Global invasion dynamics of marine macroalgae: ecological impacts, vectors of spread, and management challenges

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Abstract. Marine macroalgae play critical ecological and socioeconomic roles in coastal ecosystems, yet the global proliferation of non-indigenous macroalgal taxa poses a significant threat to marine biodiversity and habitat integrity. This mini-review synthesizes contemporary research on the most prominent invasive marine macroalgae worldwide, including *Undaria pinnatifida*, *Sargassum muticum*, *Caulerpa spp*., *Asparagopsis spp*., and the rapidly expanding *Rugulopteryx okamurae*. The literature reveals that while these species share highly competitive life-history traits, their invasion success and ecological impacts are highly context-dependent and density-driven. Direct consequences range from severe community simplification, shading, and spatial exclusion of native biota to subtle, localized alterations and unexpected facilitative interactions. Anthropogenic activities - predominantly shipping, aquaculture, and climate-induced warming - serve as primary vectors for primary introduction and secondary spread, complemented by localized biological vectors. Given the high economic and ecological costs associated with eradication post-establishment, management strategies are increasingly shifting toward predictive risk mapping, mechanism-based monitoring, and the preservation of native canopy integrity to mitigate disturbance-mediated invasions.
Keywords: anthropogenic disturbance, biodiversity loss, coastal management, ecological impacts, invasion vectors, invasive marine macroalgae.

Introduction. Marine macroalgae are fundamental components of coastal and marine ecosystems, contributing substantially to ecosystem structure, productivity, and functioning (Soumantri et al., 2024; Adrias et al., 2025; Wantania et al., 2025). Through their high photosynthetic capacity, they contribute to primary production and carbon fixation, while their biomass and complex three-dimensional structures provide habitat, refuge, and feeding grounds for a wide range of marine organisms (Ware et al., 2019). Marine macroalgae also participate in nutrient cycling and organic matter dynamics, thereby influencing energy flows and biogeochemical processes within coastal environments. Their presence can increase habitat complexity and contribute to the maintenance of ecological interactions and biological diversity, particularly in shallow marine habitats (Petrescu-Mag et al., 2026). Beyond their ecological significance, marine macroalgae have considerable economic and societal importance, being relevant to food production, biotechnology, agriculture, aquaculture, pharmaceuticals, and other bio-based applications (Gazali et al., 2023; Latuconsina et al., 2023; Warouw et al., 2024; Nur et al., 2025). Their capacity to assimilate nutrients and carbon, together with their rapid growth and biomass production, has also attracted increasing attention in the context of ecosystem restoration, climate-change mitigation, and the development of sustainable marine resources (Petrescu-Mag et al., 2023).

Despite these predominantly beneficial ecological and socioeconomic roles, marine macroalgae can also have negative consequences for ecosystem integrity under particular circumstances. When certain macroalgal taxa become established outside their native geographical ranges and develop invasive populations, their ecological effects may extend beyond their local contribution to ecosystem functioning and may negatively influence native communities and biodiversity. Thus, the ecological importance of marine macroalgae must also be considered in the context of their potential to become invasive, making invasive marine macroalgae an important subject in contemporary biodiversity and marine ecology research (Petrescu-Mag et al., 2026).

The most invasive marine macroalgae worldwide are concentrated in a relatively small set of repeatedly documented taxa, especially *Undaria pinnatifida, Sargassum muticum, Caulerpa taxifolia, Caulerpa cylindracea, Asparagopsis armata, Asparagopsis taxiformis*, and the rapidly expanding *Rugulopteryx okamurae* (Schaffelke et al., 2006; Klein & Verlaque, 2008; Montefalcone et al., 2015; Navarro-Barranco et al., 2018; Silva et al., 2021; García-Gómez et al., 2021; Laamraoui et al., 2024). Across the literature, these taxa are important not simply because they establish outside their native range, but because they can restructure habitat, alter native assemblages, and spread efficiently through shipping, aquaculture, disturbance, and warming-enabled range expansion (Schaffelke et al., 2006; Valentine et al., 2007; Mancuso et al., 2023).

