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Article

Emerging Threats in a Warming Ocean: Climate-Driven Spread of Marine Invasive Species and Regional Biosecurity Gaps

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ABSTRACT

Climate change is rapidly reshaping oceanographic conditions, expanding ecological windows for marine invasive species (MIS) through warming, altered circulation, acidification, and deoxygenation. These shifts are amplifying invasion pressure across biogeographic boundaries, destabilizing native ecosystems and threatening fisheries, coastal protection, and blue carbon storage. Here, we synthesize evidence across four domains such as climate drivers, invasion pathways, ecological impacts, and governance responses to evaluate how climate change is fundamentally altering marine invasion dynamics. This review identifies three critical global gaps: (i) the absence of climate-integrated biosecurity metrics capable of anticipating future invasion risk, (ii) limited early-warning thresholds linking environmental change to invasion probability, and (iii) weak regional coordination across shared marine pathways, particularly in semi-enclosed seas and climate-sensitive regions. Despite growing policy attention, most existing biosecurity frameworks remain static and reactive, poorly aligned with accelerating climate variability. To address these gaps, we propose a climate-smart marine biosecurity framework that integrates molecular surveillance (e.g., eDNA), dynamic risk modeling, and predictive monitoring aligned with Sustainable Development Goals and emerging global biodiversity targets. By reframing MIS management as a core component of climate adaptation rather than a standalone conservation issue, this review provides an operational pathway to shift biosecurity from post-invasion response toward anticipatory, climate-informed prevention. The urgency of this transition is underscored by the rapid emergence of new invasion corridors and the narrowing window for effective intervention in a warming ocean.

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Research Highlights

- Evidence across four domains to evaluate how climate change is fundamentally altering marine invasion dynamics.
- Proposal of a new climate-smart marine biosecurity framework aligned with Sustainable Development Goals and emerging global biodiversity targets.
- Operational pathway to shift biosecurity from post-invasion response toward anticipatory, climate-informed prevention.

1. Introduction

Marine invasive species (MIS) are among the leading drivers of ecological disruption and biodiversity loss in the ocean [1]. Once established, MIS restructure food webs, displace native species, disrupt biogeochemical cycles, and introduce new pathogens, reducing ecosystem resilience and degrading ecosystem services [2]. Human activities, especially global shipping, ballast water discharge, and hull fouling, have markedly accelerated MIS introductions, while aquaculture, the aquarium trade, and maritime infrastructure expansion serve as ongoing secondary vectors [3]. Climate change now acts as a compounding force, intensifying the probability of establishment, spread, and ecological dominance of MIS [4]. Rising sea surface temperatures (SST) (0.13 $\pm$ 0.01 °C per decade; 1982–2023) expand the thermal tolerance envelope for warm-adapted invaders, enabling poleward range shifts and year-round survival in once-inhospitable regions [5, 6]. The ocean warming rate for the upper 2000 m is 0.58 $\pm$ 0.1 W m^{-2} (1960–2023), increasing to 1.05 $\pm$ 0.2 W m^{-2} since 2005 [6]. Arctic sea ice extent is shrinking; annual mean extent is declining by $-$4.33% per decade, and September (summer) ice by $-$12.64% per decade. The Arctic Ocean surface has warmed by about 4.37 °C since 1982. Similarly, after earlier slight increases, Antarctic sea ice has shifted to a new low state, with record lows in 2022–2023 [6]. The share of the global ocean experiencing at least one marine heatwave (MHW) each year has jumped from $\sim$50% in the 1980s to $\sim$80% now. Areas affected by strong MHWs have doubled (from about 20% to $\sim$40%), and average maximum duration has doubled from $\sim$20 to $\sim$40 days since $\sim$2008 [6].

Ocean acidification and deoxygenation stress native calcifiers and oxygen-sensitive species, while favoring opportunistic invaders like jellyfish, macroalgae, and filter-feeding tunicates [7, 8]. Global surface ocean pH is decreasing at $-$0.017 pH units per decade (1985–2022) [6]. Mean pH has dropped by about 0.06 units (from 8.11 to 8.05) since 1985, corresponding to roughly a 30% increase in acidity [6]. Climate-driven shifts in ocean currents, intensified storms, and sea-level rise are also reshaping long-distance dispersal, especially along shipping routes and emerging Arctic pathways [4, 9]. Global mean sea level has risen by more than 10 cm since 1993, with the rate increasing from 2.1 mm yr^{-1} (1993–2002) to 4.5 mm yr^{-1} (2013–2023) and an overall trend of 3.4 $\pm$ 0.3 mm yr^{-1}, indicating clear acceleration [6, 10]. For the Atlantic Meridional Overturning Circulation (AMOC), observations and reanalyses show large interannual to decadal variability but no statistically robust long-term decline over 1993–2023; however, model and proxy evidence point to a potential weakening under continued greenhouse-gas forcing, and its future trajectory remains actively debated [9]. Marine invasions have thus shifted from isolated events to systemic responses in a rapidly changing ocean [11].

Marine invasions carry substantial ecological and economic costs, harming fisheries, degrading infrastructure, reducing blue carbon storage, and threatening marine-dependent livelihoods [12–14]. Global estimates place the economic burden of biological invasions at a minimum of US$1.288 trillion worldwide between 1970 and 2017, with an average of US$26.8 billion per year [15]. Most of this cost comes from damages and losses (US$892.2 billion) rather than management spending (US$66.3 billion), and modeling suggests that annual global costs have continued to rise, reaching an estimated US$46.8–162.7 billion in 2017 alone [15]. The IPBES Invasive Alien Species Assessment (2023) attributes about 60% of global animal extinctions to invasive species, which also impose disproportionately high costs on Small Island Developing States (SIDS) and developing coastal economies [16]. Furthermore, policymakers increasingly recognize invasive species as major barriers to climate adaptation and resilience, spurring targeted policy responses [17]. Target 6 of the Kunming–Montreal Global Biodiversity Framework aims to reduce the rate of new species introductions by 50% by 2030 [18, 19]. The International Maritime Organization's Ballast Water Management Convention mandates onboard treatment systems to limit species transfers [20, 21]. Despite such measures, implementation remains uneven, particularly in countries lacking strong biosecurity infrastructure, real-time surveillance, or legal frameworks for rapid response [22]. Notably, global targets such as the Kunming–Montreal Target 6 omit explicit climate change considerations, potentially overlooking climate-amplified invasion risks [23].

Although numerous regional and thematic reviews address marine invasive species, there is still no unified global framework that explicitly integrates climate-driven amplification, SDG alignment, and governance reform in a single, coherent approach [3]. In response, this review synthesizes recent evidence on climate-driven MIS establishment, highlights key weaknesses in governance, surveillance, and response systems, and proposes a climate-smart biosecurity framework [24]. This proposed framework aligns with SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 14 (Life Below Water), as well as the Kunming–Montreal Global Biodiversity Framework and the UN Decade of Ocean Science. By linking ecological mechanisms such as warming-driven range shifts and oceanographic changes to concrete policy and management levers, the framework shifts MIS management from reactive containment to an anticipatory, integrated approach [25]. The goal is to establish a system that safeguards marine biodiversity and ecosystem services in an increasingly warm and interconnected ocean.

2. Review Scope and Synthesis Approach

This review is based on a structured synthesis of documents retrieved through Scopus using advanced keyword queries linking marine invasive species with climate drivers, invasion pathways, and biosecurity or governance dimensions. The core Scopus query yielded 868 documents, supplemented by targeted queries focusing on climate-amplified invasion vectors and pathways (81 documents), early-warning and molecular surveillance approaches including environmental DNA (139 documents), and predictive risk assessment and modeling tools such as species distribution models and machine-learning applications (164 documents). These Scopus-retrieved documents formed the primary evidence base for the review and were examined thematically to identify patterns, gaps, and convergent insights across marine systems. In addition, major global assessment and policy reports from the Intergovernmental Panel on Climate Change (IPCC), the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (IPBES), and the International Maritime Organization (IMO) were referred to in order to contextualize scientific findings within current global climate, biodiversity, and biosecurity frameworks. Evidence was synthesized across five domains such as climate drivers, invasion vectors, ecological and socio-economic impacts, governance gaps, and emerging biosecurity solutions.

3. Climate Change as a Catalyst for Marine Invasions

Climate change is now widely recognized as a key driver of marine species redistribution, accelerating the global spread and establishment of invasive species [26, 27]. By altering temperature, chemistry, and circulation, it erodes environmental barriers that once constrained non-native taxa [28]. These abiotic shifts disproportionately benefit ecological generalists and opportunistic invaders, particularly in disturbed or low-diversity systems, while facilitating both natural and human-mediated dispersal [29] (Figure 1).

