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Seaweed and shellfish mariculture as nature-based solutions: Mitigating nutrient pollution from coastal fish mariculture and sewage

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ABSTRACT

Fish mariculture and sewage discharge have triggered severe eutrophication in China's coastal waters. Seaweed and shellfish culture are nature-based solutions while their effectiveness in mitigating nitrogen (N) and phosphorus (P) pollution from fish mariculture and sewage remains unclear. To fill this knowledge gap, this study comprehensively analyzed 20-year (2003−2023) data on N/P release by maricultured fish and removal by seaweed and shellfish in China. The findings showed that seaweed and shellfish mariculture could remove 89.57 gigagrams (Gg) yr^{-1} N with 11.41 Gg yr^{-1} P and 104.41 Gg yr^{-1} N with 8.09 Gg yr^{-1} P in 2023, respectively. The combined removal of seaweed and shellfish could fully offset the N emissions from fish mariculture, but not P emissions; it could completely offset sewage discharge for both N and P due to continuously decreasing discharge. Seaweeds demonstrated considerably higher N and P removal capacity than shellfish. *Gracilariopsis lemaneiformis* and *Saccharina japonica* showed the highest N (99.61 ± 52.73 g m^{-2} yr^{-1}) and P (12.54 ± 3.88 g m^{-2} yr^{-1}) removal capacity among seaweeds, respectively. The highest N (21.51 ± 0.08 g m^{-2} yr^{-1}) and P (1.57 ± 0.22 g m^{-2} yr^{-1}) removal capacities among shellfish were found in mussel and oyster, respectively. To remediate N and P released by fish per unit area, it requires 2.25- and 2.55-fold areas of seaweed, or 15.65- and 48.44-fold areas of shellfish, respectively. The findings in this study provide solid contributions to understanding the nutrient removal capacity of seaweed and shellfish and their application in mitigating eutrophication.

1. Introduction

Coastal ecosystems worldwide are grappling with the intensifying threat of eutrophication, a phenomenon driven by excessive nutrient inputs primarily from anthropogenic activities. Land-based sources, including river input, sewage discharge and agricultural runoff, contribute to the overwhelming majority of nitrogen (N) and phosphorus (P) entering marine environments (Simcock et al., 2016). For instance, the Mississippi River watershed annually delivers millions of tons of N and P to the Gulf of Mexico, fueling the formation of a hypoxic "dead zone" (Pontius and McIntosh, 2024). Similarly, the Baltic Sea has long suffered from severe eutrophication due to nutrient runoff from surrounding countries, and N and P loads have surpassed 4×10^5 and 2×10^4 ton $year^{-1}$ during the last 100 years, leading to oxygen depletion and habitat degradation (Reusch et al., 2018). In China, the problem is equally pressing. The Bohai Sea has also been experiencing severe eutrophication and red tides due to riverine inputs and nonpoint sources (Qu et al., 2025). China's coastal waters faces recurring green tides caused by *Ulva* algae blooms, which are linked to nutrient runoff from coastal cities (Feng et al., 2024).

Concurrently, the rapid expansion of intensive fish mariculture has emerged as a significant secondary source of nutrient pollution (Bouwman et al., 2013). Fish farms release substantial quantities of dissolved N and P through uneaten feed, fecal matter, and metabolic waste. Studies estimate that NP release caused by fish mariculture increased with year (2003−2020) in Guangdong Province, and reached 41.77 ± 0.40 Gg N, 8.47 ± 0.19 Gg P in 2020. The averaged P fluxes (2016–2020) due to fish mariculture is 69 % of the Pearl River that is the

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biggest river in Guangdong Province (Xiong et al., 2023). This nutrient overload disrupts the natural balance of coastal ecosystems, triggering algal blooms, oxygen depletion, and biodiversity loss (Aniebone et al., 2024; Gao et al., 2025).

Efforts to combat eutrophication have historically relied on a suite of strategies, each with distinct advantages and drawbacks. Physical methods, such as sediment dredging and artificial mixing, aim to redistribute nutrients but often prove costly and environmentally disruptive (Akinnawo, 2023). Chemical interventions, including the application of aluminum sulfate to reduce phosphorus bioavailability, can provide short-term relief but may introduce secondary pollutants and harm non-target species (Akinnawo, 2023). Biological approaches, such as the restoration of seagrass beds and wetlands, offer ecosystem-friendly solutions but require extensive time and space to achieve measurable results (Barbier et al., 2011). Engineered systems like constructed wetlands and wastewater treatment plants have shown promise in reducing nutrient loads, yet their effectiveness is constrained by high operational costs and limited scalability in open marine environments (Vymazal, 2020). Additionally, these methods often focus on point-source pollution while overlooking the diffuse inputs from aquaculture and agriculture. As a result, there is an urgent need for sustainable, nature-based solutions that can address both land-based and aquacultural nutrient sources.

Against this backdrop, seaweed and shellfish mariculture have gained traction as innovative, low-cost strategies to mitigate eutrophication. Seaweeds, such as *Ulva* and *Gracilaria*, are highly efficient at absorbing dissolved inorganic nutrients (DIN) like nitrate and phosphate through their entire thallus surface (Gao et al., 2022; Marinho-Soriano et al., 2009). Their specific growth rates could be as high as 70 %, enabling them to sequester large quantities of N and P, effectively removing these nutrients from the water column (Gao et al., 2018). Bivalve shellfish, including oysters and mussels, can also contribute to nutrient removal because they filter phytoplankton and suspended organic matter in seawater, thereby reducing algal biomass and associated nutrients. Studies in eastern Canada found that mussel farms can remove 1.6–2.0 tons of N per hectare annually, while oyster farms achieve lower rates due to differences in shell composition (Clements and Comeau, 2019). Cultivated hard clam and eastern oyster in Greenwich Bay, Connecticut, could remove 14,006 kg nitrogen year^{-1}. This nitrogen removal represents 9 % of the total annual Greenwich-specific nitrogen load, 16 % of the combined nonpoint sources, 38 % of the fertilizer sources, 51 % of the septic sources and 98 % of the atmospheric deposition to the watershed (Dvarskas et al., 2020).

Beyond nutrient mitigation, these cultures provide ancillary benefits. Seaweeds enhance water clarity, create habitats for fish and invertebrates, and act as carbon sinks (Gao et al., 2021). Shellfish reefs improve shoreline stability and support fisheries, fostering economic resilience in coastal communities (Zhao and Wu, 2024). More importantly, seaweed and shellfish can supply dietary fiber and protein for human beings.