Purpose of the Study. The primary purpose of this study is to provide a comprehensive synthesis of the global dynamics, ecological ramifications, and management challenges associated with invasive marine macroalgae. Specifically, this mini-review aims to: i) identify and contrast the trajectories of the world's most critical non-indigenous macroalgal taxa (e.g., *U. pinnatifida*, *S. muticum, C. taxifolia, C. cylindracea*, and *R. okamurae*) across highly vulnerable recipient regions such as the Mediterranean Sea, the Northeast Atlantic, and Australasia; ii) examine the precise ecological mechanisms underlying macroalgal invasions, evaluating how density-dependent competition for light and space drives habitat restructuring, taxonomic homogenization, and the alteration of native assemblages; iii) analyze the pathways of introduction and secondary spread, differentiating between major global anthropogenic vectors (shipping and aquaculture) and localized biological transport mechanisms; iv) evaluate current management paradigms, shifting the focus from reactive eradication attempts toward proactive prevention, functional trait assessment, and risk mapping.

Global Patterns. Marine macroalgae form a substantial fraction of non-indigenous marine species, and introduced taxa occur across most major algal orders, indicating that invasion is taxonomically widespread rather than restricted to a few exceptional lineages (Schaffelke et al., 2006; Epstein & Smale, 2017). At the systems level, invasive macroalgae are treated as major threats because they can monopolize space, function as ecosystem engineers, change food webs, and deplete ecosystem services (Schaffelke et al., 2006; Silva et al., 2021; Blanco et al., 2021; García-Gómez et al., 2021).

The receiving regions most emphasized in this literature are temperate Australasia, the northeast Atlantic, the Mediterranean, the Iberian Peninsula, the Strait of Gibraltar, the SW Atlantic, and island systems such as Hawaii and Ireland, showing that invasions are now geographically global rather than basin-specific (Palomo et al., 2016; South et al., 2017; Blanco et al., 2021; Mancuso et al., 2023; Laamraoui et al., 2024; Eggertsen et al., 2025; Zanolla et al., 2025). The Mediterranean stands out as especially vulnerable because introductions are accelerated by shipping, the Suez Canal, aquarium trade, and warming waters, with estimates of eight new non-indigenous species per year across the basin (Mancuso et al., 2023).

The mechanisms that repeatedly emerge are strong vector supply, suitable environmental conditions, and species traits that facilitate establishment, while disturbance is one of the clearest common facilitators of establishment and spread for several prominent invaders, including *Codium fragile, S. muticum, U. pinnatifida*, and often other canopy-forming seaweeds (Schaffelke et al., 2006; Valentine et al., 2007). Yet life-history traits alone do not reliably predict invasiveness, because different invaders succeed through different combinations of dispersal, physiology, competition, and environmental opportunity (Valentine et al., 2007; Li et al., 2023).

Major Species. Among kelps, *U. pinnatifida* is one of the best-studied and most globally successful invaders, established across 13 countries on four continents and widely regarded as one of the world's worst invasive species (Epstein & Smale, 2017; South et al., 2017). In Australasia it has persisted for at least three decades, invades open space, turf, and canopy gaps, and is expected to continue spreading because it tolerates wide temperature variation and continues to move via vessels and aquaculture (South et al., 2017). However, *Undaria* also illustrates that invasion success and ecological impact can decouple, because some invaded regions show high biomass but relatively few direct community-level impacts (Epstein & Smale, 2017; South et al., 2017).

S. muticum remains one of the classic invasive brown macroalgae, spread widely across Europe after its introduction into the UK in 1973, and is repeatedly used as a model species for studying competition, dispersal, and management difficulty (Schaffelke et al., 2006; Epstein & Smale, 2017). Abundant populations are still recorded in parts of Ireland, where it was the most widespread abundant invasive seaweed in a recent broad survey, even though some regional contraction was also detected (Zanolla et al., 2025). *Codium fragile* is another recurrent focal invader, notable mechanistically because nitrogen acquisition has been directly implicated in its invasion success, while recent Irish surveys indicate continued spatial expansion (Valentine et al., 2007; Zanolla et al., 2025).

