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REVIEW ARTICLE

Impact of climate change on invasive weeds affecting biodiversity and natural ecosystems

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ABSTRACT

Invasive weeds pose a growing threat to biodiversity and natural ecosystems, a challenge that is escalating with climate change. These resilient plants, marked by rapid growth and adaptability, outcompete native species, disrupt ecological balances, and alter critical ecosystem functions. As climate change progresses, rising temperatures along with CO_2 and shifting precipitation patterns create favorable conditions for invasive weeds to proliferate, often at the expense of native flora. The ecological consequences of these invasions are profound, leading to the displacement of native species, altered species composition, and a significant reduction in biodiversity. Herbivores, pollinators, and other wildlife are increasingly affected as their habitats and food sources are transformed by the spread of invasive plants. Additionally, the disruption caused by these weeds extends to essential ecosystem functions, including nutrient cycling, soil health, and water regulation. The management of invasive species is becoming increasingly complex due to the unpredictability of climate change. In response, adaptation strategies, such as integrated pest management (IPM), are being developed to address these evolving challenges. Predictive models and scenario analyses are providing valuable insights into potential future risks, while effective management increasingly relies on robust policies and public engagement. Despite these efforts, significant research gaps persist, particularly in understanding the long-term impacts of invasive weeds and in developing effective restoration strategies for ecosystems already compromised by their spread.

Keywords: Climate change, Biodiversity, Invasive weeds, Natural ecosystem

INTRODUCTION

Plant invasions are often facilitated by human activities such as global trade, horticulture, and agriculture, sets the stage for a dynamic and often destructive competition with native flora (Charles and Dukes 2007, Pysek *et al.* 2020, Aguin-Pombo 2012, Mashhadi and Radosevich 2004). In their native habitats, plants co-evolve with local species, maintaining ecological balance. However, in new environments, invasive weeds often escape their natural predators and diseases, giving them a competitive edge (Wang *et al.* 2009). Their rapid growth, high reproductive rates, and adaptability enable them to quickly establish, spread, and outcompete native plants for essential resources like light, water, and nutrients (Daehler 2003) which results in significant ecological consequences like reduced biodiversity and disrupted food webs (Ehrenfeld 2003, Ngondya 2017, Narango *et al.* 2018). Major invasive weeds and their ecosystem impacts have been depicted in **Table 1**.

Invasive species may fail to stabilize soil as effectively as native plants, leading to increased erosion and altered hydrological cycles due to changes in water infiltration and runoff. Furthermore, invasive weeds can alter soil chemistry, rendering it less suitable for native species (Weidenhamer and Callaway 2010). These weeds also significantly impact fire regimes and habitat structures, contributing to widespread ecological and infrastructural challenges. *Bromus tectorum*, for instance, increases the frequency and intensity of wildfires by creating a continuous layer of fine, easily ignitable fuel, leading to the destruction of native plant communities and a cycle that favors further invasion (Bradley *et al.* 2018). Dense stands of invasive plants block sunlight, inhibiting understory growth and

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Table 1. Global overview of major invasive weeds and their ecosystem impacts