Despite their potential, critical uncertainties persist regarding the scalability and effectiveness of seaweed and shellfish mariculture in real-world scenarios. First, the contribution of these cultures to offsetting nutrient loads from fish farms and sewage remains poorly quantified. While laboratory studies highlight their capacity to absorb nutrients, field-scale assessments of their impact on eutrophic hotspots are limited. Second, nutrient removal capacities of seaweed and shellfish are species-specific and limited understanding hinder their application in eutrophication treatment. In this study, we quantified N and P removal by seaweed and shellfish mariculture during 2003–2023, assessed their contribution to mitigating eutrophication caused by fish mariculture and sewage discharge, and explored N and P removal capacity of seaweed and shellfish species. This study can offer solid contribution to employing seaweed and shellfish for eutrophication treatment in coastal waters.

2. Materials and methods

2.1. Production of mariculture

The data on production and cultivation area of seaweed, shellfish and fish are from the China Fishery Statistical Yearbook for the years of 2003–2023. Annual productivity was calculated by dividing production by cultivation area. Seaweed, shellfish and fish are farmed in coastal seawaters along the coastline of China from Liaoning Province in the North of China to Hainan Province in the South of China (Figs. S1&S2). The census method is used to estimate the production and cultivation area of seaweed, shellfish and fish in China, in which data are collected from each local farmer and then compiled (Gao et al., 2021). Although there may be some errors during the data collection and compilation, census is considered to be a reliable statistical method because all the items are taken into account (Baffour et al., 2013).

2.2. N and P content in seaweed and shellfish

The data of N and P content in seaweeds are according to Xiong et al. (2023) that combined the results of literature and their own measurements.

The data of N and P content in shellfish were obtained from this study. Nine shellfish species (*Magallana angulata*, *Haliotis discus hannai*♀ × *H. fulgens*♂, *Babylonia lutosa*, *Scapharca subcrenata*, *Mytilus coruscus*, *Atrina pectinata*, *Azumapecten farreri*, *Ruditapes philippinarum*, and *Sinonovacula constricta*) that are commonly cultured in China were collected from coastal farms of China during April–May 2025. Please see Tables S1-S2 for details. Three to six samples of each species were randomly selected for the following measurements. Soft tissues and shells of shellfish were dried at 60 °C in an oven (DHG-9146 A, Jing Hong, China) till constant weight (~48 h). Dried soft tissues and shells were ground by a mortar, and the powder was then passed through a sieve with a mesh aperture of 0.15 mm. The nitrogen content in the filtered shell powder was measured by an Elementar Vario EL Cube (Elementar, Germany). Phosphorus content was determined according to the method in Solórzano and Sharp (1980).

2.3. Estimate N and P removal by seaweed and shellfish

N and P removal by farmed seaweeds was calculated by the following formula:

$$\mathrm{R1}_{\mathrm{N/P}} = \mathrm{P1} \times \mathrm{C1}_{\mathrm{N/P}} \tag{1}$$

Where $\mathrm{R1}_{\mathrm{N/P}}$ is the removed amount of N/P by farmed seaweeds, P1 is the production of seaweeds, and $\mathrm{C1}_{\mathrm{N/P}}$ represents the content of N/P.

N and P removal by shellfish was calculated by the following formula:

$$\mathrm{R2}_{\mathrm{N/P}} = \mathrm{P2} \times \mathrm{C2}_{\mathrm{N/P}} + \mathrm{P3} \times \mathrm{C3}_{\mathrm{N/P}} \tag{2}$$

Where $\mathrm{R2}_{\mathrm{N/P}}$ is the removed amount of N/P by farmed shellfish, P2 is the production of shellfish soft tissue, $\mathrm{C2}_{\mathrm{N/P}}$ represents the content of N/P in soft tissue, P3 is the production of shellfish shell, $\mathrm{C2}_{\mathrm{N/P}}$ represents the content of N/P in shell. Weight ratios of soft tissue to shell for different shellfish species are based on Song et al. (2023). When seaweeds and shellfish are harvested, the N and P in them are removed from seawater.

Assessment of N and P removal capacity by seaweeds and shellfish.

N and P removal capacity by seaweeds and shellfish was calculated by the following formula:

$$\mathrm{C}_{\mathrm{N/P}} = \frac{\mathrm{R}_{\mathrm{N/P}}}{\mathrm{A}} \tag{3}$$

Where $\mathrm{C}_{\mathrm{N/P}}$ is N/P removal capacity, $\mathrm{R}_{\mathrm{N/P}}$ is the removed amount of N/P and A is the culture area.

2.4. N and P release by fish mariculture

Released N and P by fish mariculture were calculated by the following formulas:

$$R3_{N/P} = F \times C_{N/P} \times (1 - R) \quad (4)$$

$$F = P4 \times Fc \quad (5)$$

The eqs. (4) and (5) are based on Lazzari and Baldisserotto (2008) and Gao et al. (2021), where $R3_{N/P}$ is released N or P, F = feed amount, $C_{N/P}$ = content of C, N or P in feeds, R = retention rate of feed N or P in fish, P4 = fish production, and Fc = feed coefficient, the feed consumption per unit weight increase of fish. The proportions of used artificial and wild feeds (fresh trash fish) change with time (Table S3). The contents of C, N and P in artificial feeds are 39.64 %, 7.40 % and 1.62 %, respectively， and for wild feeds they are 13.67 %, 2.71 % and 0.53 %, respectively (Xiong et al., 2023), after integrating published data and our own data. The feed coefficient is 1.52 and 6.49 for artificial and wild feeds, respectively (Gao et al., 2021). The retention rate of feed C, N and P in fish is set at 30 % based on previous studies (Herath and Satoh, 2015; Lazzari and Baldisserotto, 2008; Xu et al., 2007).

2.5. N and P release by sewage discharge

The data of released N and P by sewage discharge were obtained from the China Marine Ecological Environment Status Report which is issued by the Ministry of Ecology and Environment of the People's Republic of China.

3. Results

The maricultured seaweed production has increased by 146 % over the past 20 years, demonstrating a two-stage growth pattern (Fig. 1a). The first stage (2003−2011) was characterized by stability, with annual dry weight (DW) production ranging from 1.13 to 1.31 × 10^6 t. The second stage (2011−2023) saw a continuous upward trend, with production escalating from 1.31 to 2.78 × 10^6 t DW yr^{-1}, despite a minor dip in 2022. *Saccharina japonica* dominated the production in all years, accounting for 57–72 % of the total production. The proportion of *G. lemaneiformis* increased from 4 % in 2003 to 20 % in 2023, contributing the second largest production now.