Among green algae, *C. taxifolia* and *C. cylindracea* are the most notorious Mediterranean examples, but their long-term trajectories differ sharply. *C. taxifolia* initially spread exponentially and generated exceptional concern, yet later declined and disappeared from many formerly colonized areas in the Ligurian Sea. By contrast, *C. cylindracea* has expanded steadily since its first appearance, continues to increase its range and habitat occupancy, and now exceeds the peak abundance once attained by *C. taxifolia* in the same region (Montefalcone et al., 2015).

Among red algae, *A. armata* and *A. taxiformis* are prominent because they can simplify recipient assemblages even when effects differ by trophic level and locality (Navarro-Barranco et al., 2018; Silva et al., 2021; Mancuso et al., 2023). *R. okamurae*, although a more recent invader, now stands out for unusually rapid regional proliferation and massive detached biomass production, making it one of the most alarming contemporary cases in the eastern Atlantic-Mediterranean interface (García-Gómez et al., 2021; Laamraoui et al., 2024) (Table 1).

Table 1
Representative invasive marine macroalgae emphasized in the supplied literature, their regions of spread, and dominant impact patterns

Species	*Main invaded regions in supplied literature*	*Characteristic invasion pattern*	*Typical reported impact*
Undaria pinnatifida	Australasia, Mediterranean, NE Atlantic, Argentina	Invades gaps, turf, open space; spreads via vessels and aquaculture	Often limited or subtle community effects, but can suppress some native kelps locally (South et al., 2017; Epstein et al., 2019)
Sargassum muticum	Europe, UK seagrass beds, Canada, Ireland	Disturbance-associated spread; broad regional establishment	Shading, reduced native richness at high cover, effects on seagrass condition (White & Shurin, 2011; Firth et al., 2024)
Caulerpa taxifolia	Mediterranean	Early explosive spread followed by regional decline	Severe concern over habitat impacts, but persistence can be unstable (Montefalcone et al., 2015)
Caulerpa cylindracea	Mediterranean, Canary Islands	Sustained expansion and rising occupancy	Serious ecological concern; can facilitate other NIS and habitat shifts (Klein & Verlaque, 2008; Mancuso et al., 2023)
Rugulopteryx okamurae	Strait of Gibraltar, Mediterranean, Atlantic islands and coasts	Very rapid post-2015 expansion across two basins	Strong spatial exclusion, native biota impacts, major stranded biomass loads (Laamraoui et al., 2024; García-Gómez et al., 2021).

Ecological Impacts. The dominant direct mechanism reported across studies is competition for space and light, often producing reduced abundance, biomass, or richness of native primary producers when invaders become dense (White & Shurin, 2011; García-Gómez et al., 2021). For *S. muticum*, experimental work showed strongly density-dependent effects: high cover reduced native richness, shading was more important than space competition, and the invader's production did not compensate native biomass losses. Yet low cover did not uniformly harm native assemblages, and slight facilitative effects at low abundance were also observed (White & Shurin, 2011).

Effects on habitat-forming plants and associated fauna can extend beyond simple replacement. In UK seagrass beds, *S. muticum* co-occurrence was associated with reduced *Zostera marina* density and lower phenolic content, while photosynthetic responses were inconsistent and nutrient partitioning was unaffected, suggesting simultaneous stress and partial resilience (Firth et al., 2024). More broadly, invasive macrophytes across aquatic systems show strong negative effects on abundance, especially of macrophytes and fish, while diversity declines are less consistently detected than abundance declines (Gallardo et al., 2016).

Several studies show that some impacts are subtle rather than catastrophic. Two years of press-removal of *U. pinnatifida* found no difference in understory assemblages overall, but three native kelps increased after removal, and *Saccorhiza polyschides* responded most strongly, with 3-6 times greater abundance and biomass under reduced competition (Epstein et al., 2019). This explains why *Undaria* is often described as a high-success invader with inconsistent or location-specific ecological effects rather than a universal ecosystem transformer (Epstein & Smale, 2017; South et al., 2017).

Other invaders produce clearer biodiversity erosion. In Portuguese rock pools, *A. armata* invasion was associated with lower species richness and more constant, less variable assemblage structure, with *Ellisolandia elongata* identified as the main algal species affected (Silva et al., 2021). In the Mediterranean, *A. taxiformis* supported impoverished epifaunal assemblages compared with native *Halopteris scoparia*, with lower diversity, abundance, and species number across sites, as well as biotic homogenization of associated fauna (Navarro-Barranco et al., 2018).