Country	Invasive weed	Species	Family	Ecological impact	Reference
India	Lantana	*Lantana camara*	Verbenaceae	Forms dense thickets, outcompetes native vegetation, releases allelopathic chemicals, reduces habitat quality for native wildlife, and invades pastures and croplands.	Dar *et al*. 2019
India	Chromolaena	*Chromolaena odorata*	Asteraceae	Rapid growth smothers native vegetation, reduces biodiversity, alters fire regimes, and impacts forest regeneration.	Dar *et al*. 2019
India	Congress Grass	*Parthenium hysterophorus*	Asteraceae	Outcompetes native vegetation, reduces agricultural productivity, and causes health problems in humans and animals.	Dar *et al*. 2019
India	Water Hyacinth	*Eichhornia crassipes*	Pontederiaceae	Forms dense mats on water surfaces, blocks sunlight, depletes oxygen levels, kills aquatic organisms, impedes water flow, and provides breeding grounds for mosquitoes.	Dar *et al*. 2019
India	Mikania	*Mikania micrantha*	Asteraceae	Rapid growth overwhelms native vegetation, decreases biodiversity, and interferes with ecosystem functions.	Dar *et al*. 2019
India	Goat weed	*Ageratum conyzoides*	Asteraceae	Rapid growth chokes out native vegetation, diminishes biodiversity, and changes habitat structures.	Dar *et al*. 2019
India	Mesquite	*Prosopis juliflora*	Fabaceae	Outcompetes native vegetation, forms thick mats, diminishes grazing areas for livestock, modifies soil chemistry, and escalates water consumption.	Dar *et al*. 2019
India	Mimosa	*Mimosa pudica*	Fabaceae	Surpasses native vegetation, dense mats are formed, diminishes biodiversity, and affects agricultural lands. 4o mini	Dar *et al*. 2019
India	Morning Glory	*Ipomoea* spp.	Convolvulaceae	Smothers native vegetation by rapid spread, reduces biodiversity, and alters habitat structures.	Dar *et al*. 2019
United States	Kudzu	*Pueraria montana*	Fabaceae	Diminishes biodiversity, overwhelms native plants depletes soil nutrients and water, and disrupts habitat structures.	Marler 2000
United States	Cheatgrass	*Bromus tectorum*	Poaceae	Alters fire regimes by increasing frequency and intensity of wildfires, Forms dense monocultures, surpasses native grasses and reduces native plant populations.	Marler 2000
United States	Purple Loosestrife	*Lythrum salicaria*	Lythraceae	Invades wetlands, outcompetes native vegetation, reduces habitat quality for wildlife, and disrupts water flow and sedimentation patterns.	Marler 2000
United Kingdom	Japanese Knotweed	*Fallopia japonica*	Polygonaceae	Damages infrastructure with robust root systems Forms dense thickets that crowd out native plants, destabilizes riverbanks, and increases erosion.	Shaw *et al.* 2011
Australia	Lantana	*Lantana camara*	Verbenaceae	Releases allelopathic chemicals, Forms dense thickets, outcompetes native vegetation, reduces habitat quality for native wildlife, and invades pastures and croplands.	Shaik *et al.* 2022
Australia	Prickly Pear	*Opuntia* spp.	Cactaceae	Forms impenetrable thickets, outcompetes native vegetation, alters habitat structure, and reduces grazing land for livestock.	Shaik *et al.* 2022
South Africa	Water Hyacinth	*Eichhornia crassipes*	Pontederiaceae	Forms dense mats on water surfaces, blocks sunlight, depletes oxygen levels, kills aquatic organisms, impedes water flow, and provides breeding grounds for mosquitoes.	Zimmermann *et al.* 2004
South Africa	Black Wattle	*Acacia mearnsii*	Fabaceae	Outcompetes native vegetation, Forms dense stands, reduces water availability, and alters fire regimes.	Zimmermann *et al.* 2004
New Zealand	Old Man's Beard	*Clematis vitalba*	Ranunculaceae	Smothers native trees and shrubs, reduces biodiversity, and alters habitat structure.	Ogle *et al.* 2000
Brazil	African Tulip Tree	*Spathodea campanulata*	Bignoniaceae	Outcompetes native vegetation, reduces biodiversity, and alters habitat structure.	Pimenta *et al.* 2020
China	Mile-a-Minute Weed	*Mikania micrantha*	Asteraceae	Rapid growth smothers native vegetation, reduces biodiversity, and disrupts ecosystem functions.	Zhang *et al.* 2004
Canada	Common Reed	*Phragmites australis*	Poaceae	Establishes dense stands in wetlands, outcompetes native plants, diminishes habitat quality for wildlife, and disrupts hydrology and sedimentation patterns.	Catling, and Mitrow 2011
Mexico	Yellow Star-Thistle	*Centaurea solstitialis*	Asteraceae	Invades pastures and rangelands, outcompetes native plants, reduces forage availability for livestock, and increases management costs.	Grimsrud *et al.* 2008
Kenya	Prosopis	*Prosopis juliflora*	Fabaceae	Forms dense thickets, outcompetes native vegetation, reduces grazing land for livestock, alters soil chemistry, and increases water use.	Gichua 2014
Russia	Sosnowsky's Hogweed	*Heracleum sosnowskyi*	Apiaceae	Creates dense stands, outcompetes native vegetation, lowers biodiversity, and its toxic sap can cause severe skin burns and blindness in humans.	Chadin *et al.* 2017
Indonesia	Siam Weed	*Chromolaena odorata*	Asteraceae	Rapid growth smothers native vegetation, reduces biodiversity, and alters habitat structure.	Tjitrosoedirdjo *et al.* 1991
Philippines	Cogon Grass	*Imperata cylindrica*	Poaceae	Forms thick mats, outcompetes native vegetation, decreases biodiversity, and increases fire risk.	Walpole 2005
Sri Lanka	Salvinia	*Salvinia molesta*	Salviniaceae	Forms dense floating mats, reduces light penetration, depletes oxygen in water bodies, and harms aquatic ecosystems.	Kariyawasam *et al.* 2021
Zimbabwe	Water Lettuce	*Pistia stratiotes*	Araceae	Creates dense mats on water surfaces, obstructs sunlight, depletes oxygen, and disrupts aquatic ecosystems.	Mujaju *et al.* 2021
Thailand	Mimosa Pigra	*Mimosa pigra*	Fabaceae	Outcompetes native vegetation, establishes dense stands, decreases biodiversity, and disrupts wetland ecosystems.	Pramual *et al.* 2011
Egypt	Giant Reed	*Arundo donax*	Poaceae	Increases fire risk, alters riverbank habitats, forms dense stands, and outcompetes native vegetation.	Galal and Shehata 2016
Fiji	Koster's Curse	*Clidemia hirta*	Melasto-mataceae	Forms dense thickets, displaces native vegetation, reduces biodiversity, and disrupts forest regeneration.	Conant 2009
Nigeria	Tithonia	*Tithonia diversifolia*	Asteraceae	Displaces native vegetation, changes soil chemistry, and affects agricultural productivity.	Ayeni *et al.* 1997