The mariculture area of seaweeds increased by 84 % during the past 20 years, and the increase extent is much smaller than production (Fig. 1b). This trend also followed a two-stage pattern: (1) 2003–2009, during which the area fluctuated between 76.42 and 107.30 × 10^3 ha, showing initial increase followed by decline; (2) 2010–2023, with a gradual rise from 116.75 to 145.06 × 10^3 ha. In contrast to production, *Pyropia* dominated the culture area from 2008 to 2023 (44–57 %), while *Saccharina japonica* accounted for 31–50 % over the past two decades. The mean productivity of seaweeds increased by 34 % during the past 20 years, with a range of 1.05–1.92 kg DW m^{-2} yr^{-1} (Fig. 1c). During 2003–2008, *Undaria pinnatifida* had the highest productivity (2.45–3.16 kg DW m^{-2} yr^{-1}). During 2009–2016, *Saccharina japonica* led the productivity list while *Gracilariopsis lemaneiformis* caught up with *Saccharina japonica* during 2017–2023, reflecting shifts in cultivation strategies.

Shellfish production has increased by 73 % during the past 20 years (Fig. 2a). From 2003 to 2006, annual fresh weight (FW) production rose from 8.99 to 10.09 × 10^6 t, followed by a decline to 9.32 × 10^6 t in 2007. Since then, production has demonstrated a sustained upward trend through 2023. Oysters and clams remained the top two contributors, accounting for 34–43 % and 28–34 % of total production, respectively. The shellfish culture area expanded from 845.07 to 1357.53 × 10^3 ha over 20 years, marked by significant fluctuations (Fig. 2b). It first peaked at 965.02 × 10^3 ha in 2006, then dropped to 728.01 × 10^3 ha in 2007. A rapid increase followed, reaching 1404.10 × 10^3 ha in 2013, before declining to 1176.56 × 10^3 ha in 2015. Since then, the area has remained stable (1085.77–1233.09 × 10^3 ha). During 2003–2009, the culture area of clam was the biggest, contributing of 40–43 % the total area. Afterwards, it was replaced by scallop till 2020. The third largest area was oyster with a range of 90.44–276.82 × 10^3 ha. The mean shellfish productivity increased from 1.06 kg FW m^{-2} yr^{-1} in 2003 to 1.28 kg FW m^{-2} yr^{-1} in 2023 (Fig. 2c). Oysters consistently showed the highest productivity, ranging from 2.41 to 3.60 kg FW m^{-2} yr^{-1}, followed by mussels with productivity fluctuating between 1.45 and 2.61 kg FW m^{-2} yr^{-1}.

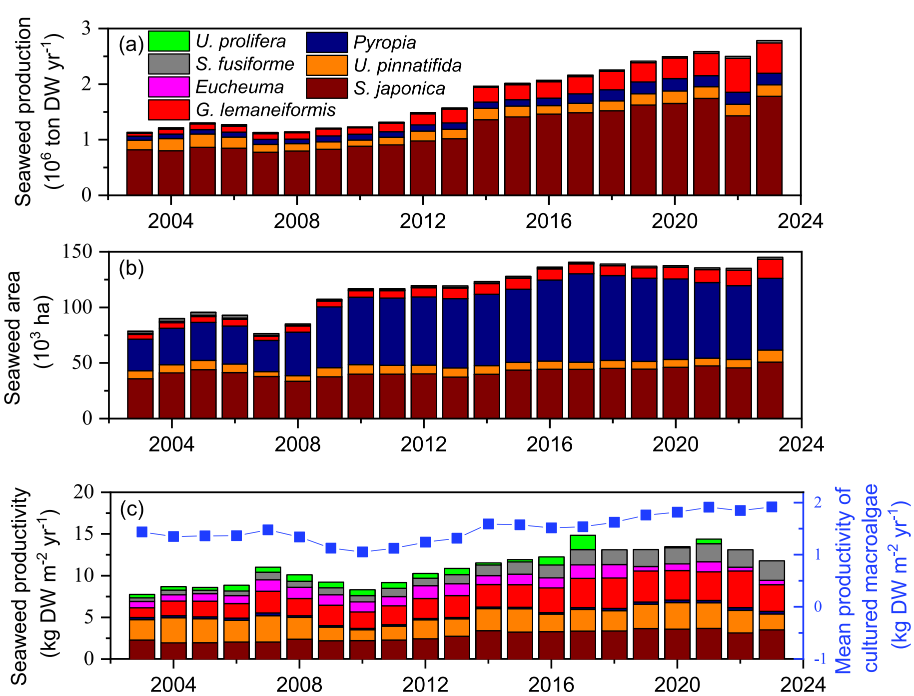

Fig. 1. Seaweed production (a), area (b) and productivity (c) in China during 2003–2023, with the contribution of different species.