The emerging case of *R. okamurae* is notable for aggressive colonization across many resident taxa and substrates. It can settle on a wide range of natural and artificial substrata, interacted with 43 resident macroalgal species in surveys, and was generally favored in spatial growth success over resident species. Observed overgrowth and epiphytic interactions affected multiple resident taxa, indicating a broad capacity for spatial exclusion rather than species-specific interference alone (García-Gómez et al., 2021).

Impacts are not restricted to the Northern Hemisphere. On the SW Atlantic coast of Argentina, *Ahnfeltiopsis sp***.** increased from 3 to 11% cover over five years while biomass rose 27-fold, and *Schizymenia dubyi* also expanded across tidal levels; together they altered substrate and the structure and composition of benthic assemblages (Palomo et al., 2016). In Hawaii, invasive macroalgae include six recognized invasive species on O'ahu, and trait-based analysis suggests that successful invaders share highly competitive traits while reducing overall functional diversity where they dominate (Eggertsen et al., 2025).

Impacts also include facilitation and community reassembly rather than only outright suppression. Some invasive seaweeds can increase primary productivity or provide biogenic habitat, as reported for *Undaria* in Australasia, and *S. muticum* at low cover can increase native richness relative to complete removal (White & Shurin, 2011; South et al., 2017). This is why the literature repeatedly cautions against treating all invasive macroalgae as uniformly high-impact across all regions and all response variables (Epstein et al., 2019) (Table 2; Figure 1).

Table 2

Comparison of the main response variables used to infer ecological impact in the supplied macroalgal invasion literature

Species	*Evidence type*	*Main biological response*	*Interpretation*
Undaria pinnatifida	Long-term removal experiment	Native annual kelp increased 3-6× after removal	Often subtle, but real competitive effects can emerge experimentally (Epstein et al., 2019)
Sargassum muticum	Density-manipulation experiment	High cover reduced native richness through shading	Impact strength is density dependent (White & Shurin, 2011)
Asparagopsis armata	Rock-pool exclusion experiment	Lower richness and more homogenized algal assemblages	Community simplification is likely (Silva et al., 2021)
Asparagopsis taxiformis	Faunal comparison across sites	Lower epifaunal diversity, abundance, and species number	Strong bottom-up effects on associated fauna (Navarro-Barranco et al., 2018)
Rugulopteryx okamurae	Multi-year field surveys	Broad substrate use and favored spatial growth over residents	High contemporary invasion risk (García-Gómez et al., 2021).