reducing plant diversity, which in turn affects animals dependent on the understory for food and shelter. In aquatic environments, invasive species like *Eichhornia crassipes* clog waterways, disrupting water flow and quality, reducing oxygen levels, and harming aquatic life (Yigermal and Assefa 2019). Additionally, *Fallopia japonica* can cause severe infrastructure damage by penetrating foundations and pavement with its roots, leading to costly repairs. Invasive aquatic weeds also clog pipes and irrigation systems, resulting in significant maintenance and repair expenses (Docking 2024).

Invasive weeds spread and establish themselves through various natural and human-induced mechanisms. They use wind, as seen with *Taraxacum* spp. and *Cirsium* spp., which have lightweight seeds with plumes or wings for easy dispersal (Abbas *et al.* 2023). Water-dispersed species like *E. crassipes* spread through currents in rivers and lakes, while animals contribute by transporting seeds on their fur or in their digestive tracts, with birds, mammals, and insects playing key roles (da Cunha *et al.* 2022). Human activities further exacerbate their spread: contaminated agricultural products, transportation methods such as vehicles, ships, and planes, and global trade facilitate the movement of seeds and plant fragments (Perrault *et al.* 2003). Horticulture and landscaping practices, exemplified by *F. japonica* and *Lythrum salicaria*, can lead to the escape of ornamental plants into the wild (Donahue 2017). Vegetative reproduction through rhizomes, stolons, or tubers allows species like *F. japonica* to quickly form dense stands, while aquatic weeds such as *Hydrilla verticillata* can grow from small fragments. Invasive weeds also exhibit high phenotypic plasticity, adapting to diverse environmental conditions and rapidly outcompeting native species (Stahlman 2016). Some use allelopathy, releasing chemicals that inhibit the growth of surrounding plants, as seen with *Juglans nigra* and *Alliaria petiolate* (Srivasava *et al.* 2017). They often colonize disturbed habitats such as roadsides and construction sites, establish quickly before native species can recover, and thrive in post-fire environments by rapidly germinating in nutrient-rich ash. Additionally, escaping natural predators and diseases from their native ranges, combined with traits that confer resistance to local pests, and hybridization with local or introduced species further enhance their invasiveness (Daly *et al.* 2023). This amalgamation of dispersal methods, reproductive strategies, adaptability, and lack of natural enemies facilitates their successful colonization and dominance in new environments.