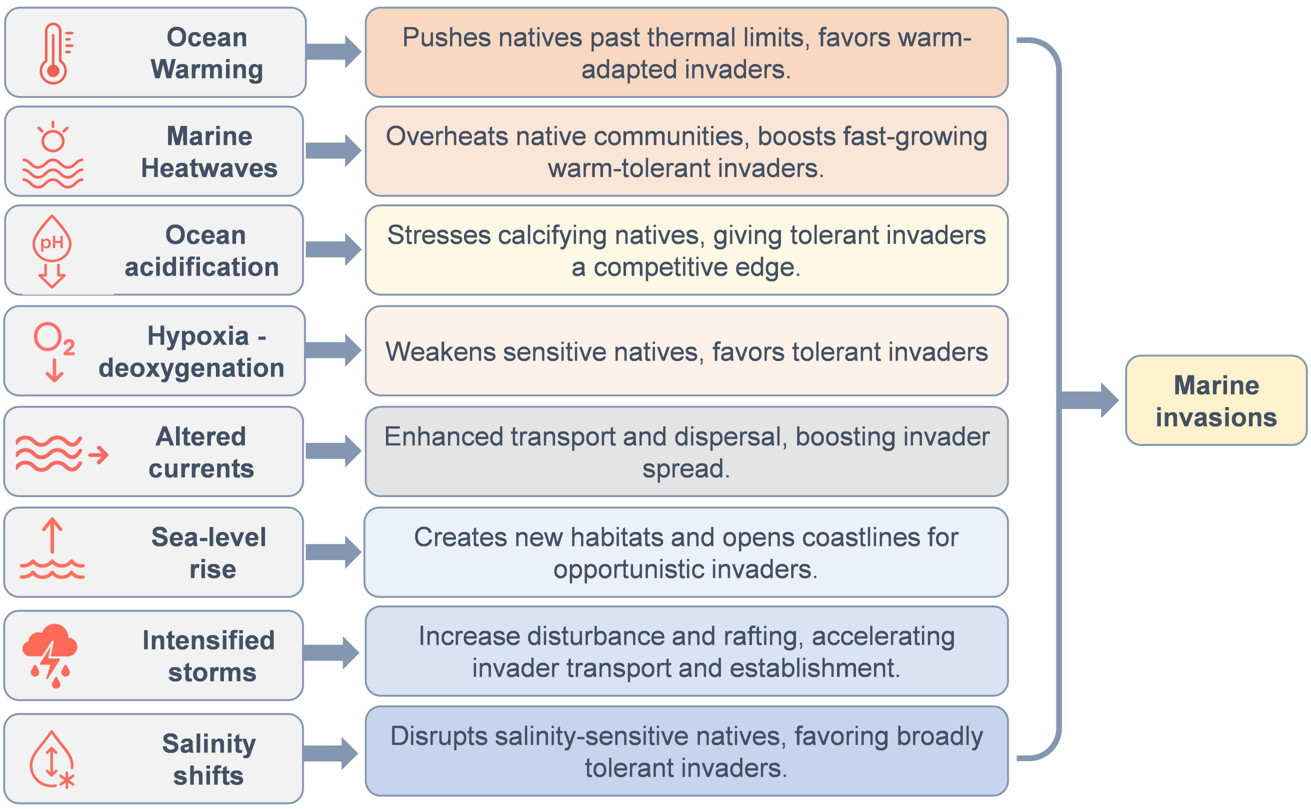

Figure 1. Climate-change drivers and their mechanistic pathways that facilitate marine invasions.

3.1. Mechanistic Drivers of Climate-Enhanced Invasion

(i) Thermal niche expansion: Warming sea surface temperatures (SSTs) reduce physiological constraints on growth, reproduction, and overwintering in warm-adapted species, enabling poleward range shifts [30]. These shifts are especially evident in semi-enclosed seas and western boundary current regions, where SST rise exceeds the global mean. Thermal range expansion often coincides with declines in native cold-water taxa, weakening biotic resistance and enhancing invasion success [31, 32]. The kelp species *Undaria pinnatifida* (Asian kelp) has proliferated across the North Atlantic and Pacific via marina fouling and aquaculture, thriving in warmer winters and outcompeting native kelps through space monopolization and phenological plasticity [33].

(ii) Chemical stress gradients: Ocean acidification and deoxygenation, both driven by elevated atmospheric CO_2, intensify physiological stress on native species such as calcifiers and stenotherms, while favoring stress-tolerant invaders [34]. Acidification weakens shells and reduces larval viability in corals and molluscs, while hypoxia constrains aerobic scope and impairs reproduction in fish and crustaceans [35, 36]. These stressors alter competitive dynamics, benefiting hardy MIS such as macroalgae, filter feeders, and gelatinous zooplankton. For example, *Mnemiopsis leidyi* (warty comb jelly) proliferated in the hypoxic, eutrophic Black Sea during the 1980s, triggering a collapse in zooplankton biomass and pelagic fisheries [37–39].

(iii) Circulation and dispersal connectivity: Climate-driven changes in ocean stratification and circulation are reshaping the spatial and temporal dynamics of propagule transport [40]. Increased stratification reduces vertical nutrient flux, altering productivity regimes and potentially influencing community susceptibility to invasion [41, 42]. Concurrently, shifts in major current systems, such as weakening of the Atlantic Meridional Overturning Circulation, changes in El Niño–Southern Oscillation patterns, and polar sea-ice retreat, extend larval and rafting dispersal pathways [9]. These oceanographic changes often act synergistically with anthropogenic vectors like ballast water, hull fouling, and aquaculture escapes to facilitate species spread [43]. The Mediterranean Sea has already been invaded by hundreds of exotic species, largely due to the opening of the Suez Canal in 1869 [44]. The recent expansion of the Suez Canal, together with rapid warming in the Eastern Mediterranean, has accelerated Lessepsian migration, enabling Indo-Pacific species such as the silver-cheeked toadfish (*Lagocephalus sceleratus*) to spread widely into the Mediterranean Sea [44–47]. Similarly, the expansion and salinification of the Panama Canal have turned Lake Gatun from a freshwater barrier into a brackish corridor, with marine fish richness jumping from 18 to 29 species just four years after the 2016 expansion, greatly increasing the risk of trans-ocean invasions [46]. These invaders have contributed to native species declines and a functional homogenization of marine communities [24].

3.2. Broader Patterns and Systemic Implications

Thermal, chemical, and hydrodynamic changes interact synergistically to reshape the biogeography of MIS while eroding the resilience of native assemblages [48]. Mid-latitude and semi-enclosed basins, once buffered by climatic or geographic barriers, are now increasingly susceptible to colonization and ecological regime shifts [49]. Mediterranean warming, for example, has facilitated the establishment of numerous Red Sea (Indo-Pacific) species, demonstrating the breakdown of previously insurmountable thermal boundaries. Once established, MIS can restructure trophic networks, disrupt sediment and nutrient cycling, and trigger feedback loops that destabilize ecosystems [50–52]. The convergence of biological invasions with other anthropogenic pressures such as pollution, overexploitation, and habitat fragmentation further elevates the risk of irreversible ecological transitions [53, 54]. Addressing this growing threat requires predictive surveillance strategies that integrate species distribution models with oceanographic forecasts to identify future invasion hotspots under climate change scenarios [55]. Molecular tools like environmental DNA (eDNA) provide scalable, sensitive methods for early detection of new incursions, while inter-jurisdictional data-sharing frameworks are critical for managing transboundary risks [56, 57]. In practice, treating invasive species management as integral to climate adaptation on par with extreme weather preparedness or coastal defense will be crucial. Collectively, these interacting thermal, chemical, and circulation changes, summarized in Figure 1, shift marine invasions from isolated events to systemic, climate-driven reorganization of ocean biogeography.

4. Vectors and Pathways in a Changing Ocean

Marine invasive species are dispersed through a wide array of anthropogenic and natural vectors, many of which are being intensified or transformed by climate change [24]. Traditional pathways such as ballast water, hull fouling, and aquaculture remain primary drivers of global spread, while emerging vectors linked to ocean warming, polar ice loss, coastal development, and intensified trade create new invasion opportunities [58]. These shifts underscore the need for adaptive, climate-informed biosecurity strategies that reflect the evolving spatial and temporal dynamics of vector activity (Figure 2).

4.1. Traditional Vectors under Climate Amplification

Traditional vectors for MIS include ballast water, hull fouling, aquaculture escapes, the ornamental (aquarium) trade, and marine debris [59]. Climate change significantly amplifies each of these pathways (Figure 3 and Table 1).

