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Impacts of Urbanization-Driven Coastal Eutrophication on Coral Reefs

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Abstract:
Rapid urbanization has fundamentally altered coastal environments by intensifying nutrient loading from agriculture, wastewater, aquaculture, and land-use change. This review synthesizes current studies on the effects of urbanization-driven eutrophication on coral reefs, from individual physiological stress to population decline, community restructuring, and loss of ecosystem services. Excessive inputs of nitrogen and phosphorus, especially under imbalanced N:P ratios, disrupt coral–algae symbiosis, reduce calcification, and heighten susceptibility to bleaching. At the population and community levels, sustained nutrient enrichment causes sensitive coral species to decline. Elevated dissolved inorganic nitrogen significantly alters the composition and relative abundance of coral symbiotic microorganisms, reshaping microbial community structure and consequently impacting the overall health and ecological function of coral reefs. These changes have disrupted crucial ecosystem services, including fishery yields, coastal protection, and cultural services, all of which are essential for the well-being of coastal communities. The review also highlights that integrated land-sea management, improved wastewater treatment, restoration of ecological buffer zones, and coordinated cross-regional governance are urgently needed to address the pressures of eutrophication. These measures are vital for maintaining the ecological integrity and socioeconomic benefits of coral reefs in expanding urban coastal areas.

Keywords: Urbanization; Coastal eutrophication; Nutrient enrichment; Coral reefs.

1. Introduction

With the rapid progression of global urbanization, coastal regions are experiencing increasing population concentration. By 2020, low-lying coastal areas within 100 kilometers of the shore were home to approximately 2.15 billion people, a growth of nearly one billion since 1990 [1]. Coastal population growth typically drives extensive land development and infrastructure construction, leading to substantial discharges of domestic, agricultural, and industrial wastewater into marine environments. These inputs cause excessive accumulation of nitrogen and phosphorus in nearshore ecosystems. Eutrophication, driven by the over-enrichment of such nutrients, triggers a cascade of ecological problems, including algal blooms, water turbidity, and hypoxia [2]. Urbanization often leads to nutrient inputs that are larger in scale, faster in rate, and more persistent than those from natural sources. These cumulative pressures have become a major contributor to coastal eutrophication. This is particularly concerning as coastal waters are important habitats for many marine species. Ecosystems such as seagrass beds, coral reefs, and mangroves provide feeding, breeding, and shelter grounds for fish, crustaceans, shellfish, marine mammals, and many other organisms. Such nutrient enrichment often stimulates algal blooms, destabilizing coastal food webs. Furthermore, nutrient overloading can alter the community structure of planktonic and benthic organisms, reducing the competitive fitness of organisms adapted to low-nutrient conditions [3]. These changes undermine the ability of coastal ecosystems to remain stable and resilient.

Coral reef ecosystems are among the most ecologically and economically valuable habitats in the ocean. Despite covering less than 1% of the ocean floor, coral reefs host approximately 25% of all marine biodiversity and deliver vital services, including fisheries, coastal protection, and tourism [4]. In response to accelerating coral reef degradation, the international community has prioritized their protection and restoration. For instance, Sustainable Development Goal 14 established a target to protect at least 10% of marine and coastal areas by 2020 [5]. Complementing this policy commitment, the International Coral Reef Initiative (ICRI) has made significant contributions to protection of reef ecosystems and their integration into global environmental governance. In this context, an increasingly concerning issue is the eutrophication of coastal waters, which poses a growing threat to coral survival. This challenge is closely linked to the rapid expansion of urban development in coastal areas. Nutrient inputs from urban development endanger the health and survival of corals. They also diminish the capacity of coral reefs to support marine biodiversity and supply essential ecosystem services. These combined effects increase the risk to the ecological functions of these ecosystems.

Existing studies have shown that under urbanization pressures, agricultural runoff, sewage discharge, and aquaculture expansion significantly contribute to nutrient inputs in coastal waters [6]. However, there is still a lack of systematic reviews that explicitly adopt "urbanization-driven eutrophication" as a central framework. This review summarizes studies on how coastal eutrophication driven by urbanization affects coral reefs. Impacts are reviewed at physiological, community, and ecosystem scales, with attention to governance and management strategies. It aims to provide a scientific basis for preserving the ecological integrity of coral reefs in increasingly urbanized coastal regions.