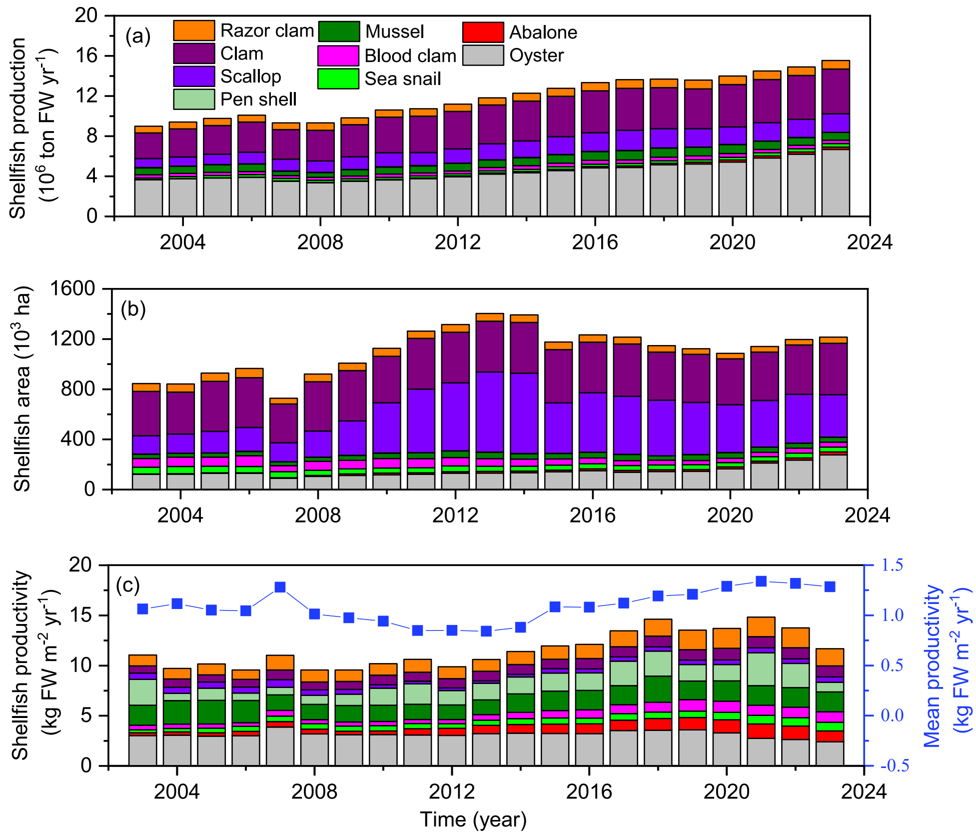

Fig. 2. Shellfish production (a), area (b) and productivity (c) in China during 2003–2023, with the contribution of different species.

The fish production increased by 252 % during 2003–2023 (Fig. 3a). Unlike seaweed and shellfish that had fluctuations, fish production shows a continuous increase, although there are minor stagnations, like 2006–2008 and 2020–2022. *Dicentrarchus labrax* (sea bass) dominated production from 2003 to 2013, accounting for 20–24 % of the total, before being succeeded by *Larimichthys crocea* (19–25 %) through 2023. Fish culture area fluctuated significantly between 60.73 and 87.31 × 10^3 ha over the period (Fig. 3b). Meanwhile, mean productivity surged

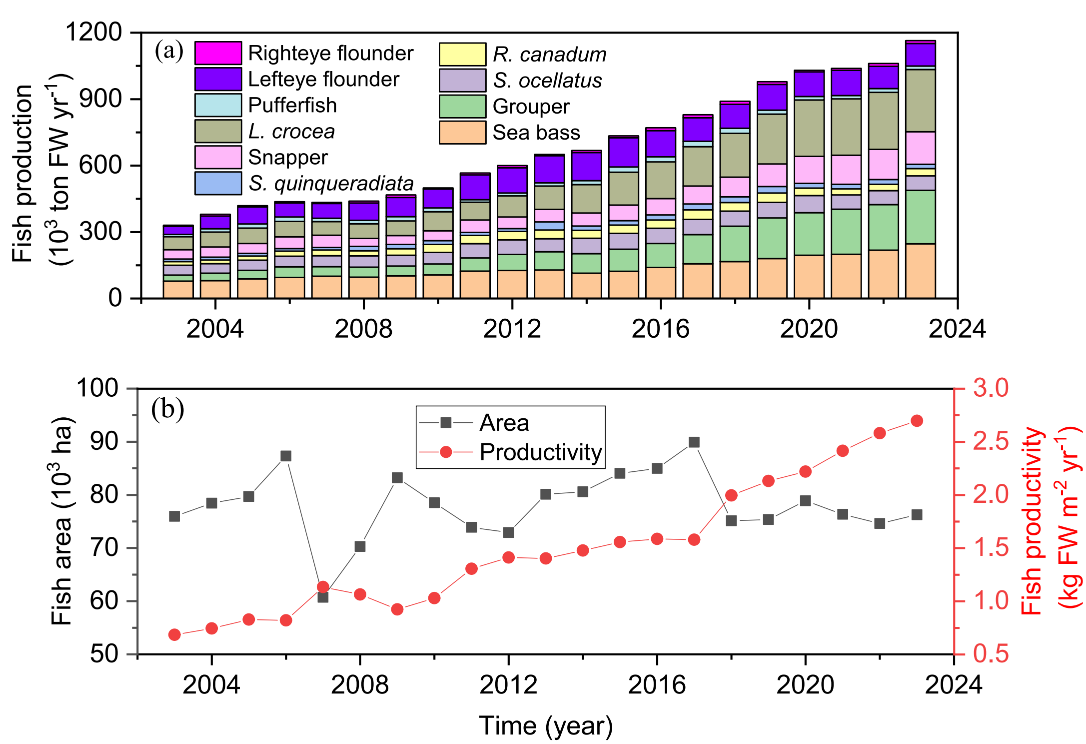

Fig. 3. Fish production (a), area and productivity (b) in China during 2003–2023, with the contribution of different species to total production.

by 295 %, escalating from 0.68 kg fresh weight (FW) m^{-2} yr^{-1} in 2003 to 2.70 kg FW m^{-2} yr^{-1} in 2023 (Fig. 3c).

N removal by farmed macroalgae increased by 151 % over the past 20 years, rising from 35.67 to 89.57 Gg yr^{-1} (Fig. 4a). The trend exhibited an initial increase followed by a decline during 2003–2007, before accelerating continuously through 2023. *Saccharina japonica* remained the dominant contributor, accounting for 49–64 % of total N removal annually. *Undaria pinnatifida* was the second-largest contributor from 2003 to 2010 (11–23 %), after which *Gracilaria lemaneiformis* assumed this role (13–27 %) through 2023. N removal by farmed shellfish increased by 75 % over the same period, from 62.81 to 109.81 Gg yr^{-1} (Fig. 4b). A similar pattern of initial increase and subsequent decline was observed during 2003–2007, followed by sustained growth from 2008 onward—interrupted by a short plateau in 2017–2019. Oysters and clams were the primary contributors, constituting 28–35 % and 24–28 % of total N removal, respectively.

From 2003 to 2023, phosphorus (P) removal by seaweed culture increased by 141 %, rising from 4.74 to 11.41 Gg yr^{-1} (Fig. 5a). The trend featured a gradual increase during 2003–2013, followed by an accelerated growth phase. *Saccharina japonica* dominated P removal, contributing 64–78 % of the total, while *Pyropia* served as the second-largest contributor from 2007 to 2021. P removal by shellfish culture increased by 75 % over the same period, from 4.82 to 8.45 Gg yr^{-1} (Fig. 5b). A pattern of initial increase followed by decline was observed during 2003–2007, with continuous growth thereafter through 2023. Oysters (35–44 %) and clams (26–31 %) were the primary contributors to total P removal.