Climate change and its effects on invasive weeds

Global climate change has profound implications for ecosystems, particularly through its effects on invasive weeds. (Ramesh *et al.* 2017, Finch *et al.* 2021). Warmer temperatures hasten the growth rates of invasive weeds due to extended growing seasons and increased physiological processes like photosynthesis and respiration. For instance, *Pueraria montana var. lobata* in the southeastern United States grows more rapidly with rising temperatures, smothering native vegetation and lessening biodiversity (Kato-Noguchi 2021). Similarly, *Lepidium latifolium* and *Arundo donax* display enhanced growth and competitiveness in warmer conditions. These temperature-driven changes enable invasive weeds to outpace native species and rapidly dominate new areas (Jimenez-Ruiz *et al.* 2016). Increased rainfall benefits species like *Heracleum mantegazzianum* and *F. japonica*, which thrive in moist conditions and expand their range by monopolizing water resources (Seeney 2018, Marigo and Pautou 1998). In contrast, drought-tolerant species such as *Cenchrus ciliaris* and *B. tectorum* gain a benefit in arid regions, where they outcompete native plants, alter fire regimes, increase soil erosion, and degrade ecosystem services (Walther 2019). Water hyacinth also showed increased flowering and seed production rates under higher temperatures, contributing to their spread in freshwater systems (Yan *et al.* 2017). The shift in climatic conditions transforms previously unsuitable regions into promising environments for these invasive species. For example, *Lythrum salicaria,* a native of Europe has moved northward in North America, threatening wetlands, while *C. ciliaris* has migrated to higher elevations, altering fire regimes and diminishing native plant diversity (Harper-Lore *et al.* 2007).

Storms, floods, and droughts can spread aquatic weeds such as *Eichornia. crassipes* and *Hydrilla. verticillata*, leading to the formation of dense mats that block sunlight, deplete oxygen, and disrupt water flow, thereby collapsing native aquatic ecosystems (Ta *et al.* 2017). In terrestrial situations, shifting wind patterns and animal behavior further facilitate the spread of invasive seeds. For instance, seeds of *Arundo donax* and *Tamarix* spp. are dispersed more widely by wind and water as temperatures rise (Gonzalez *et al.* 2017). Increased atmospheric CO_2 increases photosynthesis, resulting in higher biomass production for invasive species like *Pueraria montana var. lobate* and *Cirsium arvense,* which outcompete native plants for resources and form dense stands that alter habitats (Ziska 2011). Higher

CO_2 favors water-use efficiency by reducing stomatal conductance, benefiting arid-adapted species such as *B. tectorum* and *C. ciliaris*, allowing them to flourish during dry periods and outperform water-sensitive natives (Dukes and Mooney 1999), which leads to changed hydrological cycles and more intense fire regimes, impacting water availability and soil properties, eventually compromising ecosystem health (Ryan *et al.* 2012).

Severe storms, hurricanes, and floods significantly enable the spread of invasive weeds like seeds of *A. donax* and *Tamarix* spp. over long distances, aiding their colonization in new areas and *Triadica sebifera* colonized in the Gulf Coast after Hurricane Katrina (Felger *et al.* 2013, Henkel *et al.* 2016). Floods aggravate this issue by dispersing seeds and vegetative fragments like *E. crassipes* and *Salvinia molesta* to form dense mats that choke native plants and disrupt water quality favor species like *F. japonica*, which rapidly colonizes riparian zones and alters riverbank stability (Akpabey 2012, Rapp 2006). Drought's stress makes native vegetation vulnerable to drought-tolerant invasives like *B. tectorum C. ciliaris C. solstitialis* and *Salsola tragus* (Schmitz and Jacobs 2007) (**Figure 1**). To mitigate these effects and preserve ecosystem health, it is crucial to develop and implement adaptive management strategies that address the complex dynamics of invasive weeds in a rapidly evolving climate.