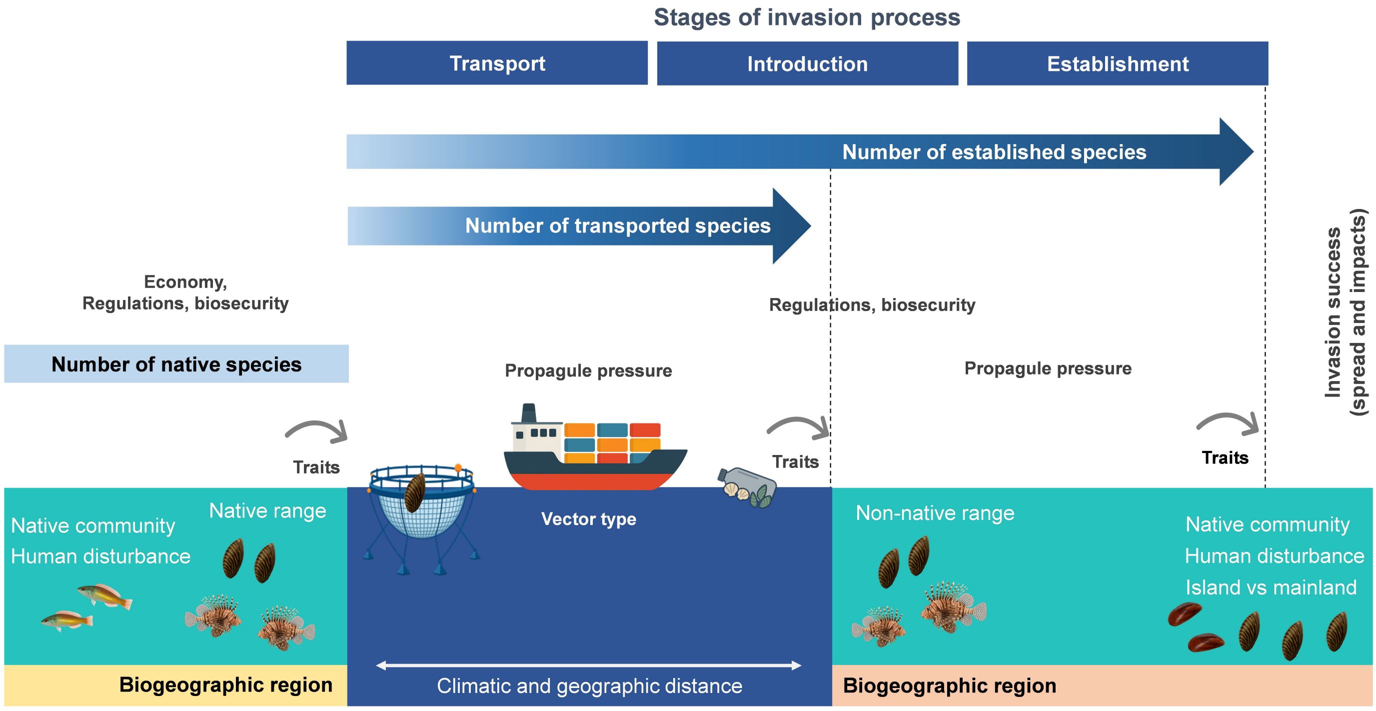

Figure 2. Major marine invasion stages and dominant anthropogenic pathways [60].

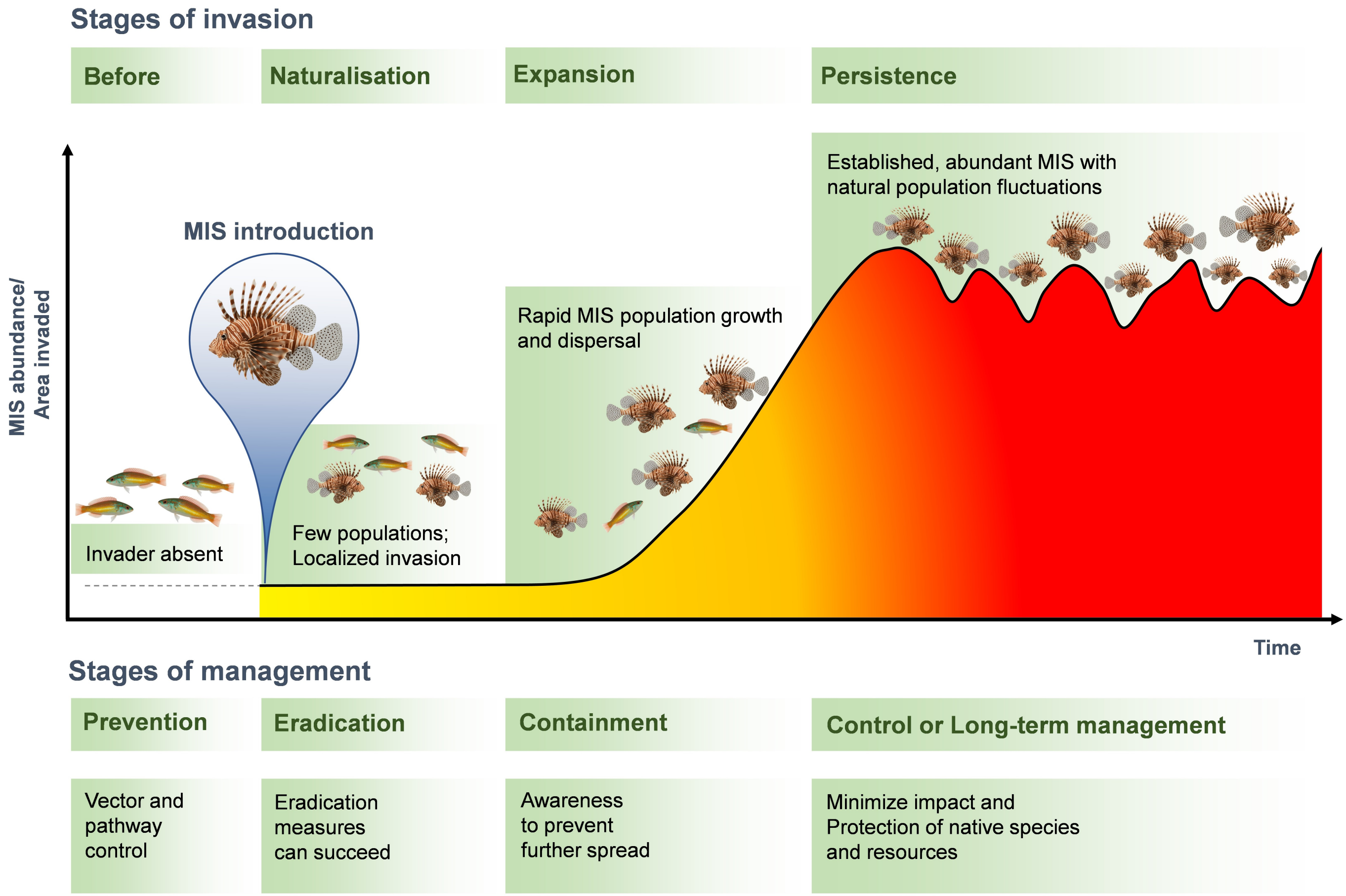

Figure 3. Management opportunities along the marine invasion pathway [61].

Table 1. Traditional marine invasive species vectors and climate-driven amplification of risk.

Vector	Mechanism of Spread	Climate-Change Interactions	Amplified Risks & Challenges	Reference
Ballast Water	Transports planktonic larvae, propagules, and microbes in discharged ballast water.	Warmer transit temperatures increase organism survival and settlement success, especially along tropical/subtropical routes.	Long voyages under warm conditions enhance stowaway viability; weak enforcement in small/developing ports heightens exposure risk.	[62, 63]
Hull Fouling	Sessile species (e.g., barnacles, tunicates, algae) attach to vessel hulls and underwater structures.	Elevated SSTs promote faster growth and survival of fouling organisms in regions that were formerly too cold.	The geographic range of fouling communities expands; antifouling coatings degrade faster in warmer waters; small private vessels often remain unregulated.	[64–66]
Aquaculture & Ornamental Trade	Escape or release of farmed species and hitchhiking organisms (e.g., via aquaculture gear or aquarium dumping).	Milder winters and warmer waters extend establishment windows and range for escaped tropical and temperate species.	Higher risk of establishment from aquaculture escapes (e.g., oysters, shrimps, and their pathogens) and aquarium releases; new areas become suitable for non-natives.	[64, 67–69]
Marine Debris (Rafting)	Floating plastics and debris serve as rafts transporting entire fouling communities across oceans.	Stronger storms increase debris input; longer drift durations in warmer currents allow rafted biota to survive.	Greatly increased long-distance dispersal potential; events that were once rare (e.g., trans-oceanic rafting) may become regular invasion pathways under more frequent extreme storms.	[70–72]

4.2. Emerging Vectors and Climate-Linked Corridors

Climate change is reshaping marine invasion dynamics by intensifying established vectors and generating new dispersal corridors. As environmental conditions and human activities evolve, novel pathways for MIS are emerging [73]. Table 2 outlines key climate-linked vectors and corridors likely to drive future invasions.

Table 2. Emerging climate-driven vectors facilitating marine invasive species spread.