Unlike seaweeds and shellfish, fish mariculture releases nitrogen (N) and phosphorus (P) due to exogenous feed dependency. From 2003 to 2023, N release from fish farming increased by 182 %, rising from 39.45 to 111.19 Gg yr^{-1} (Fig. 6a). The trend included growth during 2003–2006, a plateau in 2006–2010, continuous increase thereafter, and a second plateau in 2019–2022. *Dicentrarchus labrax* (sea bass) was the primary contributor (21–24 %) from 2003 to 2013, succeeded by *Larimichthys crocea* (19–25 %) through 2023. P release from fish mariculture mirrored N trends, increasing by 166 % from 9.89 to 26.34 Gg yr^{-1} over the same period (Fig. 6b). Integrating N removal by seaweeds and shellfish with fish N release revealed a net N removal of 59.03–88.19 Gg yr^{-1} from 2003 to 2023 (Fig. 6c). This balance stabilized during 2003–2006, dropped to 49.40 Gg in 2007, then rose from 49.76 to 79.59 Gg yr^{-1} in 2008–2014, followed by a plateau in 2015–2023. Conversely, net P balance showed continuous release, increasing from 0.33 Gg yr^{-1} in 2003 to 6.47 Gg yr^{-1} in 2023 (Fig. 6d), indicating a cumulative P input to marine ecosystems from mariculture activities.

In addition to fish mariculture, nutrient release from sewage

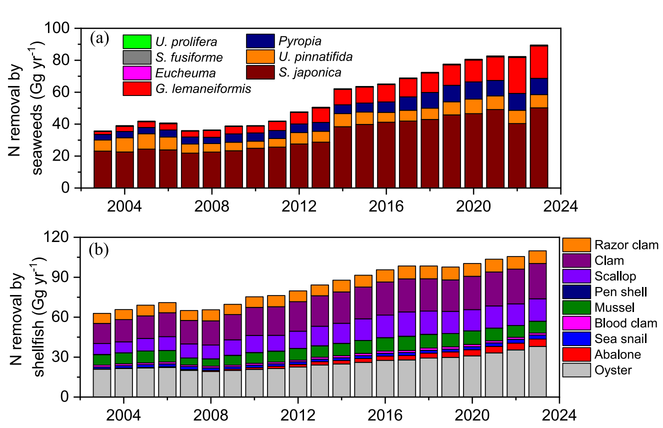

Fig. 4. Nitrogen removal by maricultured seaweeds (a) and shellfish (b) in China during 2003–2023, with the contribution of different species.

discharge was also analyzed since it is an important pollution source for coastal waters. N discharge increased from 46.55 to 50.56 Gg yr^{-1} during 2006–2007 and then rapidly decreased to 15.40 Gg yr^{-1} in 2015 (Fig. 7a). It surged to 64.47 Gg yr^{-1} in 2016 and then showed a slow decrease trend to 53.37 Gg yr^{-1} in 2023. P discharge by sewage was 11.98 Gg yr^{-1} in 2006 and then dropped to 4.81 Gg yr^{-1} in 2007 (Fig. 7b). Afterwards, it showed a slow decreasing trend to 0.97 Gg yr^{-1} in 2023. The results of sewage treatment with seaweed and shellfish were presented as well. It turns out a net N removal, suggesting that seaweed and shellfish culture could completely absorb N release by sewage discharge (Fig. 7c). Net N removal showed two increasing stages: 44.98–139.57 Gg yr^{-1} in 2007–2015 and 96.25–146.01 Gg yr^{-1} in 2016–2023. In contrast, net P removal was negative in 2007 suggesting a net P release (Fig. 7d). However, it became positive in 2007 and showed a continuous increasing trend to 18.89 Gg yr^{-1} in 2023.

Furthermore, mariculture (including seaweed, shellfish and fish) and sewage were integrated to assess whether seaweed and shellfish mariculture can neutralize the combination of fish mariculture and sewage discharge. Net N removal was positive all the time except for 2007 (Fig. 8a). It increased from 13.12 Gg yr^{-1} in 2006 to 64.79 Gg yr^{-1} in 2014. Afterwards, it dived to 15.39 Gg yr^{-1} in 2016 and then increased to 40.12 Gg yr^{-1} in 2021. Different from N, net P removal was negative for all years (Fig. 8b), suggesting that seaweed and shellfish mariculture did not completely offset the sum of P release by fish mariculture and sewage discharge. Net P release was 14.34 Gg yr^{-1} in 2006 and then decreased to 8.01 Gg yr^{-1} in 2007. Afterwards, it had a small fluctuation of 4.89–8.29 Gg yr^{-1} between 2008 and 2023.

Gracilariopsis lemaneiformis showed the highest N removal capacity of 99.61 ± 52.73 g m^{-2} yr^{-1}, followed by *Undaria pinnatifida* (99.59 ± 15.83 g m^{-2} yr^{-1}) and *Saccharina japonica* (78.92 ± 24.40 g m^{-2} yr^{-1}) (Fig. 9a). *Eucheuma* has the lowest N removal capacity of 8.00 ± 1.18 g m^{-2} yr^{-1}. Different from N, *Saccharina japonica* has the highest P removal capacity of 12.54 ± 3.88 g m^{-2} yr^{-1}, followed by *Gracilariopsis lemaneiformis* (7.71 ± 4.08 g m^{-2} yr^{-1}) and *Undaria pinnatifida* (6.75 ± 1.07 g m^{-2} yr^{-1}) (Fig. 9c). The lowest P removal capacity was also found in *Eucheuma* (0.87 ± 0.13 g m^{-2} yr^{-1}). Compared to seaweed, the N and P removal capacities of shellfish are usually lower. The highest N removal capacity (21.51 ± 0.08 g m^{-2} yr^{-1}) was found in mussel, followed by oyster (17.95 ± 2.49 g m^{-2} yr^{-1}), abalone (17.70 ± 12.77 g m^{-2} yr^{-1}), and razor clam (15.78 ± 5.05 g m^{-2} yr^{-1}) (Fig. 9b). Blood clam had the lowest N removal capacity (3.10 ± 1.85 g m^{-2} yr^{-1}). Different from N, the highest P removal capacity was found in oyster (1.74 ± 0.24 g m^{-2} yr^{-1}), followed by mussel (1.11 ± 0.00 g m^{-2} yr^{-1}), razor clam (0.99 ± 0.32 g m^{-2} yr^{-1}), and abalone (0.81 ± 0.58 g m^{-2} yr^{-1}) (Fig. 9d). The lowest P removal capacity was also found in 0.14 ± 0.09 g m^{-2} yr^{-1}.