Interactions between climate change and invasive weed management

In recent years, climate change has significantly impacted both natural and human ecosystems, with agriculture (Ainsworth and Long 2005, Chauhan *et al.* 2014, Kang and Banga 2013). Shifts in weather patterns affect all components of agricultural systems, especially weeds, and their management (Ramesh *et al.* 2017). However, in agricultural ecosystem, weeds and crops coexist, requiring a more integrated method to understanding their interactions under changing climate conditions (Chauhan *et al.* 2014, Kang and Banga 2013). Prevention is better than cure, and weed management should be supported by comprehensive prevention measures. To manage this, countries must conduct risk assessments for national planning to address new threats from invasive weeds (Chandrasena 2009). Gathering data through local and regional surveys, sharing data on the distribution and abundance of potential invasive weeds, and enhancing border protection via quarantine are crucial preventive steps.

Cultural control strategies, such as adjusting sowing times to create a less weedy environment, have proven effective in reducing weeds like *Phalaris minor* and *Avena fatua* in North India. Incorporating climate-smart, weed-suppressing crops into cropping systems can further help manage invasive weeds (Jinger *et al.* 2016). Furthermore, developing new crop varieties with higher yield potential and resilience

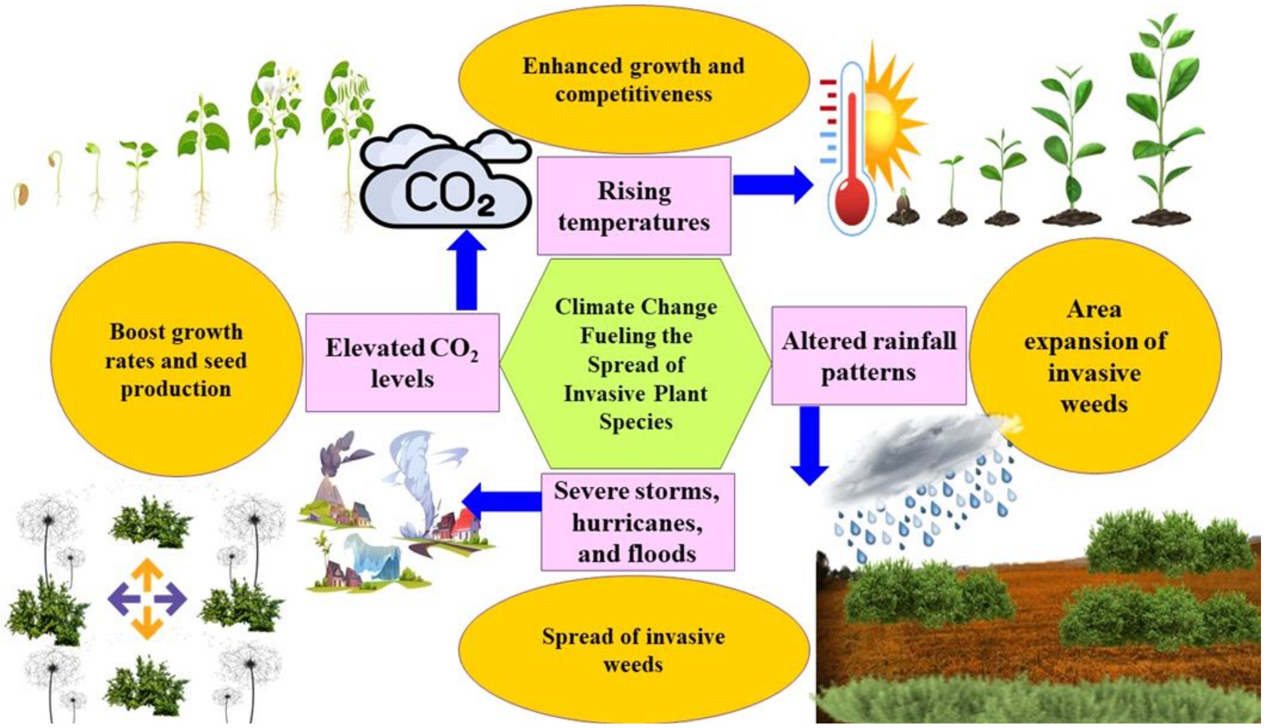

Figure 1. Visual representation of climate change impacts on invasive weed dynamics

to changing climatic factors, such as drought and elevated CO_2 levels, will enhance weed management.

