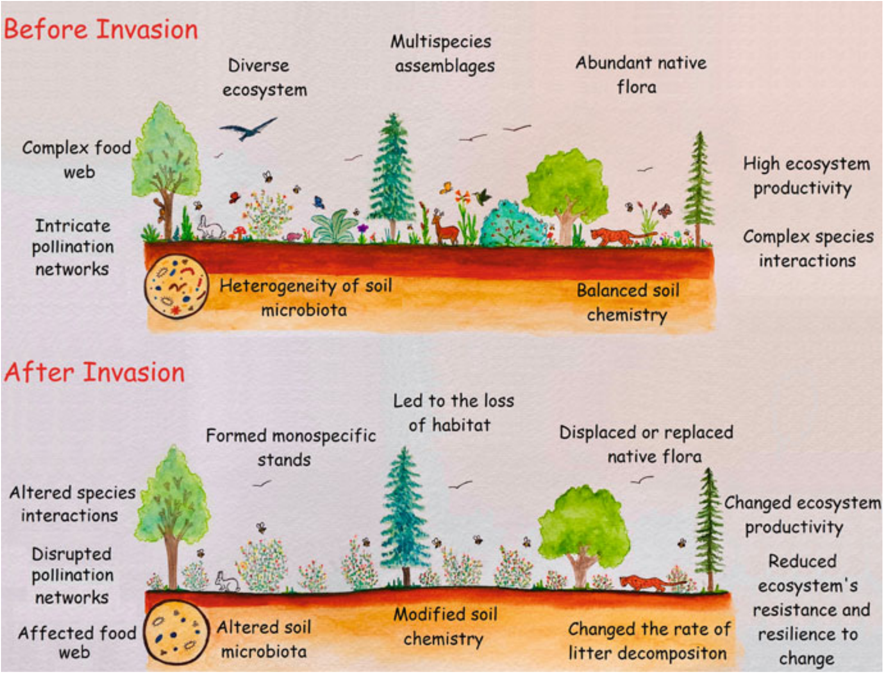

Fig. 1.3 Diagrammatic representation of changes in ecosystem structure and functions after invasion by an alien plant species

niches that continue to exist over longer periods even after the elimination of invading species (known as legacy impact), thereby inhibiting the resurgence of indigenous species and restoration of invaded habitats (Zhang et al. 2021). Moreover, when numerous invaders coexist, the effects on native plant diversity and soil characteristics are comparatively more severe (Vujanović et al. 2022).

There are very few statistical reports that show how much of a hazard invasive plant species are to the local biodiversity; nonetheless, several regional studies offer intriguing insights. Researchers contend that rather than causing species extinctions, non-native plants seem to result in the displacement of native biota, thus resulting in community-level changes. For instance, these decreased the species number from 602 to 410 in case of plants and from 68 to 19 in case of birds in the United States, working in conjunction with natural and anthropogenic disruptions (Gurevitch and Padilla 2004). Likewise, 166 native plant taxa are now categorized as endangered and 113 as vulnerable in New South Wales owing to the ongoing expansion of alien plants (Coutts-Smith and Downey 2006). Both plant and animal invasions can be blamed for nearly one-fourth of the extinct and extinct in the wild endemic flora to a certain extent (Bellard et al. 2016). Although non-native flora interventions do not straightforwardly cause species disappearance, they are clearly liable for changing the extinction trajectory of the species (Downey and Richardson 2016).

1.4.2 Socio-Economic Impacts

Invasive species also represent a serious risk to forestry, fishing, agriculture, and other ecosystem services (Bhowmik 2005). Several invaders that are hazardous weeds of significant staple and commercial crop species cause a significant loss of yield, if not managed properly (Kaur et al. 2022b). The practice of animal husbandry has also been impacted by the invasion of grasslands by alien plant species, which decreases the accessibility of pastures for the animals (O'Connor and van Wilgen 2020). By endangering ecosystem services, invasive plant species may potentially result in noteworthy financial losses (Szabó et al. 2019). Also, local flora, which once offered essential supplies of food, fuel, fodder, and medical services, is discovered to have disappeared as a result of the invasion and habitat drift (Kohli et al. 2006).