4. Discussion

4.1. Temporal dynamics of nutrient removal and release by mariculture

Nitrogen and phosphorus removal by seaweeds increased by 151 % and 141 % over the past 20 years, primarily driven by a 146 % expansion in seaweed production. This growth is attributed to rising market demand for seaweeds as functional foods, fueled by increasing recognition of their health benefits (Kumar et al., 2023). *Saccharina japonica* and *Gracilaria lemaneiformis* showed particularly pronounced increases, owing to their dual use as human food and abalone feed, with the latter also serving as a key agar source (Cao et al., 2024). In contrast, N (74 %) and P (75 %) removal by shellfish exhibited more moderate increases, aligning with a 73 % rise in shellfish production. This disparity stems from multiple factors: seaweeds serve diverse purposes (food, feed, industrial raw materials), whereas shellfish are predominantly consumed as food. Additionally, seaweeds demonstrate greater resilience to environmental fluctuations, facilitating culture area expansion. Policy support further reinforces this trend: seaweed culture is actively promoted

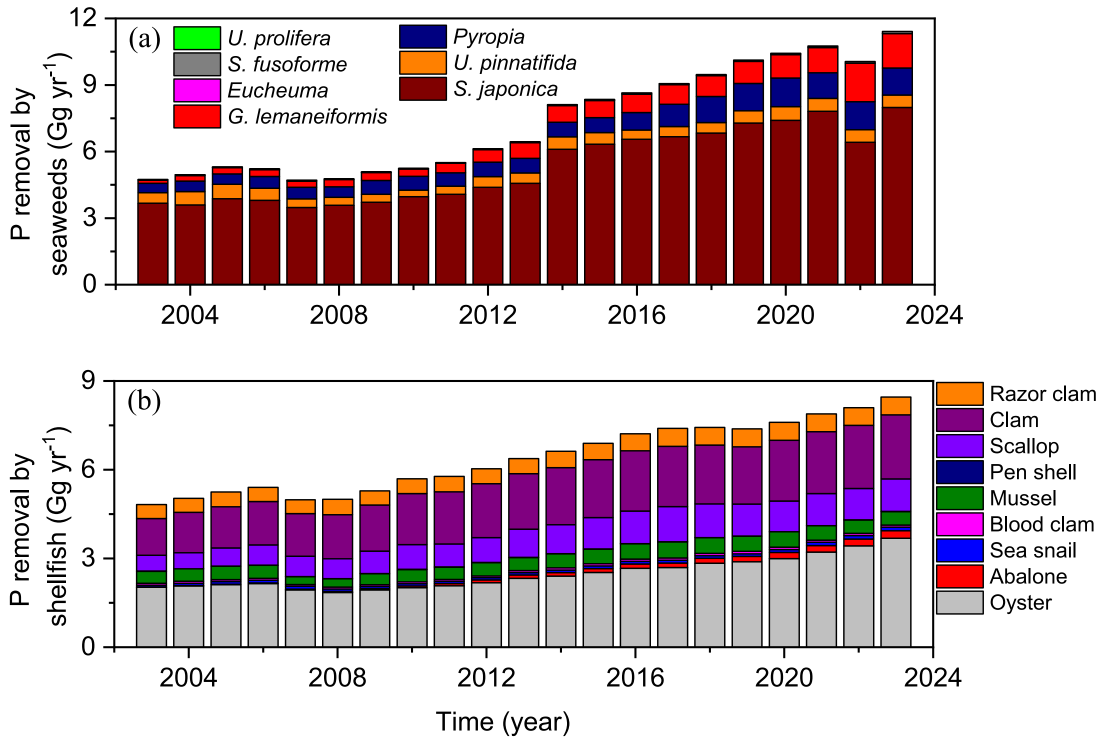

Fig. 5. Phosphorus removal by maricultured seaweeds (a) and shellfish (b) in China during 2003–2023, with the contribution of different species.