Mechanical control is widely used for managing invasive weeds in developing countries. However, climate change can complicate this method by altering the root-to-shoot ratio in plants. For example, elevated CO_2 can lead to increase below-ground carbon storage and growth in perennial invasive weeds like *Lantana* spp., making its mechanical control more challenging (Rogers *et al.* 1994) and such as *Chondrilla juncea* and *Solanum elaeagnifolium* (Ziska *et al.* 2004, Kriticos *et al.* 2010).

Biological control success of bioagents relies on their ability to feed exclusively on the target weed (Kriticos *et al.* 2010). However, climate change can impact the efficacy of these biological control agents by altering their biology or the ability of the host weed to tolerate or resist herbivores or pathogens (Singh *et al.* 2016). Elevated CO_2 can also change the profile of secondary compounds in weeds, affecting weed-herbivore interactions (Ziska *et al.* 2005), and changes in the carbon-to-nitrogen (C: N) ratio in weeds (Malarkodi *et al.* 2017). Drought conditions may increase the levels of insect-resistant allelochemicals in some weed species (Gerard *et al.* 2010), and can alter the distribution of both invasive weeds and their biological control agents. For example, with elevated temperatures potentially causing bioagents to move from subtropical to temperate regions, affecting their efficacy (Reeves 2017). Thus, as invasive weeds and their biological control agents respond differently to various climate change factors (Holt and Hochberg 1997). Kumar *et al.* (2021) when offered leaves of Parthenium grown in open top under elevated CO_2 and temperature *Zygogramma bicolorata* recorded increase in consumption, slower food conversion rates, increase in developmental period with reduced reproduction efficiency. They interpreted that the reproduction efficiency of *Z. bicolorata* is likely to be reduced as the climate changes, despite increased feeding rates exhibited by grubs and adult beetles on parthenium weed foliage.

The use of novel herbicide molecules to control invasive weeds is considered one of the most cost-effective methods and are now widely used in managing invasive weeds (Clout and Williams 2009; Radosevich *et al.* 2007). However, the success of herbicide-based weed management profoundly depends on climatic situations, particularly for foliage-applied post-emergence herbicides (Kudsk and Kristensen 1992, Ziska 2020). Climate factors like temperature, CO_2 levels, soil moisture, and wind speed can significantly influence herbicide coverage, persistence, mode of action, efficacy, selectivity, herbicide volatility, altering selectivity for both pre- and post-emergence herbicides (Madafiglio *et al.* 2000, Medd *et al.* 2001, Bailey 2004). Higher temperatures may hasten plant growth, narrowing the window for effective herbicide application before the critical crop-weed competition period begins (Howden *et al.* 2007).

Predictive modeling of invasive weed dynamics

An ecological model is any form of simplification of the relationship between a species and its environment (Kriticos 1996). Ecological niche models (ENMs) are used to predict suitable ecological niches for a species across a landscape and niche concept is central to ENMs and is based on Hutchinson's (1957) concept of fundamental and realized niches (Araujo and Guisan 2006). There is a risk of invasion in the unoccupied part of the fundamental niche of introduced range (Soberon and Nakamura 2009). Ecologists have used ecological niche models (ENMs) to map suitable areas for potential invaders to guide conservation and management strategies (Gama *et al.* 2017). These models found correlations among environmental conditions and species occurrence records to identify suitable climatic conditions (Broennimann *et al.* 2012). It has been highlighted that invasive species often show a wider range of climatic conditions during the invasion process, than those described in their areas of origin (Rodrigues *et al.* 2016). Thus, in order to capture a major part of suitable conditions for the invader, ENMs must be calibrated bearing in mind both the native and invasive geographic ranges of the species (Sales *et al.* 2017). To effectively study the impact of climate change on invasive weeds, several decision support tools have been successfully utilized.

Policy and legislation

Nearly 50 international legal instruments or guidelines deal with some aspects of invasive alien species including invasive weeds (IAS),) prevention or management. They provide a baseline for national legal frameworks. The longest-established agreements focus on controlling the introduction and spread of pests and diseases to protect animal and plant health by means of quarantine systems. The International Plant Protection Convention and policy guidelines by IUCN. Biodiversity-related tools focus on IAS threats to native species and ecosystems. e.g. CBD, CITES and particularly Biodiversity Act 2002 in India. Technical guidelines and codes of conduct are also there to minimize risks of unwanted introductions through specific transport or trade pathways. It includes WTO's SPS agreement. Of these, the important ones are discussed briefly below.