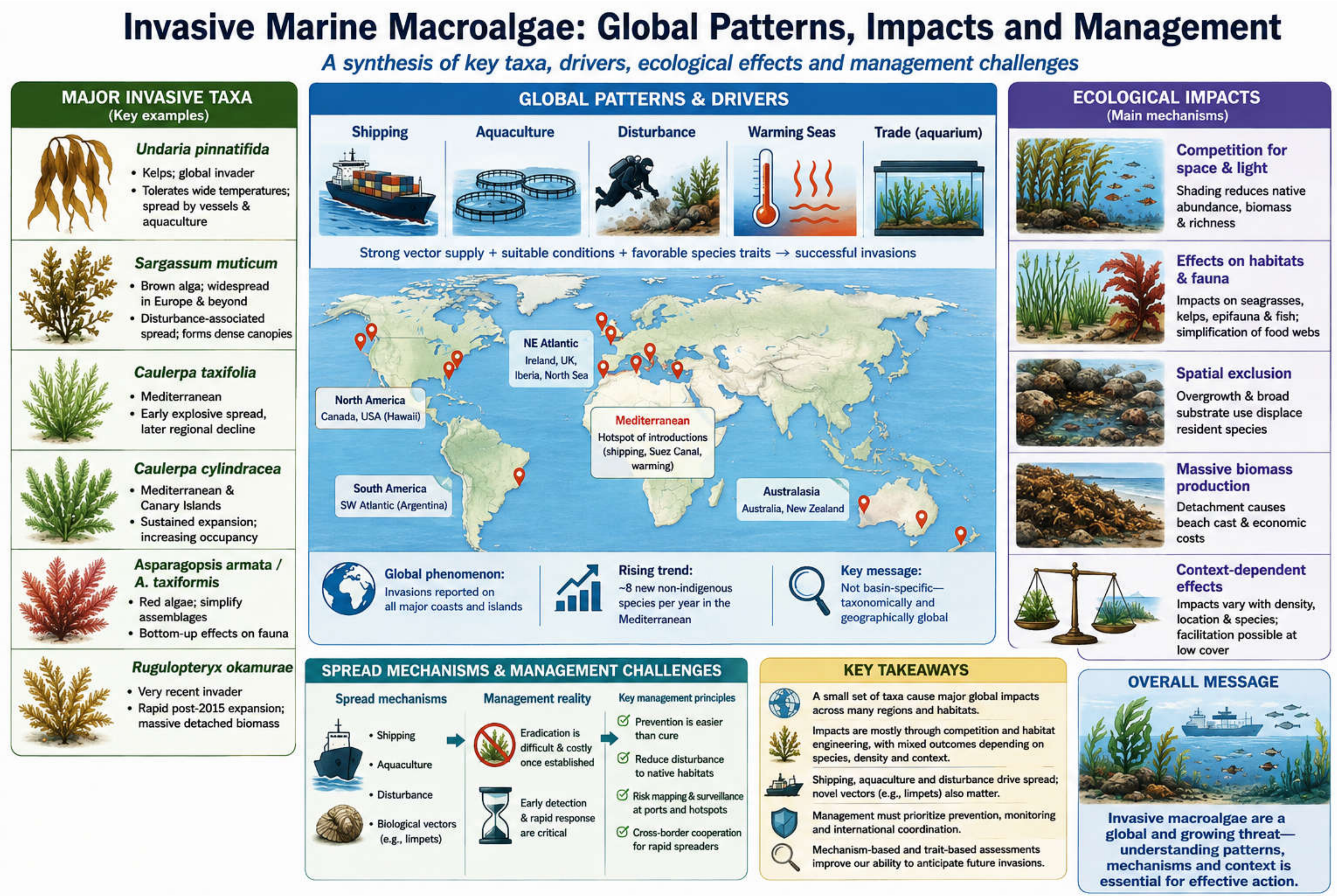

Figure 1. Global distribution and ecological impacts of major invasive marine macroalgae.

Spread and Management. The most consistently supported introduction and secondary spread vectors are shipping, aquaculture, and disturbance-linked human activity (South et al., 2017; Blanco et al., 2021; Mancuso et al., 2023; Firth et al., 2024). Distribution modelling on the Iberian Peninsula showed that physico-chemical variables explained much of invasive macroalgal occurrence, but anthropogenic variables such as vessel size, shipping lines, port distance, and population density substantially improved predictions. This combination of environmental suitability and propagule pressure helps explain why southern Galician rias emerged as invasion hotspots and why ports are emphasized as surveillance priorities (Blanco et al., 2021).

The literature also documents less conventional spread mechanisms. In UK seagrass systems, limpets acted as epibiotic carriers of *S. muticum*, with 15% of rocky-shore occurrences attached to live limpets and 5% of seagrass-bed occurrences attached to dead limpets, identifying a previously unreported transport pathway into sensitive habitat. Such findings matter because they show that invasion pathways cannot be reduced to shipping alone; local biological vectors can mediate final delivery into recipient habitats (Firth et al., 2024).

Eradication and control are generally difficult once marine macroalgae are established. *U. pinnatifida* management is repeatedly described as minimally successful overall, even though very early rapid response can work in exceptional cases at very high cost (Epstein & Smale, 2017; South et al., 2017). The same broader lesson appears across seaweed invasion theory: prevention is easier and less costly than cure, and when disturbance facilitates establishment, reducing anthropogenic disturbance to native canopies can lower risk before dominance becomes self-maintaining (Valentine et al., 2007).