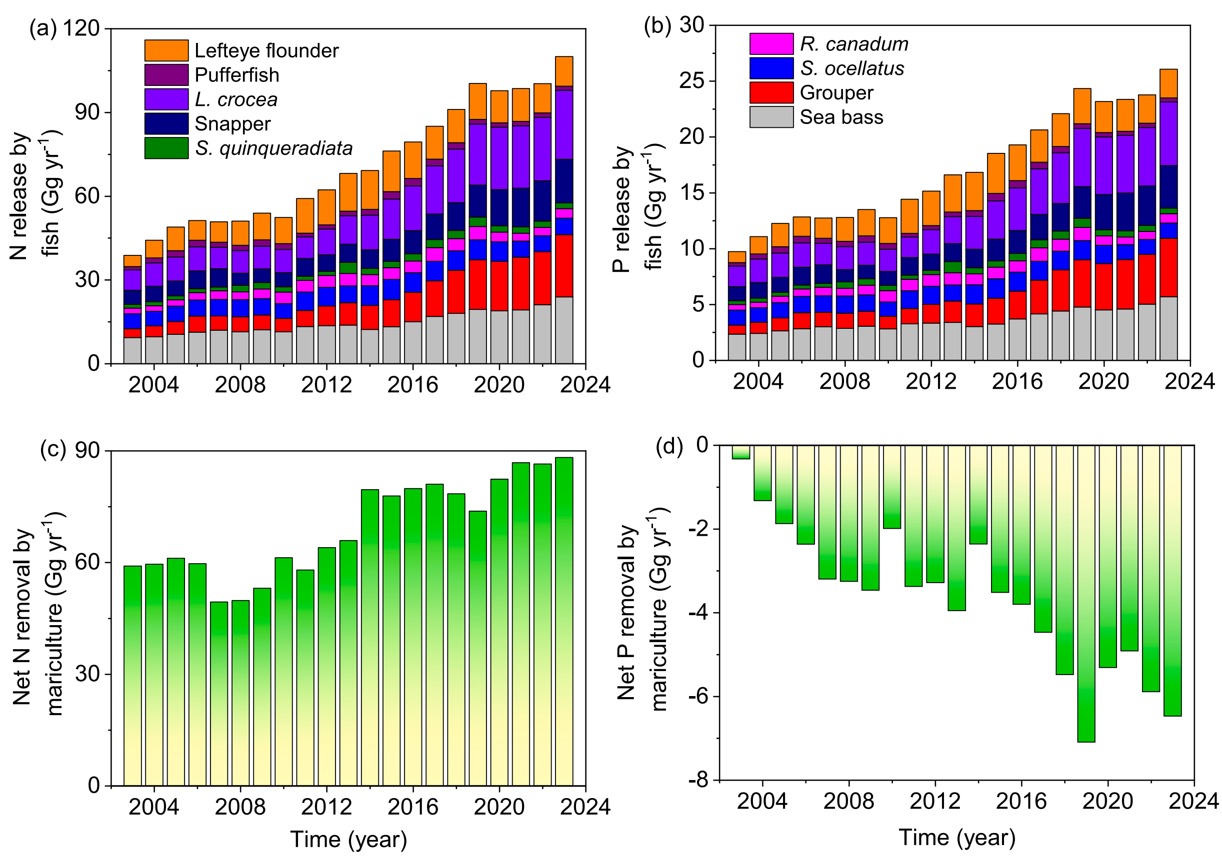

Fig. 6. Nutrient release by fish and net nutrient removal by mariculture during 2003–2023. Mariculture includes seaweed, shellfish and fish. (a) Nitrogen, (b) Phosphorus, (c) Net nitrogen, (d) Net phosphorus.

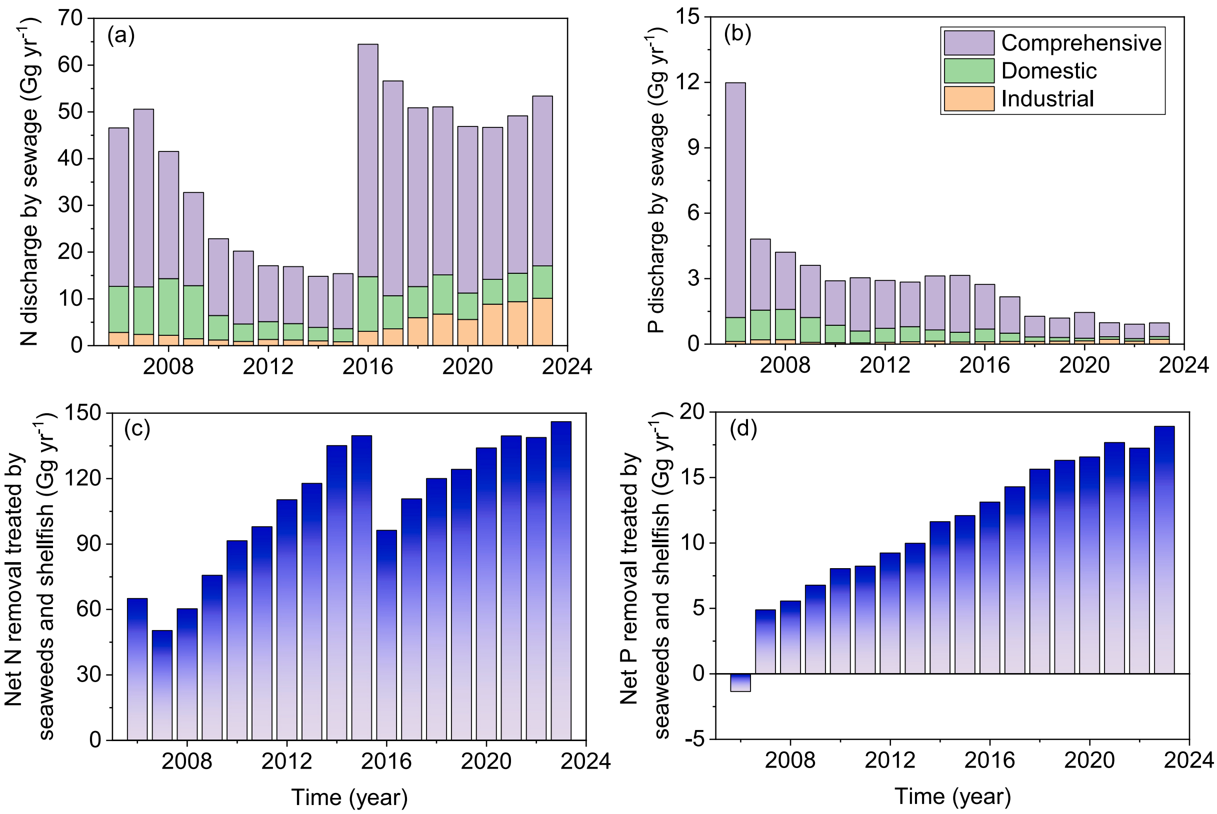

Fig. 7. Nutrient discharge by sewage and net nutrient removal following sewage treated by seaweed and shellfish mariculture during 2006–2023. (a) Nitrogen, (b) Phosphorus, (c) Net nitrogen, (d) Net phosphorus.

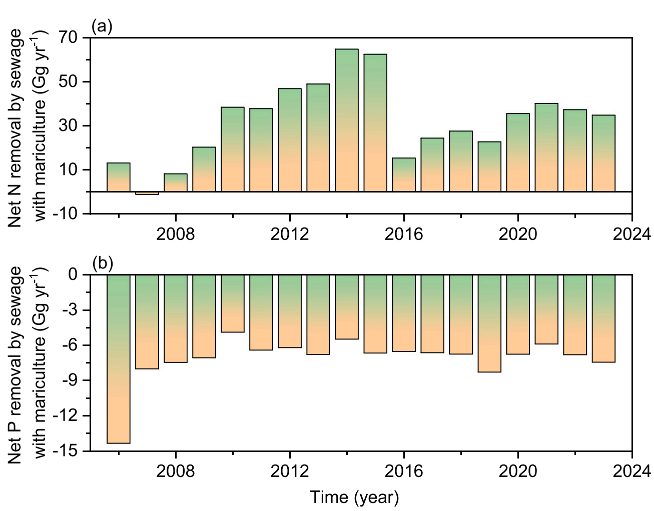

Fig. 8. Net nitrogen (a) and phosphorus (b) loading after integrating mariculture and sewage during 2006–2023. Mariculture includes seaweed, shellfish and fish.

for its ecological services (e.g., nutrient removal and carbon sequestration) (Gao et al., 2021), while shellfish culture's role in carbon sequestration remains controversial and its eutrophication mitigation efficacy is less defined (He et al., 2025; Song et al., 2023). The significant declines in shellfish area observed in 2007 and 2015 are primarily attributable to key policy interventions. In 2006, the Chinese government initiated stricter regulations on nearshore aquaculture, targeting over-intensive farming practices and pollution in ecologically sensitive areas. This led to the clearance of many farming zones and a direct reduction in shellfish cultivation area. Subsequently, the introduction of the "Water Ten Measures" in 2015 further reinforced these efforts by explicitly calling for the control and downsizing of nearshore mariculture operations. These measures significantly impacted raft-style hanging culture systems commonly used for species such as oysters, scallops, and mussels, thereby contributing to the observed declines.