- The International Plant Protection Convention offers a framework for international cooperation to prevent the spread of pests of plants and plant products between countries and to help appropriate measures for their control within countries. Hence, IAS of weeds are covered by the IPPC as they qualify as pests of plants or plant products (Shine 2024)
- United Nations Convention on the Law of the Sea (1982) works for the marine environment, introductions of non-native species are covered in a general way (Article 196).
- Ramsar Convention on Wetlands sees after coastal and inland wetlands, parties to the Ramsar Convention on Wetlands are urged to address issues relating to invasive alien species in a decisive and holistic manner, making use of tools and guidance developed by various institutions and under other conventions (resolution VIII.18, November 2002).
- United Nations Environment Programme (UNEP) under Regional Seas Programme in Annex V of the Convention for the Protection of the Marine Environment of the North-East Atlantic (1992) provides for listing and management of human activities capable of causing adverse impacts on the marine environment, including introductions of alien or genetically modified species.
- UN Sustainable Development Goal 15, concerned with life on land states its target 15.8 to "reduce the impact of invasive alien species on land and water ecosystems and control or eradicate the priority species." The measure for the accomplishment of this target is the "proportion of countries adopting relevant national legislation and adequately resourcing the prevention or control of IAS (Shine *et al.* 2000)
- Legislation relating to IAS in India works on the Prevention and Control of Infectious and Contagious Disease in Animals Act 2009; The Plant Quarantine (Regulation of Import into India) Order, 2003; The Destructive Insects and Pests Act, 1914 and amendments; The Plants, Fruits & Seeds (Regulation of Import into India) Order 1989 (PFS Order 1989); Livestock Importation Act, 1898 and the Livestock Importation (Amendment) Ordinance, 2001; Environment Protection Act, 1986; The Biological Diversity Act, 2002; Indian Forest Act, 1927; Wildlife (Protection) Act, 1972 ; Forest (Conservation) Act, 1980

Regional focus: Climate change has significantly impacted weed spreading and behavior in various ways. The expansion of thermophile weeds, such as *Amaranthus retroflexus*, *Abutilon theophrasti*, *Panicum dichotomiflorum*, and *Datura stramonium*, has been observed in more northern regions of Europe (Guillerm *et al.* 1990, Breitsameter *et al.* 2014). Additionally, late-emerging weeds like *Chenopodium* spp., and millet weeds including *Echinochloa* spp., *Setaria* spp., *Digitaria* spp., and *Sorghum halepense*, have also extended their distribution ranges (Mehrtens *et al.* 2005, Otte *et al.* 2006). In the past two decades, Greenland and Antarctic ice sheets have been losing mass, and global glaciers are shrinking [IPCC 2013]. Climate change could shift climatic zones significantly, for example Mediterranean climates will move northward, and deserts could advance 400-800 km north into subtropical regions.

Research and knowledge gaps

Although, it is well-established that climate change can aggravate the spread and impact of invasive species, the specific mechanisms by which these factors interact, mainly in different types of ecosystems, are not fully understood. There is a need for more research on how unstable climate patterns influence the phenology of invasive species relative to native species, which could provide insights into the timing and effectiveness of management interventions (Panda *et al.* 2018). Another less-researched area is the role of invasive weeds in altering ecosystem services under changing climatic conditions (Mainka and Howard 2010). For instance, research is needed to determine how invasive plants like *P. hysterophorus* in India might affect soil carbon storage in agricultural and forested landscapes under varying climatic scenarios. (Ahmad *et al.* 2019). One capable area of research is the development of predictive models that integrate climate change projections with the potential spread and impact of invasive species (Smith *et al.* 2012). Another important research direction involves exploring the genetic and physiological adaptations of invasive species to changing climates. For example, studying the genetic diversity and adaptive traits of *L. camara* in various regions of India could reveal insights into how this invasive species might respond to future climate conditions, enabling more precise and effective management strategies (Bhagwat *et al.* 2012).

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