This management challenge is intensified by species-specific dynamics. *C. taxifolia* and *C. cylindracea* followed divergent spread kinetics, showing that one invader can collapse after rapid expansion while another continues steady increase in the same sea, so generalized forecasting is unsafe (Montefalcone et al., 2015). *R. okamurae* likewise now requires international monitoring and cross-border policy coordination because its spread since 2015 already spans Mediterranean and Atlantic coasts of Europe and Africa (Laamraoui et al., 2024).

Several recent studies therefore shift emphasis from simple species listing toward risk mapping, mechanism-based monitoring, and functional assessment. Trait-based work from Hawaii argues that invaders can reduce functional diversity while introducing competitively advantageous trait combinations, offering a way to anticipate future impacts before total dominance occurs (Eggertsen et al., 2025). Recent Irish baseline mapping similarly shows that even where only a few species are currently abundant, broader distribution of multiple invasive seaweeds constitutes a dormant threat that warrants continued surveillance (Zanolla et al., 2025).

Conclusions. Marine macroalgal invasions represent a complex and context-dependent component of global marine biodiversity change. The evidence synthesized in this mini-review indicates that invasive macroalgae can substantially modify coastal communities through competition for space and light, habitat restructuring, spatial exclusion, community simplification, and changes in associated fauna, although the magnitude and direction of these effects vary considerably among species, habitats, invasion stages, and environmental conditions. High abundance and rapid spread do not necessarily translate into uniformly severe ecological impacts, as demonstrated particularly by *U. pinnatifida* and *S. muticum*, for which ecological effects may range from subtle competitive responses to pronounced reductions in native abundance and richness at high densities. Conversely, taxa such as *A. armata*, *A. taxiformis*, and *R. okamurae* illustrate how invasive macroalgae can generate broader changes in community structure and associated biodiversity. The contrasting trajectories of *C. taxifolia* and *C. cylindracea* further demonstrate that invasion dynamics cannot be reliably inferred from a single generalized model, even within the same biogeographic region.

Overall, invasion success appears to emerge from the interaction among propagule pressure, environmental suitability, disturbance, dispersal capacity, and species-specific functional traits rather than from life-history characteristics considered in isolation. Shipping and aquaculture remain major pathways of introduction and secondary spread, while localized biological transport mechanisms may facilitate the final transfer of invasive material into vulnerable habitats. These interacting processes, together with climate-driven environmental change, increase the difficulty of predicting where and when new invasions will become established. The evidence also reinforces the principle that management becomes progressively more difficult and costly after establishment, whereas prevention, early detection, targeted surveillance, and the maintenance of intact native canopy-forming communities can reduce invasion risk before populations become self-sustaining.

The most appropriate management perspective is therefore not based solely on attempting to eradicate established invaders, but on anticipating invasion risk and understanding the ecological mechanisms that determine impact. Predictive distribution modelling, functional-trait assessment, mechanism-based monitoring, and sustained regional surveillance should be integrated with measures aimed at reducing propagule pressure and anthropogenic disturbance. Such an approach is particularly important in regions exposed to intense maritime traffic, aquaculture, warming waters, and repeated introductions. Ultimately, invasive marine macroalgae should be regarded not as uniformly destructive organisms, but as context-dependent ecological agents whose effects can range from relatively limited competitive interactions to profound alterations of habitat structure and biodiversity. Recognizing this variability while prioritizing prevention and early intervention provides the strongest basis for protecting the ecological integrity and resilience of coastal marine ecosystems.

Acknowledgements. OpenAI ChatGPT-5.3 - https://openai.com - was used for plate editing. The authors assume full responsibility for the content and materials selected and processed for publication.

Authors Contributions. Conceptualization: IBD; Writing - original draft: IBD, ZAG, IGO; Writing - review & editing: AMD, IVPM.

Conflict of Interest. The authors declare that there is no conflict of interest.

Data Availability. Not applicable.

Funding. This research received no external funding.

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Received: 29 July 2026. Accepted: 03 September 2026. Published online: 07 September 2026.
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How to cite this article:
Bănățean-Dunea, I., Grabán, Z. A., Oroian, I. G., Petrescu-Mag, I. V., Dăescu, A. M. (2026). Global invasion dynamics of marine macroalgae: ecological impacts, vectors of spread, and management challenges. *AACL Bioflux*, *19*(5), 2073-2082.