Vector	Mechanism of Spread	Climate-Change Interactions	Amplified Risks & Challenges	Reference
Arctic Shipping Routes	The opening of the Northern Sea Route and Northwest Passage enables trans-Arctic connectivity between previously isolated bioregions.	Sea-ice decline allows seasonal shipping passage; cold-adapted species can now move between the Pacific and Atlantic basins.	Increased risk of MIS introductions into historically invasion-resistant Arctic waters; novel inter-ocean species exchanges occur.	[74, 75]
Extended Operational Seasons	Longer port, marina, and aquaculture activity windows in temperate/high-latitude regions.	Milder winters and prolonged warm seasons increase propagule pressure and the survivability of non-natives.	Higher establishment potential for non-native species in areas once protected by seasonal cold; longer breeding seasons for invaders.	[76–78]
Offshore Structures as Stepping Stones	Biofouling on oil rigs, wind farms, and other offshore infrastructure allows species to leapfrog across seascapes.	Expansion of offshore energy and coastal infrastructure creates dense artificial habitats that support fouling communities and connect distant marine areas.	Non-native species colonize artificial substrates and then invade adjacent natural habitats; mitigation measures for offshore installations are underdeveloped.	[79, 80]
Live Seafood and Bait Trade	The movement of live seafood and fishing bait introduces unintended hitchhikers (e.g., algae, small invertebrates, pathogens).	Climate-driven shifts in fisheries and sourcing increase trade from tropical zones to new regions.	Warmer destination waters raise survival odds of hitchhikers; insufficient inspection of live commodities exacerbates biosecurity gaps.	[81, 82]
Canal Expansion & Inter-Basin Waterways	Human-made canals (e.g., the Suez and Panama Canals) and proposed inter-basin water transfer projects connect previously isolated marine regions.	Warming canal environments increase the survivability of tropical invaders; more non-natives can overwinter in temperate zones.	Accelerated biogeographic mixing; tropical species are more likely to survive and establish in temperate basins beyond their historical range.	[83, 84]
Storm-Driven Rafting	Debris and vegetation mats dislodged during extreme storms carry entire marine communities across ocean basins.	More intense and frequent cyclones, hurricanes, and tsunamis boost rafting frequency and distance.	Elevated trans-oceanic dispersal; species can "island hop" or cross barriers once thought impassable, introducing biota to far-flung coasts.	[71, 85]

4.3. Global Trends and Future Outlook

Over the past 30 years, global shipping traffic and aquaculture production have both more than doubled, especially in Asia and the Mediterranean, greatly increasing opportunities for the spread of marine invasive species [86, 87]. Climate change amplifies the impact of these vectors by enhancing organism survival during transport and expanding the environmental suitability of recipient regions. Under projected climate scenarios, several key risks emerge [88]. First, higher propagule viability is expected during transit, as warmer and more stable voyage conditions reduce cold stress in ballast tanks and on hulls, increasing survival rates [89]. Second, climate-driven changes in temperature, salinity, pH, and oxygen broaden the invasion niche, rendering previously unsuitable regions viable for establishment [24]. Third, increased temporal synchrony between vector activity and invader life cycles, for example earlier springs and extended warm seasons, may align shipping schedules with peak spawning periods, while marine heatwaves can weaken native biota during critical windows [90]. These trends expose the limitations of static vector management systems: traditional assumptions about "safe" seasons, geographic barriers, and narrow tolerance ranges are becoming obsolete. A dynamic, climate-informed strategy is essential, using environmental forecasts to identify high-risk ports, routes, and periods and to adjust inspection protocols, treatment technologies, and vector priorities accordingly [91]. As Arctic shipping lanes expand, biosecurity resources must also be reallocated to this emerging frontier [75]. A more detailed framework for climate-smart, adaptive vector management is developed in Section 8.

5. Impacts on Marine Biodiversity and Ecosystem Services

The proliferation of MIS is a major and escalating driver of ecosystem degradation. Once established, MIS trigger cascading biotic and abiotic disruptions that diminish native biodiversity, compromise habitat integrity, destabilize food webs, and reduce ecosystems' capacity to deliver essential services [92, 93]. While the magnitude and nature of these impacts vary across climate zones, habitat types, and local stressor regimes, MIS collectively contribute to a systemic erosion of marine ecosystem functionality and resilience [94].

5.1. Ecological Disruption

MIS exert both direct and indirect pressures on native communities through multiple mechanisms. First, they compete with endemic species for space and resources; for example, the European green crab (*Carcinus maenas*) has displaced native bivalves and restructured benthic invertebrate communities in many temperate estuaries [95, 96]. Second, invasive predators can severely reduce prey populations; the Indo-Pacific lionfish (*Pterois volitans*) has caused major declines in juvenile reef fish biomass across the Atlantic and Caribbean, disrupting trophic dynamics [97, 98]. Third, hybridization with native species may occur when closely related taxa interbreed, reducing genetic integrity. Invasive *Mytilus* mussels, for instance, have hybridized with native mussel populations in Europe, producing complex hybrid swarms that complicate management [99–101]. Fourth, MIS can alter biogeochemical processes: invasive filter feeders (e.g., tunicates, bivalves) and ecosystem engineers may significantly affect nutrient cycling, sedimentation, and water clarity [102–104]. Collectively, these pathways reduce native species richness, suppress recruitment, and diminish community resistance to compounding stressors such as warming, hypoxia, and eutrophication, often resulting in less diverse, more invasion-prone ecosystems [105].

5.2. Habitat Degradation

MIS can directly impact habitat-forming species, leading to structural simplification and functional decline across key marine ecosystems [106–108]. Invasive macroalgae such as *Kappaphycus* and *Caulerpa* overgrow coral reefs, forming dense mats that block light and smother corals, driving reef degradation and shifting systems from coral- to algal-dominated states. This disrupts reef-associated fish and invertebrate communities [109]. In the Mediterranean, invasive rabbitfish (*Siganus* spp.) have heavily grazed native seaweeds and seagrasses, leading to the decline of seagrass meadows and the associated loss of habitat complexity and nursery grounds [110]. Additionally, invasive bioeroders such as the tropical boring urchin (*Diadema setosum*), now expanding its range, and certain invasive sponges accelerate reef framework degradation. When combined with ocean acidification, this bioerosion can cause calcium carbonate loss to exceed accretion, weakening reef integrity [111]. In mangrove and saltmarsh systems, invasive insects and fungal pathogens introduced via global trade can decimate foundational plant species, risking habitat collapse at the land–sea interface [112]. Collectively, MIS degrade critical habitats such as coral reefs, oyster beds, kelp forests, and seagrass meadows, eroding the physical infrastructure essential to marine biodiversity [106, 113]. This habitat degradation undermines ecosystem services including coastal protection (reefs, mangroves), water filtration (oyster reefs), and carbon sequestration (seagrasses, mangroves), thereby weakening both ecological resilience and human well-being [114].

5.3. Trophic Disruption and Food Web Destabilization

Marine invasions often introduce novel feeding interactions and perturb established trophic dynamics, potentially simplifying or even collapsing local food webs [115]. Invasive species can outcompete or eliminate native keystone organisms. An invasive starfish preying on reef mussels could eliminate a species that many others depend on, causing a cascade of secondary extinctions. Blooms of *Mnemiopsis leidyi* in the Black Sea, as another example, not only consumed vast amounts of zooplankton but also outcompeted native fish larvae, contributing to fisheries collapse [116]. Each such disruption can make the ecosystem more prone to additional shocks, since functional redundancy is lost and energy flow is altered [50]. Over time, repeated invasions can lead to fundamentally different community structures, in which the native food web architecture is replaced by a novel assemblage.

5.4. Loss of Ecosystem Services

The ecological consequences of MIS translate into measurable declines in a variety of ecosystem services, the benefits that humans derive from ecosystems. These include provisioning services (like fisheries), regulating services (water quality, carbon sequestration, coastal protection), and cultural services (recreation, tourism). Many of these are tied to international sustainability goals such as the UN Sustainable Development Goals (SDGs) [117]. The following table summarizes the major impacts of MIS on key marine ecosystem services and their relevance to specific SDG targets (Table 3).

Table 3. MIS impacts on ecosystem services and related SDG targets.

Ecosystem Service	MIS Impact Summary	Relevant SDG Targets	Reference
Fisheries (Provisioning)	Declines in wild fish and shellfish due to habitat destruction, competition, and predation by invaders (e.g., lionfish preying on reef fish; invasive snails preying on bivalves).	2.1 (food security); 14.4 (sustainable fisheries)	[118]
Coastal Protection (Regulating)	Degradation of coral reefs, overgrazing of seagrass beds, and die-off of mangroves by invasives reduces natural coastal defense against storms and erosion.	11.5 (disaster risk reduction); 14.2 (ecosystem restoration)	[119]
Carbon Sequestration (Regulating)	MIS alters or destroys blue carbon ecosystems (kelp forests, salt marshes, and mangroves), thereby reducing their carbon sequestration capacity.	13.1 (climate adaptation); 14.3 (ocean acidification mitigation)	[120, 121]
Water Quality (Regulating)	Some invasives (e.g., filter-feeders) can improve water clarity but also concentrate pollutants; others (e.g., *Caulerpa* algae) trigger harmful algal blooms or eutrophication.	6.3 (water quality); 14.1 (marine pollution reduction)	[122]
Tourism & Recreation (Cultural)	Jellyfish blooms, nuisance seaweed accumulations, and the loss of charismatic coral reef species diminish the appeal of marine tourism (e.g., beach use and dive tourism).	8.9 (sustainable tourism); 14.7 (sustainable economic benefits from marine resources)	[7, 53]

5.5. Regional Variation in Impact Severity

The severity and expression of MIS impacts differ strongly across climate zones and ecosystem types, depending on local stressors and exposure to invasion pathways [24, 64, 123]. In tropical systems, invasive algae, herbivorous fish, and invertebrates often overgrow or overgraze corals and seagrasses, driving shifts from reef- to algal-dominated states and eroding fisheries and tourism revenues [44, 124–129]. Temperate regions are more prone to invasions that target foundation species such as kelps, seagrasses, oysters, and mussels, leading to habitat loss, altered nutrient cycling, and reduced nursery functions for commercially important fish [130–133]. Polar and subpolar seas, once buffered by cold temperatures and ice, are now increasingly exposed to boreal and temperate invaders as sea ice retreats, threatening simple food webs and climate-relevant processes such as carbon sequestration [134, 135]. These contrasts underline that biosecurity cannot be one-size-fits-all; vector control, monitoring priorities, and management objectives must be tailored to regional ecological vulnerabilities and socio-economic dependencies (Figure 4).