2. Sources of Eutrophication in Coastal Waters

The sources of coastal eutrophication primarily include agricultural inputs, wastewater discharges, atmospheric deposition, and aquaculture. Over the period from the 1860s to 2010s, global anthropogenic nitrogen inputs underwent a marked increase, rising to 267.23 Tg N yr^{-1} from 29.05 Tg N yr^{-1} [7]. Since 1961, global synthetic fertilizer use has increased more than fivefold, reaching 20 Tg yr^{-1} by 2020, and has become the dominant agricultural source of nitrogen [2]. Beyond agricultural inputs, urban sewage has also emerged as a major and growing source of nutrients to coastal waters. In 2020, municipal sewage discharged 9.3 Tg N yr^{-1}, of which 6.2 Tg N yr^{-1} was delivered directly to coastal waters, equivalent to about 40% of the agricultural nitrogen input [2, 8, 9]. Among these discharges, 63% originated from sewered systems, 32% from untreated direct discharges, and 5% from septic systems [2]. In addition to nitrogen, phosphorus derived from agricultural and human sources is another major driver of eutrophication. Collectively, these figures demonstrate that multiple nutrient sources contribute to eutrophication in nearshore waters, and the rapid urbanization of coastal regions has become a primary force driving the degradation of coastal ecosystems.

3. Responses of Coral Reefs to Eutrophication

3.1 Individual-Level Responses

Urbanization-driven coastal eutrophication alters coral metabolism, nutrient uptake, and symbiosis at the individual level. In lab experiments, *Acropora millepora* and *Platygyra crosslandi* exposed to DIN levels from 53 to 348 $\mu mol \cdot L^{-1}$ and DIP from 0.54 to 8.13 $\mu mol \cdot L^{-1}$ showed reduced calcification within the 19-140 $\mu mol \cdot L^{-1}$ DIN range, with net skeletal dissolution at higher concentrations [10]. $\delta^{13}C$ in tissue and symbionts was slightly depleted compared to controls, and tissue $\delta^{15}N$ increased (by 50% in *A. millepora* and 16% in *P. crosslandi* under

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high nutrients), suggesting a shift toward greater heterotrophy and changes in nitrogen sources. At an N:P ratio of approximately 106, *P. crosslandi* exhibited significantly reduced nutrient uptake rates and ΦPSII, suggesting phosphorus limitation and photoinhibition. Nutrient enrichment also alters the allocation of diazotroph-derived nitrogen (DDN) from host to symbiont, disrupting nutrient sharing and compromising coral physiology at the individual level [10].

Nitrogen loading increases coral susceptibility to heat stress. A field study in Moorea, French Polynesia, during a moderate 2016 heat stress event surveyed over 10,000 colonies of the branching corals *Pocillopora* and *Acropora*, showing that the degree of bleaching correlated positively with total thermal exposure and nutrient nitrogen [11]. Across these two coral genera, severity increased up to twofold under high nitrogen conditions during relatively low heat stress. These results demonstrate that excess nitrogen lowers the thermal threshold for severe coral bleaching and decreases the return time between events, making reefs more vulnerable [11].

3.2 Population and Community-Level Responses

The physiological stress induced by eutrophication at the individual level extends to coral populations, affecting their survival, growth, and recruitment. Elevated nitrogen levels can stimulate excessive proliferation of zooxanthellae, leading to phosphorus limitation within the coral holobiont. This nutrient imbalance reduces photosynthetic efficiency and increases susceptibility to thermal stress and bleaching events [12]. Additionally, nutrient enrichment promotes macroalgal overgrowth, which competes with corals for space and light, thereby further suppressing coral larval settlement and survival. These direct and indirect effects contribute to population declines and undermine the regenerative capacity of reef-building corals.