The expansion of non-native plant species also has a direct or indirect impact on many other aspects of human life, including water supplies, pollination, ecotourism, and leisure pursuits such as boating, fishing, hiking, etc. (O'Connor and van Wilgen 2020; Ginn et al. 2021). These may also impact conservation practices such as wetland restoration, forest regeneration, etc. (Lázaro-Lobo et al. 2021; Charles et al. 2022). Additionally, certain invasive plants have an immediate impact on human well-being (allergic reactions, dermatic conditions, breathing issues, etc.), whereas others have an indirect impact by spreading pests that infect people with diseases (Rai and Singh 2020; Bernard-Verdier et al. 2022).

Further, managing invasive species requires significant financial resources, which may not even fit into the budgets of nations with weak economies. The over 5000 invasive plants found in the United States cause an annual economic suffering of nearly 35 billion USD (Pimentel et al. 2005). According to research, approximately 38 million USD were exhausted to manage non-native plants in the Cape Floristic's reserved areas, and another 11–175 million USD would be needed in the succeeding times to handle the problem (van Wilgen et al. 2016). Post-removal restoration practices are even more challenging, demanding handsome investments (Adams et al. 2020). However, the enormous data gaps typically found in financial assessments indicate that these projections are considerably understated (Cuthbert et al. 2020). Moreover, it has been confidently projected that these numbers will be dramatically increased in the near future given the unchecked spread of invasive species and upcoming environmental concerns.

1.5 Future Climate Change and Invasive Plants

Invasive plant species are anticipated to be directly impacted by changes in climatic characteristics (temperature, precipitation, atmospheric CO_2 concentrations, etc.), seasonal fluctuations, and any ensuing and extreme weather event (Shrestha and Shrestha 2019; Wang et al. 2022). At the same time, studies have also shown the stimulative impact of invasive plants on volatile emissions, eutrophication, and greenhouse gas emissions (Sage 2020; Bezabih Beyene et al. 2022). Climate change

Table 1.2 Studies predicting the probable impacts of the most significant components of climate change on the plant invaders

Global change	Impact	References
Increased temperature	Positive (enhanced growth, competitive ability and resistance; increased habitat suitability, phenological, and ecophysiological adaptations)	Blumenthal et al. (2016), Liu et al. (2017), Cavieres et al. (2018), Peng et al. (2019), Howell et al. (2020), Nguyen et al. (2020), Duell et al. (2021), Bao et al. (2022), Sun et al. (2022), Adhikari et al. (2023)
	Negative (reduced plant growth, tolerance, plasticity, and defence)	Johnson and Hartley (2018), He and He (2020), Birnbaum et al. (2021)
Increased carbon dioxide concentrations	Positive (increased growth, performance and reproductive potential; improved herbicidal resistance)	Liu et al. (2017), Johnson and Hartley (2018), Bajwa et al. (2019), Cowie et al. (2020)
Increased precipitation	Positive (enhanced growth and competitiveness; niche width expansion)	Blumenthal et al. (2008), Irl et al. (2021), Bao et al. (2022), Li et al. (2022b), Ren et al. (2022), Adhikari et al. (2023)
	Negative (reduced habitat suitability)	Bradley (2009)
Decreased precipitation	Positive (enhanced germination, growth performance, phenotypic plasticity, and resilience to abiotic stress)	Gao et al. (2018), Vetter et al. (2019), Mojzes et al. (2020), Duell et al. (2021), Leal et al. (2022)
	Negative (low seed dormancy)	LaForgia et al. (2018)
Nitrogen deposition	Positive (enhanced growth and competitiveness)	Valliere et al. (2017), Cavieres et al. (2018), Liu et al. (2018), Peng et al. (2019)

usually eases invasions, and invasive species in turn magnify the negative effects of climate change (Sage 2020). For example, an invasive plant *Pueraria montana* (Lour.) Merr. colonizes aggressively with global warming, raised CO_2 levels, and eutrophication (Sage 2020). In turn, the expansion of *P. montana* promotes the emission of volatile organics and CO_2, thereby impacting the microclimatic conditions and promoting climate change (Sage 2020). Although invasive species and climate change both represent a serious risk to the ecological functions, biodiversity, and agronomic systems, an understanding of the interactions between these phenomena and their synergistic effects on ecosystem health and productivity will strongly affect our perception of the potential environmental consequences. Such research aspects demand specific acknowledgements rather than being disregarded or incorporated into conventional invasion science studies.

The futuristic projections and forecasts about the spatiotemporal distribution of non-indigenous species under potential climate change scenarios rely mainly on sophisticated modelling techniques (Table 1.2). The documented spread of invasive plant species in their indigenous and non-indigenous geographical range is used by habitat suitability models to quantify key niche dimensions and foretell new possible invasion locations (Adhikari et al. 2019). The most influential predictors in such studies generally include mean temperature, water deficit, precipitation periodicity, and fire regimes (McMahon et al. 2021). Also, cold deserts and prairies are suspected to be the most vulnerable ecoregions and invasive forb and grass species are expected to demonstrate the maximum expansion (McMahon et al. 2021).