6. Biosecurity Gaps and Governance Shortfalls

Despite increasing scientific understanding of MIS and their accelerating risks under climate change, biosecurity governance remains fragmented, reactive, and under-resourced [136]. Global, regional, and national frameworks are often poorly aligned with emerging ecological realities, leaving ecosystems, especially those in ecologically sensitive or politically complex regions, exposed to elevated invasion pressure. The absence of integrated, forward-looking systems constrains early detection, weakens rapid response capacity, and hampers long-term mitigation (Figure 5).

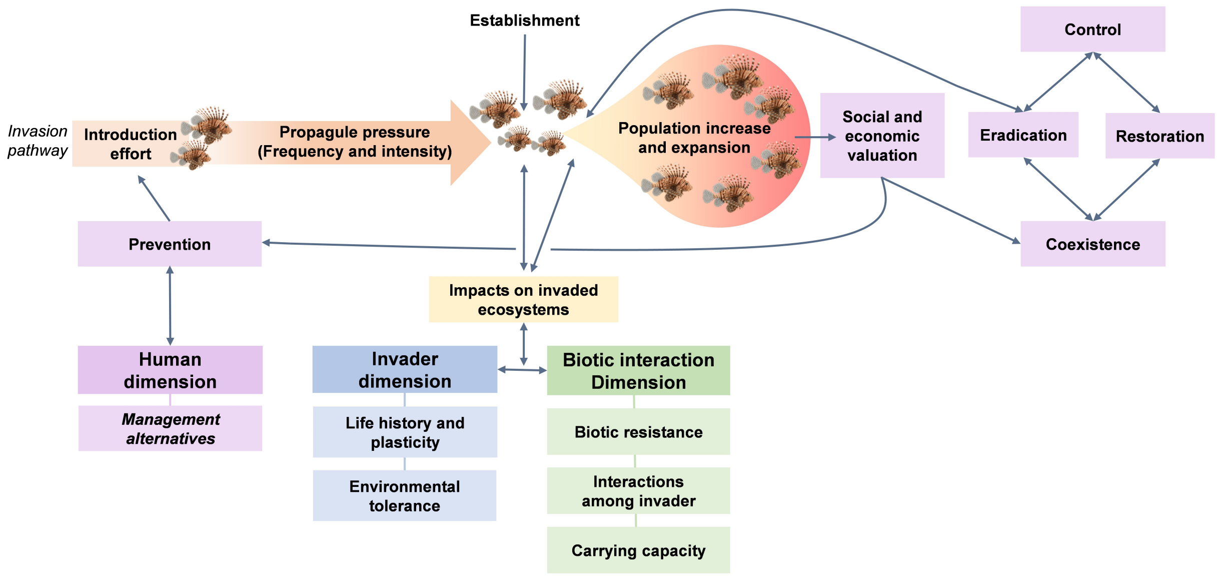

Figure 4. Socio-ecological framework illustrating how invasion pathway dynamics, species traits, biotic interactions, ecosystem impacts, and human dimensions shape management outcomes [137].

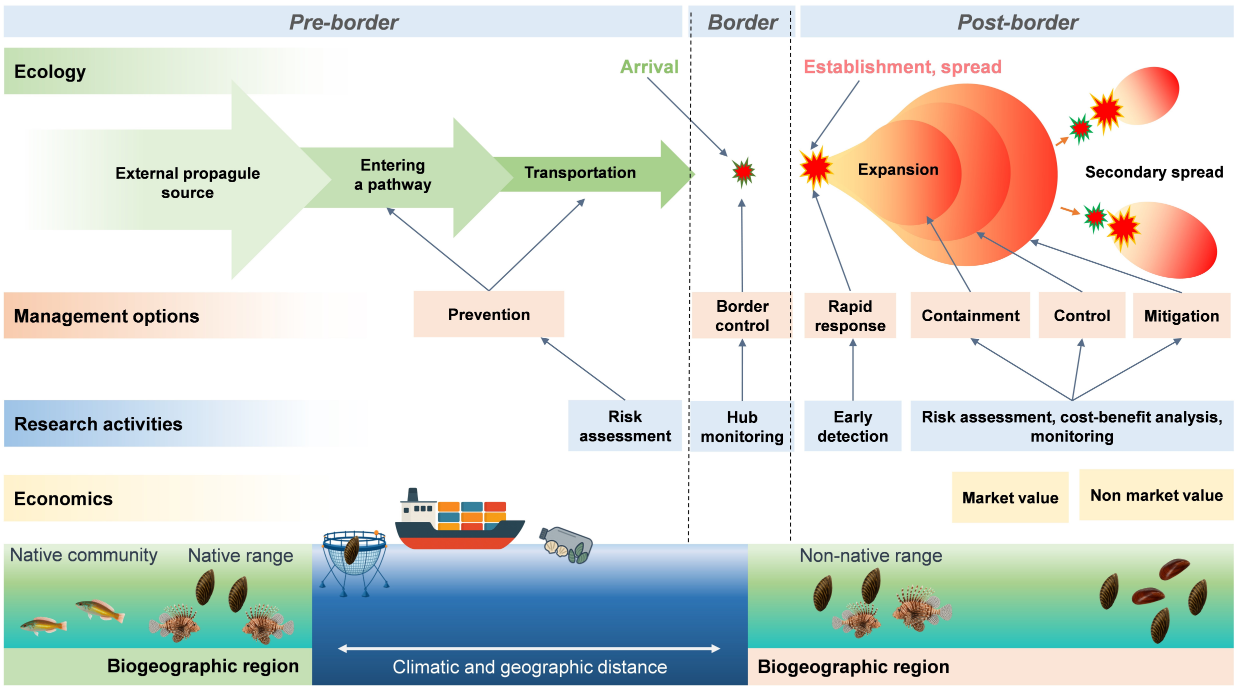

Figure 5. Integrated pathway framework linking ecological processes, management actions, research priorities, and economic considerations across the pre-border, border, and post-border stages of marine invasions [138].

6.1. Weak Implementation of International Mechanisms

Several international instruments address MIS risks. These include the International Maritime Organization's Ballast Water Management Convention (in force since 2017), which mandates ballast water treatment on vessels [22]; the Convention on Biological Diversity (CBD), which established Aichi Target 9 and now Kunming–Montreal Target 6 on invasive species [139, 140]; and the new 2023 BBNJ Agreement for areas beyond national jurisdiction [141], which introduces environmental impact assessment provisions for activities that could introduce invasives [142]. While these frameworks provide a legal foundation, their implementation remains weak and uneven. Many signatory states struggle with inadequate technical infrastructure, limited trained personnel, and insufficient enforcement mechanisms to meet treaty obligations [22]. In this regard, ballast water port inspections are inconsistently applied, especially in small or developing countries that lack sampling labs or monitoring capacity. National MIS strategies, where they exist, are frequently outdated, not aligned with climate change projections, or lack legal teeth for enforcement [143]. Additionally, voluntary clauses in agreements (such as the CBD's guidance on invasives) mean there are few consequences for non-compliance. A notable illustration of implementation gaps is the spread of *Caulerpa taxifolia* in the Mediterranean; despite early warnings in the 1980s, the lack of coordinated action allowed this invasive alga to establish widely, ultimately costing governments (e.g., France) millions of euros in control efforts [144, 145]. This case highlights how international awareness did not translate into effective local action.

6.2. Limited Early Detection and Rapid Response (EDRR)

Effective early detection and rapid response (EDRR) is critical to managing MIS, yet most regions lack the core elements needed for timely action [102]. First, many areas lack baseline biodiversity surveys and taxonomic capacity, making it difficult to identify non-native species. The shortage of taxonomists and the limited availability of genetic identification tools hamper the detection of cryptic or early-stage invaders [102]. Second, molecular diagnostics such as eDNA, qPCR, and metagenomics offer powerful early detection methods but are rarely applied outside research settings. Few countries conduct routine eDNA monitoring at ports [146]. Third, even when detection occurs, rapid response often stalls due to the absence of dedicated emergency funds or clear legal frameworks. Quick actions such as quarantining affected areas or swiftly removing invaders require financial and legal readiness that many jurisdictions lack [147]. Fourth, poor cross-border coordination means neighboring countries are often not alerted in time to mount a shared response, especially where diplomatic ties are weak. As a result, invasions are often only recognized after severe damage has occurred [148]. The collapse of Black Sea fisheries due to *Mnemiopsis leidyi* and the unchecked spread of lionfish in the western Atlantic highlight the high costs of delayed response [149]. Strengthening EDRR through investment in monitoring, diagnostics, legal preparedness, and regional coordination offers high returns by preventing costly ecological and economic damage.