Beyond population impacts, eutrophication also drives significant restructuring of coral reef communities. Nutrient enrichment significantly restructures the coral-associated microbial communities, including zooxanthellae, bacteria, and archaea. Importantly, nutrient enrichment altered the coral symbiotic microbial community in both relative abundance and composition, with dissolved inorganic nitrogen enrichment being a key influencing factor [13]. These findings highlight that nutrient enrichment affects not only the coral host but also the intricate microbial communities that underpin reef health and ecosystem functioning.

3.3 Ecosystem Services

The degradation of coral reefs by eutrophication threatens vital ecosystem services that sustain coastal communities. This process is primarily driven by nutrient enrichment, which reduces coral abundance and decreases the structural complexity of reefs. This reduction in habitat leads to a decline in fish populations and recruitment. Such declines directly diminish fishery yields, threatening local livelihoods. The weakening of reef structure also reduces its capacity to act as a natural breakwater, thereby diminishing its ability to buffer coastlines from storm surges and wave energy [14].

Moreover, the proliferation of macroalgae on degraded reefs alters reef trophic structures and displaces ecologically valuable coral species. This transition reduces species diversity and ecosystem productivity, weakening trophic network complexity that underpins resilience. Cultural services are also compromised. The aesthetic and recreational value of reefs is diminished by increased susceptibility to bleaching, algal overgrowth, and shifts in community composition, reducing support for recreational and leisure activities [14]. In severely eutrophic areas, these losses are further compounded by increased coral disease prevalence and reduced recovery potential of the reef system. Overall, these changes underscore the profound impact of eutrophication on coral reef-based ecosystem services, from biodiversity support to economic sustainability.

4. Mitigation and Management Strategies

Mitigating coastal eutrophication requires integrated land-sea management strategies. The main sources of nutrient pollution, including excessive inputs from agriculture, wastewater, and groundwater, originate on land and cannot be effectively addressed through marine conservation measures alone. While marine protected areas contribute to conserving biodiversity and supporting ecosystem resilience, they are limited in their ability to reduce nutrient inflow. In the context of rapid coastal urbanization, effective mitigation depends on controlling land-based sources such as untreated sewage and urban runoff. Key strategies include upgrading urban wastewater treatment systems to remove nitrogen and phosphorus, implementing green infrastructure for stormwater control, and applying land-use planning measures that minimize nutrient leakage from expanding cities. In addition, restoring natural buffers like wetlands, mangroves, and salt marshes can help retain and process nutrients, improve water quality, and strengthen the capacity of coastal ecosystems to recover from disturbance, especially for coral reefs vulnerable to eutrophication-induced hypoxia and habitat loss. This restoration work is helpful in addressing urban pressures, environmental conditions and the impact on coral reef biodiversity. Long-term solutions should also account for climate-related factors that interact with urban pressures and intensify eutrophication risks, requiring coordinated policy responses across sectors and regions to maintain coastal ecosystem health [15].

5. Conclusion

Urbanization has significantly intensified coastal eutrophication, primarily through increased nutrient inputs from agriculture, wastewater, and land-use change. This review summarizes the major sources, mechanisms, and profound impacts of coastal eutrophication driven by urbanization on coral reef ecosystems. Elevated nitrogen and phosphorus levels, particularly under imbalanced N:P ratios, impair coral calcification, destabilize coral–algae symbiosis, and heighten bleaching risk. Over time, sensitive species decline while nutrient-tolerant taxa and macroalgae proliferate, leading to biodiversity loss and structural simplification.

These ecological shifts undermine critical ecosystem services such as fisheries, coastal protection, and cultural services, especially in urbanized regions. Addressing eutrophication requires integrated land-sea strategies, targeting upstream nutrient sources through improved wastewater treatment, green infrastructure implementation, and restoration of coastal buffers. In the face of compounding climate stressors, cross-sectoral and long-term efforts are essential to preserve coral reef integrity and the benefits they provide to human societies. Moreover, current research remains largely focused on single study areas, with limited cross-regional comparisons and synthesis. Future studies should strengthen comparative and integrative analyses across different regions to better reveal the general patterns and regional variations of urbanization-driven eutrophication impacts on coral reef ecosystems.

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