Habitat suitability projections put forward by different studies vary in relation to geographical attributes and target species, with some emphasizing invasive species' range expansion, while others implicating shifts in their habitats. A study by Shrestha and Shrestha (2019) predicted that nearly 75% of the plant invaders in Nepal are going to expand in terms of distribution as well as intensity under future climate change scenarios. Another study examined the probable spread of six plant invaders in North America in response to projected climate change and noticed a shift in their suitable habitats in the coming years (Wang et al. 2022). A study by Fulgêncio-Lima et al. (2021) suggests that the potential distribution and impacts of current invasive plants will not be exacerbated by climate change, but novel invasive species may invade previously uninhabited or lesser-inhabited ecosystems. Certain findings also provide a contradictory opinion that climate change and invasion may individually impact native vegetation; however, climate change will not make invasions worse and it might even lessen the consequences of invasive species (He and He 2020; Kelso et al. 2020; Birnbaum et al. 2021).

In addition to the modelling approach, significant advancements have been accomplished in the latest years in understanding how invasive alien species' establishment, spread, and influence will be altered by climate change and rising carbon dioxide levels by propagating these plants under simulated environments (Ziska 2022; Table 1.2). When the populations of an invasive weed, *Ambrosia artemisiifolia* L. were exposed to two factors, i.e., simulated treatment of temperature warming and herbivory by a biocontrol agent, it was observed that high temperatures diminished the effects of biocontrol agent by producing vigorous and more defensive plants, instigated via genetic changes and transgenerational induction of defenses (Sun et al. 2022). Similarly, the results of a common garden experiment demonstrated that climate warming increased phenological overlapping between native and invasive species, consequently increasing the level of competition for pollination (Giejsztowt et al. 2020). Another multispecies experiment established that while soil fauna may aid in native ecosystems' resistance to alien plant invasions, this benefit may be diminished during periods of drought (Jin et al. 2022).

Even though we now understand more about how different environmental conditions affect the process and distribution of invasive plant species, there are still many information gaps. To make precise predictions about the possible effects of invaders, ecologists must develop frameworks that take species' abundance and not just their presence into account (Funk et al. 2020). Additionally, it is crucial to comprehend how the local plant communities adapt to climate change and whether this results in increased or decreased resistance to invasion. According to Luan et al. (2021), a mechanistic and more accurate prediction regarding the impact of plant invaders on ecosystem functioning can be provided by interpreting changes in macrofauna, along with their relationship with litter traits under changing climatic conditions in comparison to a sole functional trait-based approach. Also, instead of climate extremes, research has mostly concentrated on how species would react to average changes in climatic parameters. Through a number of understudied mechanisms, extreme climatic events (such as floods and droughts) can increase the acclimatization, spread, and effects of invasive species, and such detailing needs more attention from researchers worldwide (Diez et al. 2012). Furthermore, predictions on invasion trends of exotic plants along with simulation of suitable plantations that can block invasion can be of high practical significance for the anticipation and management of plant invasion (Fang et al. 2021). Using a combination of computational modelling and experimental research methods to create predictions about the potential trait adaptations, niche-width expansion, and favourable recruitment sites for invasive plants might serve as the most pragmatic, rational, and reliable approach to deal with the issue (Guerra-Coss et al. 2021).

1.6 Conclusions

Plant invasion is a significant driver of environmental change on a worldwide scale. Invasive species damage invaded locale in a way that triggers a series of ecological changes, which end up modifying most of the habitat components and consequently altering the landscape, productivity, resistance, and resilience of an ecosystem. These threats posed by invasive plants will probably grow as a result of the existing paradigm of global climate change. By altering the seasonal patterns, particularly in the most fragile ecosystems that provide crucial ecosystem services, climate change has the potential to generate conditions and localities in the future that are more conducive for invading species. Therefore, it is imperative for conservation managers to provide a framework for accurately predicting and managing alien plant invasions and/or reducing their cascading impacts on the local biodiversity and ecology. Future studies should concentrate on the mechanisms, complex interactions, and positive/negative feedbacks by which extreme climatic events can hasten the distribution, establishment, and consequences of invasive alien plants and vice-versa.

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