6.3. Institutional and Jurisdictional Fragmentation

Governance of MIS is often split among multiple agencies and economic sectors, such as environment, fisheries, shipping, agriculture/quarantine, and tourism [59]. This siloed institutional structure leads to poor coordination. Agencies may have overlapping mandates or, conversely, gaps where each assumes the other is handling a particular aspect. For instance, an Environment Ministry might manage invasive species inside marine protected areas, while a Fisheries Department manages invasive fish outside those areas, and a Port Authority handles ballast water, often with minimal communication between them [73]. The result is that responsibilities fall through the cracks, leading to slower decision-making and inefficiencies in surveillance and control efforts.

6.4. Regions of Elevated Risk

Certain regions face compounded risks from MIS yet remain under-served by existing governance frameworks. Two categories stand out: (1) enclosed and semi-enclosed seas, and (2) Small Island Developing States (SIDS) and other developing coastal nations.

Enclosed and Semi-Enclosed Seas: Marine ecosystems like the Mediterranean Sea, Red Sea, Arabian Gulf, Black Sea, and Baltic Sea are highly vulnerable. They have limited water exchange with open oceans (long residence times), meaning any introduced species can persist and build up [150]. These seas also typically have heavy maritime traffic (major shipping lanes, oil transport) and dense coastal development. Jurisdictionally, enclosed seas are bordered by many countries, often with tense politics or varying capacities, complicating coordinated action [151]. The Mediterranean includes EU nations, North African nations, and Middle Eastern nations, each with distinct resources and priorities. While regional bodies exist (e.g., the Barcelona Convention for the Mediterranean), few have strong mandates or funding specifically for MIS management. The result is that invaders such as lionfish and pufferfish have spread across the Mediterranean with only patchy response efforts from individual countries [152]. The Arabian Gulf is another prime example; extremely high shipping volume, extreme environmental conditions (heat and salinity) that limit native resilience, and eight littoral countries with overlapping claims and no unified MIS monitoring system [153]. Enclosed seas thus represent "hot zones" where invasions can establish and spread largely under the radar.

Small Island Developing States (SIDS) and Developing Coastal Nations: SIDS and many developing coastal nations face high vulnerability to MIS but often lack the capacity to manage them. These regions depend heavily on marine resources for food security, tourism, and coastal protection, making the stakes particularly high [154]. However, many such nations have weak or non-existent marine biosecurity laws, a shortage of technical expertise and laboratory infrastructure, limited funding for surveillance or rapid response, and high exposure due to busy ports and favorable tropical conditions for invasions [155]. Climate change compounds these risks by increasing stress on native ecosystems (e.g., coral bleaching, hypoxia) and intensifying introduction pathways via storms and shifting shipping routes. This has widened the capacity gap between high- and low-income nations [77]. New Zealand maintains a robust marine biosecurity system, while many South Pacific islands lack the resources to monitor or respond to threats like crown-of-thorns starfish outbreaks. Building capacity in these vulnerable regions is critical to global biosecurity, as invasions can quickly spread beyond their shores.

6.5. Summary of Governance Limitations

Table 4. Systemic limitations in marine invasive species (MIS) management and their consequences.

Limitation	Description	Implications	Supporting Evidence	Reference
Weak Enforcement	Existing regulations (e.g., ballast water rules) are poorly enforced; inspections are irregular and under-resourced.	Non-compliant vessels discharge invasive organisms unchecked, weakening international protocols.	Found inconsistent ballast checks in many ports worldwide.	[156, 157]
Reactive Surveillance	Detection often occurs post-establishment rather than during the early incursion phase.	Delayed detection and response reduce the probability of eradication and increases long-term control costs.	Eradication success plummets once species are established.	[158, 159]
Siloed Institutions	Fragmentation among responsible agencies leads to poor coordination and overlapping or unclear mandates.	Slower decision-making, duplicated efforts, and inefficiency in surveillance and control.	CBD Technical Series No. 91: Advocates for integrated "whole-of-government" MIS strategies.	[160]
Funding Deficits	MIS programs suffer from inconsistent or short-term funding.	Prevents sustained monitoring, outreach, and maintenance of rapid response capacity.	Budget constraints severely hinder long-term invasive species action plans.	[161, 162]
Legal Ambiguity	Outdated or unclear laws create confusion about roles and responsibilities during invasion events.	Delays action and weakens accountability among institutions.	France's delayed response to *Caulerpa taxifolia* was partly due to unclear authority	[163, 164]
Cross-Border Inertia	Lack of regional cooperation and harmonized responses across neighboring states.	Invaders re-enter from unmanaged areas, undermining local eradication efforts.	Highlighted the failure of coordinated MIS planning in the Mediterranean.	[165]

6.6. Toward a Transformative Biosecurity Framework

Marine biosecurity must shift from passive containment to a proactive, climate-smart approach. Predictive risk modeling that integrates ocean forecasts, species distribution data, and vector activity can identify future invasion hotspots, enabling early surveillance and intervention. Cross-sector coordination is essential, with regular collaboration between environmental, fisheries, maritime, and tourism agencies to ensure real-time data sharing and joint action. Legal frameworks should be updated to include climate-driven invasion risks, and regional policies must be harmonized to prevent weak links in the chain of defense [166]. Institutions need clear mandates, stable funding, and the capacity to respond quickly, including contingency funds and trained personnel for emergency action. Equally important is technology transfer and capacity building, so that low-income countries and small island states have access to affordable tools and training to participate fully in global biosecurity efforts [167]. These actions are critical not only for protecting biodiversity but also for ensuring food security, sustaining coastal economies, and advancing global sustainability in a rapidly changing ocean.

7. Surveillance and Risk Assessment Innovations

The intensification of MIS under climate change underscores the urgent need to transition from conventional, labor-intensive monitoring to scalable, real-time, and predictive surveillance systems. Innovations in molecular biology, autonomous sensing, and artificial intelligence (AI) offer robust, climate-resilient tools to support anticipatory biosecurity across broad spatial scales and jurisdictional boundaries [49]. This section provides the operational toolbox that underpins the climate-smart framework in Section 8.

7.1. Molecular Diagnostics for Early, Non-Invasive Detection

Traditional methods (net tows, diver surveys, visual inspections) are labor-intensive, spatially restricted, and often fail to detect invasive species present at low densities or in cryptic life stages [168]. In contrast, molecular diagnostic tools offer high sensitivity and broad applicability, making them powerful additions to marine biosecurity efforts. Environmental DNA (eDNA) sampling detects genetic material shed by organisms into their surroundings, allowing identification of target species from water samples alone [169]. This technique is non-invasive and effective even at early life stages or in low-abundance environments, making it suitable for early warning in high-risk sites such as ports, canals, and aquaculture facilities [57]. Quantitative PCR (qPCR) enables both detection and quantification of specific species, supporting routine monitoring of known threats, for example, tracking spores of the invasive kelp *Undaria pinnatifida* in marina environments. Metabarcoding and metagenomics extend detection to the entire biological community within a sample, capturing a broad range of organisms and highlighting unexpected or novel species. As DNA reference databases improve, these tools will become even more effective for horizon scanning and biodiversity assessment [170]. A major innovation is the automation of molecular diagnostics, with autonomous platforms capable of on-site DNA analysis and remote data transmission. These systems, such as robotic eDNA samplers or "labs-on-a-buoy," can provide continuous monitoring in remote or logistically challenging environments. Overall, molecular tools greatly enhance early detection capabilities, are cost-effective and minimally invasive, and complement traditional approaches, together increasing the likelihood of timely and effective responses to marine invasions.

7.2. Remote Sensing and Autonomous Observation Systems

Remote sensing and robotic technologies are significantly enhancing MIS surveillance by improving both spatial coverage and temporal resolution [171]. Satellite imagery, including multispectral and hyperspectral sensors, can detect changes in coastal ecosystems such as algal blooms, jellyfish swarms, or mangrove die-offs that may signal the presence of invasives [121, 172–175]. Although satellites cannot identify species directly, they highlight anomalies that warrant further investigation. Unmanned Aerial Vehicles (UAVs, i.e., drones) provide flexible, cost-effective monitoring of coastlines, reefs, and mangroves, helping detect visible invasives in remote or inaccessible areas. Autonomous Underwater Vehicles (AUVs) and gliders conduct underwater surveys using video, sonar, and environmental sensors, and some are now equipped with eDNA samplers, enabling both visual and molecular detection. Biogeochemical Argo floats, enhanced with optical sensors and eDNA capabilities, enable the detection of planktonic invaders and the monitoring of ocean features linked to invasion risk [176]. Fixed ocean observation platforms, including instrumented buoys and coastal radar systems, offer continuous environmental monitoring. For example, identifying marine heatwaves or hypoxia events that may facilitate invasions [73]. Collectively, these technologies create a near-continuous monitoring network for marine systems. While remote sensing often provides indirect evidence of invasions, pairing these tools with field verification (e.g., diver surveys, eDNA analysis) supports a robust and proactive surveillance framework.

7.3. AI-Driven Risk Modeling and Forecasting

Artificial intelligence is reshaping how marine invasion risk is assessed by enabling integration and analysis of complex, high-volume datasets and by generating adaptive, predictive outputs [177]. AI-enhanced species distribution models (SDMs), such as MaxEnt and boosted regression trees, can identify non-linear relationships between species occurrences and environmental variables. When coupled with climate projections (e.g., IPCC's Representative Concentration Pathway or Shared Socioeconomic Pathway scenarios), these models can forecast future invasion hotspots. AI is also being applied to horizon scanning: by analyzing large datasets such as shipping logs, aquarium trade records, and species life-history traits, machine-learning algorithms can prioritize species with high invasion potential based on similarities to known invaders, rising trade volumes, or matching climate conditions. Integrating phylogenetic and climate data further enhances precision, allowing agencies to focus monitoring on high-risk candidates [178]. In addition, AI enables the creation of dynamic risk maps by combining real-time data sources, including ship traffic (via Automatic Identification System, AIS), satellite-derived environmental conditions, and eDNA surveillance results. These maps can be continuously updated, alerting authorities when environmental and transport conditions align to elevate invasion risk, similar to early warning systems in weather forecasting [179]. AI also supports decision-making by simulating the outcomes of various management strategies. It can evaluate how increased hull cleaning or expanded marine protected areas might influence invasion probability, or optimize eDNA sampling schedules to maximize detection within limited budgets [59]. Collectively, these tools address a core challenge of marine biosecurity: monitoring vast, dynamic ecosystems with limited resources. By directing attention and action to areas of highest predicted risk, AI increases the efficiency and responsiveness of surveillance systems. Real-world applications, such as New Zealand's AI-assisted biofouling detection during hull inspections, demonstrate AI's potential to strengthen proactive biosecurity management [180].

7.4. Integrated Surveillance Networks: Toward Hybrid Biosecurity Systems

Effective management of MIS under climate change requires a coordinated, multi-layered surveillance approach that integrates diverse tools and knowledge systems. Combining molecular diagnostics with remote sensing enhances detection accuracy. A satellite-detected algal bloom anomaly can be followed up with eDNA sampling to confirm the presence of an invasive species [181]. AI-based risk models can guide targeted deployment of drones or AUVs for site inspections [182]. Interoperable data platforms are critical for real-time information sharing across regions and agencies. Cloud-based systems that integrate eDNA results, ship traffic data, oceanographic conditions, and even citizen observation reports enable a unified view of invasion risk. Importantly, including Traditional Ecological Knowledge (TEK) and citizen science contributions adds local insight, often detecting anomalies before automated systems. Community reporting apps and structured "citizen ranger" programs can thus enhance early warning capacity and ground-truth automated alerts. An ideal system enables bidirectional information flow; automated detections trigger stakeholder responses, while human observations feed back into the system to refine risk models [183]. Cross-border communication ensures timely action beyond national boundaries. These integrated networks support adaptive, climate-responsive monitoring, intensifying surveillance during events like marine heatwaves or reallocating resources based on emerging data. Beyond targeting invasive species, they also contribute to general ocean health monitoring (e.g., detecting algal blooms or pollution), offering broad ecological and policy co-benefits.

7.5. Alignment with Global Sustainability and Science Frameworks

Modernizing marine biosecurity surveillance directly supports multiple global sustainability agendas [184]. Early detection and control of MIS help safeguard biodiversity, blue carbon habitats, and fisheries, contributing to SDG 14.2 and 14.4. Investment in tools such as eDNA, autonomous observing systems, and AI-enabled risk models advances ocean science capacity and technology transfer, consistent with SDG 14.a and SDG 17.6. Improved, shared data streams on invasions and ecosystem status address SDG 17.18 by strengthening the evidence base available to developing countries. These efforts also align with the Kunming–Montreal Global Biodiversity Framework and the UN Decade of Ocean Science, which both call for integrated observing systems and actionable knowledge. Framing surveillance upgrades as contributions to these existing commitments can unlock funding and political support while positioning MIS management as a core component of climate adaptation and sustainable ocean governance.

8. Toward Climate-Smart Marine Biosecurity

As climate change increases the frequency, scale, and unpredictability of marine invasions, it exposes the limitations of traditional biosecurity systems. These legacy frameworks, typically static, reactive, and fragmented, are ill-equipped to manage a rapidly evolving risk landscape. In response, a paradigm shift is needed toward climate-smart marine biosecurity: a proactive, integrative approach that couples real-time environmental data with flexible surveillance strategies, ecological modeling, and inclusive governance [185]. This emerging paradigm prioritizes foresight over containment and resilience over ad-hoc response, aligning MIS management with broader climate adaptation and biodiversity protection goals. Recent literature has begun to define and call for this approach, emphasizing that managers and policymakers need to address the interactive effects of climate change and invasions jointly.

8.1. Dynamic Risk Assessment: From Static Lists to Predictive Maps

Traditional biosecurity frameworks often rely on static "blacklists" of species or generalized risk matrices that do not account for future environmental conditions [146]. Climate-smart biosecurity, by contrast, emphasizes dynamic, scenario-based risk assessment that integrates climate projections, ecological indicators, and human activity data. One key advancement is incorporating climate forecasting into risk models. Rather than dismissing a species based on current unsuitability, assessments should consider future scenarios (e.g., $+2\ ^\circ$C of warming, increased acidification). A species unable to survive today may thrive under projected conditions and should therefore be treated as a current risk. Identifying ecological thresholds and warning signs further supports proactive management. For example, declines in native biodiversity or the loss of functional groups (e.g., top predators, reef builders) can signal increased vulnerability to invasion. A mass coral bleaching event, for instance, can create ecological space for invasive algae or sponges to establish. Monitoring such thresholds offers early warnings of potential invasions [186]. Integrating human activity patterns using GIS allows for spatial risk overlays; mapping shipping routes, fishing intensity, tourism, and aquaculture alongside environmental vulnerability can reveal invasion windows periods and locations where introduction risk is elevated due to the convergence of high propagule supply and susceptible habitat. Agencies can then intensify monitoring and control during these high-risk windows. Crucially, to remain relevant, risk models must be regularly updated. As new data emerge, such as an invader's spread in a nearby region or revised climate projections, risk maps and priority species lists should evolve. To ensure operational relevance, dynamic risk assessments can be paired with simple performance metrics, such as reductions in time-to-detection before establishment, changes in predicted invasion hotspots under warming scenarios, or shifts in composite regional risk scores derived from integrated indices. This "living document" approach is gaining traction, with countries like Australia revising their national invasive species watchlists based on ongoing horizon scanning. Overall, dynamic, climate-informed risk assessment enables agencies to strategically focus efforts on areas and timeframes where prevention and control are most feasible. For example, if a small estuary is identified as both highly vulnerable *and* logistically manageable, it becomes a priority for early interventions like eDNA monitoring or public outreach [187]. In contrast, areas where control is less feasible might benefit more from building ecological resilience. This adaptive framework ensures that limited resources are directed for maximum impact.

8.2. Flexible and Climate-Responsive Surveillance Systems

Conventional monitoring of marine invasive species, built around fixed sites and rigid schedules, is poorly aligned with a climate-driven risk landscape that shifts rapidly in space and time, often resulting in detection years after establishment [188]. Clear operational benchmarks are therefore essential and should include short time-to-detection targets (eg. weeks rather than years), minimum surveillance coverage such as routine eDNA monitoring across a defined proportion of high-risk ports and canals, and documented activation of response measures following early-warning signals. Climate-smart surveillance replaces this static approach with an adaptive, risk-based logic in which sampling intensity increases during high-vulnerability periods, including marine heatwaves and post-storm disturbances, and in emerging invasion frontiers such as newly accessible Arctic ports. Multiple data streams from satellites, *in-situ* sensors, eDNA surveys, port inspections, and citizen science are integrated into a common platform, enabling cross-validation of alerts and near-real-time risk mapping. Predefined trigger thresholds, such as detection of a priority species' DNA or anomalous thermal events in high-traffic ports, activate rapid, standardized responses, allowing surveillance effort to scale up when and where risk peaks and relax during stable conditions, making monitoring both more efficient and more effective.

8.3. Community-Based Monitoring and Indigenous Knowledge Integration

Equity and inclusivity are central to climate-smart biosecurity, particularly for managing marine invasive species in socially and ecologically exposed regions [59]. Engaging local communities, including Indigenous peoples, strengthens both the effectiveness and legitimacy of surveillance and response by embedding monitoring within lived coastal systems. Indigenous and local knowledge provides deep, place-based insight into environmental variability, species behavior, and historical baselines, improving interpretation of ecological signals and guiding targeted eDNA sampling. Community-based monitoring expands surveillance capacity at low cost by mobilizing trained fishers, divers, students, and coastal residents as a distributed observation network; in the Mediterranean, for example, citizen divers have played a key role in tracking and removing invasive lionfish, directly reducing local impacts. Digital tools such as mobile applications and messaging platforms enable rapid reporting, geotagged documentation, and scientific verification, shortening detection-to-response timelines. Beyond surveillance, community involvement strengthens governance by building trust and compliance, as stakeholders who co-develop management strategies are more likely to adhere to regulations, consistent with SDG 16 on inclusive institutions. Co-management arrangements in which local groups lead control actions with institutional support, such as community-led lagoon cleanups or volunteer rapid response teams, are increasingly effective in marine settings. This approach aligns with the UN Decade of Ocean Science's emphasis on multi-knowledge integration and advances environmental justice, as Indigenous and coastal communities often experience the earliest and most severe invasion impacts. Effectiveness can be evaluated through indicators such as community participation rates, reporting latency from first observation to verification, spatial coverage of community surveillance, and the proportion of community-triggered alerts that result in confirmed detections or management action.

8.4. Building a Global Framework for Climate-Smart Biosecurity Hubs

Climate-smart marine biosecurity requires both local action and global coordination. A strong international framework would include regional early-warning hubs that use tools such as eDNA, AI, and remote sensing to detect threats and guide responses [185]. Legal harmonization between countries that share marine pathways would ensure consistent standards, shared watchlists, and joint response plans. Technology transfer and funding support for vulnerable nations would help build essential capacity for monitoring and control. Inclusive governance platforms involving governments, scientists, industries, and communities would improve trust and implementation. A global coordination body could connect regional efforts, standardize methods, and facilitate data sharing, including a shared database of invasive species genomes. Together, these steps would create a more unified, adaptive system for protecting marine ecosystems and coastal economies in a changing climate.

9. Policy and Research Recommendations

Effectively addressing MIS under accelerating climate change requires a shift from reactive containment toward a proactive, integrated, and climate-informed biosecurity regime. This section outlines five strategic pillars: monitoring, governance, technology, restoration, and metrics, that collectively underpin a resilient and adaptive framework for marine biosecurity. Each recommendation supports global policy instruments, including the SDGs, the Kunming–Montreal Global Biodiversity Framework, and the UN Decade of Ocean Science [189].

9.1. Monitoring

A climate-ready biosecurity system requires a global early-warning network that couples molecular detection with autonomous observing and predictive analytics [57, 190]. Progress in monitoring implementation can be assessed using indicators such as the proportion of high-risk entry points under routine molecular surveillance, reductions in detection lag following introduction events, and the frequency with which early warnings trigger management action. Core infrastructure would include eDNA sampling stations at major ports, shipping chokepoints, ballast discharge areas, aquaculture hubs, and climate-sensitive habitats, routinely screening for priority invaders. These data streams should be linked with AIS vessel tracking and oceanographic observations so that AI models can flag high-risk events, such as the arrival of ships from invasion hotspots during marine heatwaves. Positive detections or flagged conditions can then trigger targeted inspections, containment, or rapid eradication efforts. Sharing results through interoperable regional platforms would allow detections in one hub (e.g., Singapore) to act as early warnings for connected ports (e.g., Dubai), reflecting real trade connectivity. Such a network simultaneously advances SDG 14.a (marine research and technology) and SDG 17.6 (scientific cooperation), while making monitoring more strategic, faster, and cheaper than purely manual approaches.

9.2. Governance

Legally binding regional biosecurity compacts are essential for effectively managing MIS across borders, especially under climate change [167]. Since most MIS pathways cross borders via shipping, aquaculture, or ocean currents, governance must be regional, not solely national. These compacts should incorporate dynamic, climate-informed risk assessments, requiring each member country to update invasive species watchlists annually based on projected environmental changes. They should also establish coordinated response mechanisms, such as a regional rapid-response team or emergency fund, to assist affected countries quickly after an invasion is detected. This mirrors disaster response models and enables faster containment. Compacts can be built into existing structures, such as Regional Seas Programs or Regional Fisheries Management Organizations (RFMOs), with dedicated MIS mandates to streamline implementation. Harmonizing surveillance protocols, enabling real-time data sharing, and coordinating actions across borders will reduce fragmentation and improve collective preparedness. These compacts support SDG 14.c by strengthening international marine conservation law, SDG 16.6 by enhancing institutional effectiveness, and SDG 17.14 by aligning environmental, trade, and maritime policies toward a shared biosecurity goal.

9.3. Technology

Incentivizing the adoption of low-risk marine infrastructure and antifouling innovations is a key strategy for preventing the spread of MIS [191]. Infrastructure-related vectors, particularly hull fouling and open-water aquaculture systems, are major contributors to invasions. To address this, governments and industry bodies can offer financial incentives such as tax credits, subsidies, or certification advantages for vessels using advanced antifouling coatings and hull designs that minimize biofouling (e.g., smoother hull surfaces or internal seawater systems) [192]. Support should also be directed toward closed-loop or land-based aquaculture, which reduces the risk of escapes. Fast-tracking permits and providing innovation grants can encourage uptake of these safer technologies. Similarly, investment in research on effective yet environmentally safe biocidal coatings will help meet both biosecurity and environmental goals. Ports can further reduce risks by installing in-water cleaning stations that capture and treat biofouling debris, preventing live organisms from being released during hull maintenance. Embedding MIS prevention into the design and operation of maritime infrastructure transforms mitigation from a reactive measure into a proactive, source-level strategy. These actions align with SDG 9.5 (innovation in industry and infrastructure) by promoting sustainable maritime technologies, and SDG 12.4 by encouraging safer chemical use and cleaner antifouling methods.

9.4. Restoration

Restoring native blue carbon and foundation habitats is a vital strategy to enhance ecosystem resistance to MIS [193]. Healthy, biodiverse systems offer natural biotic resistance, reducing the likelihood that invaders can establish. Restoration goals should explicitly include MIS resilience. For example, restoring oyster reefs or seagrass beds with hardy, genetically diverse stock (and associated fauna) to better resist invasive mussels or algae. Key habitats like mangroves, salt marshes, coral reefs, kelp forests, and seagrass meadows not only support biodiversity and fisheries but also create complex, biomass-rich environments that are less susceptible to invasion [121]. A vibrant coral reef, for instance, is more resistant to algal overgrowth, and dense native seagrass meadows can outcompete invasive species such as *Halophila stipulacea*. Restoration sites should be paired with ongoing biosecurity monitoring; they can serve as defended strongholds where any invasive arrivals are detected early and removed before they become established. Care must also be taken to avoid unintentionally introducing invaders during restoration by using clean, locally sourced materials. This approach harnesses ecosystem strength as a natural barrier to invasions, delivering multiple co-benefits: enhanced biodiversity, improved fisheries, greater carbon sequestration, stronger coastal protection, and increased climate resilience. It directly supports SDG 13.1 (climate adaptation), SDG 14.2 (marine ecosystem restoration), and SDG 15.3 (land and ecosystem rehabilitation), reinforcing the role of restoration as both a conservation and a biosecurity strategy.

9.5. Metrics and Decision Tools

A Marine Invasive Risk Index (MIRI) can support policymakers by integrating key drivers of marine invasion risk into a single, quantitative and updateable score. The index would combine indicators of climate exposure (e.g., frequency of marine heatwave days, sea surface temperature anomalies), vector intensity (e.g., shipping traffic volume, aquaculture extent), ecosystem sensitivity (e.g., native biodiversity levels, habitat degradation), and management capacity (e.g., surveillance coverage, early detection and rapid response readiness) [194, 195]. Higher MIRI values would indicate greater overall invasion risk.

Spatially explicit MIRI outputs could be mapped to identify invasion hotspots and updated periodically to track temporal trends. By providing a consistent, trackable measure of invasion risk, MIRI offers a practical mechanism for assessing progress toward climate-resilient biosecurity and supports evaluation of commitments under the Kunming–Montreal Global Biodiversity Framework, particularly Target 6. As such, declining MIRI values over time would signal improving biosecurity performance and climate adaptation effectiveness.

9.6. Summary of Climate-Smart Biosecurity Action Pillars

Climate-smart marine biosecurity rests on five key pillars:

- Build a global eDNA and AI-enabled monitoring network for real-time detection and rapid response to invasions.
- Establish regional biosecurity compacts with shared legal frameworks and coordinated protocols to address transboundary risks.
- Promote antifouling innovation and MIS-safe practices in aquaculture and shipping to reduce vector pressures.
- Restore blue carbon and foundation habitats to enhance native ecosystem resistance to invasions.
- Implement a Marine Invasive Risk Index (MIRI) to map and track risk, guiding policy and resource allocation.

Together, these actions offer a scalable, proactive approach to reduce invasion threats, support climate adaptation, and protect coastal economies.

10. Conclusion

This review establishes that climate change is no longer a secondary modifier of marine invasion dynamics but a primary accelerator, reshaping invasion pathways, lowering establishment barriers, and increasing the scale and persistence of marine invasive species impacts. Three key findings emerge. First, climate-driven warming, circulation shifts, and disturbance regimes are systematically expanding invasion windows and opening new biogeographic corridors. Second, existing biosecurity and governance frameworks remain largely static and reactive, lacking climate-integrated risk metrics, effective early-warning systems, and coordinated regional responses. Third, although tools for anticipatory biosecurity now exist including molecular surveillance, predictive modeling, and composite risk indices their uptake into routine management remains limited and uneven. Together, these findings highlight the need to shift marine biosecurity from post-establishment control toward climate-smart, predictive, and coordinated systems that can support timely intervention and long-term ecosystem resilience.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI and AI-assisted Technologies

During the preparation of this work, the authors used ChatGPT (OpenAI) for initial writing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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