Fish culture showed a 252 % production increase over the same period, outpacing seaweeds and shellfish. This surge is driven by: (1) global demand for fish as a low-fat protein source, in contrast to the primarily Asian consumption of seaweeds and shellfish (Boyd et al., 2022); (2) technological advancements, including facility-based aquaculture and deep-sea cage systems that expanded farming from inshore to open oceans (Dong et al., 2024); and (3) breeding breakthroughs, such as heat-tolerant large yellow croaker and disease-resistant flounder, which enhanced growth and stress resistance (Wu et al., 2021; Yanez et al., 2023). Notably, N (182 %) and P (166 %) release from fish culture increased less than production, attributed to the shift from wild feeds (e.g., fresh trash fish) to artificial feeds with lower feed coefficients (0.68–2.64 vs. 3.18–10.21) (Gao et al., 2021; Li et al., 2024).

4.2. *Nutrient offsetting by mariculture against fish and sewage pollution*

Despite fish production exceeding that of seaweeds and shellfish, the latter completely neutralized fish-derived N release, underscoring their robust N removal capacity. However, they could not fully offset fish-derived P release, leading to increasing net P release—attributable to divergent N:P ratios among cultures. For example, mean N:P ratios (2019–2023) were 17 for seaweeds, 29 for shellfish, and 9 for fish (Table 1). These ratios deviate substantially from the classical Redfield ratio (16:1), which describes the typical balance of N and P in marine ecosystems. The higher N:P ratios of seaweeds and shellfish reflect a relatively lower affinity for P uptake compared to N, whereas the lower N:P ratio of fish implies a disproportionately high release of P relative to N. This stoichiometric imbalance limits the ability of extractive species

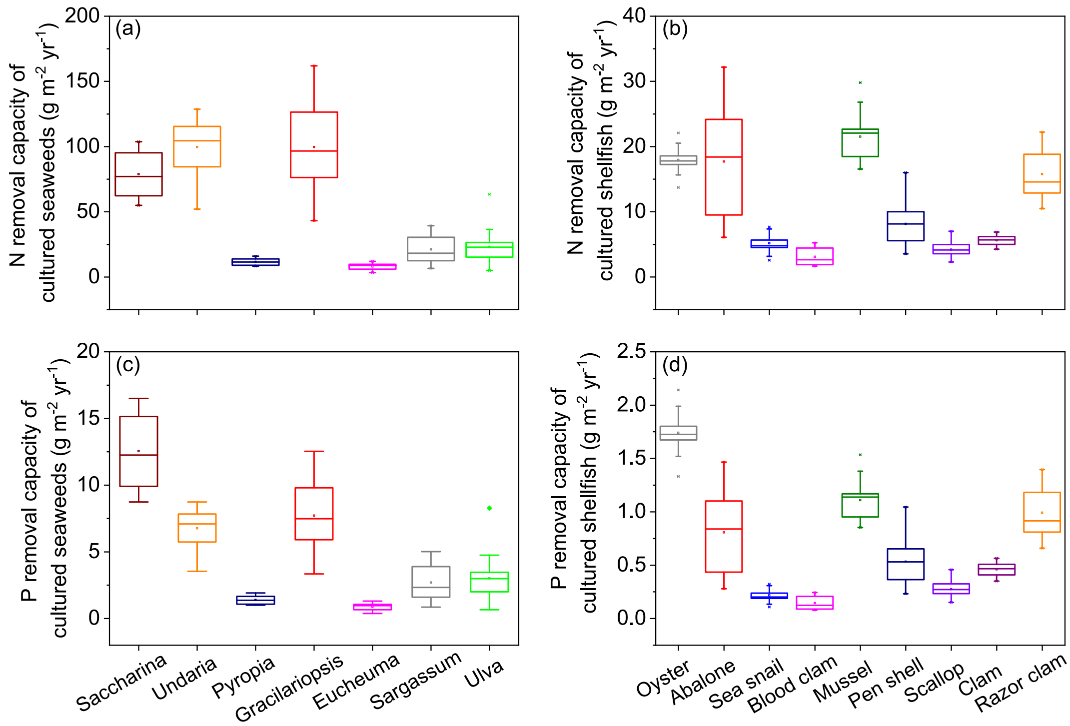

Fig. 9. Nitrogen and phosphorus removal capacity by seaweeds (a, c) and shellfish (b, d) based on the data of 2003–2023.

Table 1
Comparison of nutrient fluxes of different sources in China. To represent the current status, the fluxes are the averaged values ± SD of 2019–2023. DIN and DIP represents dissolved inorganic nitrogen and dissolved inorganic phosphorus, respectively.

Source	DIN flux (Gg yr^{-1})	DIP flux (Gg yr^{-1})	DIN/DIP (mol/mol)	DIN density (g m^{-2} yr^{-1})	DIP density (g m^{-2} yr^{-1})	DIN density ratio of release to removal[a]	DIP density ratio of release to removal[a]
Fish mariculture	102.41 ± 6.85	24.37 ± 1.23	9.30 ± 0.78	134.31 ± 7.84	31.97 ± 1.34	/	/
Sewage	49.42 ± 1.63	1.10 ± 0.16	102.21 ± 19.37	/	/	/	/
Seaweed mariculture	82.55 ± 8.46	10.55 ± 0.91	17.32 ± 0.28	59.78 ± 3.60	12.56 ± 0.29	2.25	2.55
Shellfish mariculture	103.37 ± 8.58	7.89 ± 0.76	29.04 ± 0.37	8.99 ± 0.27	0.68 ± 0.03	14.93	47.01

[a] represents the ratio of fish release to seaweed or shellfish removal; / represents data unavailable.

to sequester all excess P released by fish, underscoring the importance of ecological stoichiometry in designing sustainable aquaculture systems with balanced nutrient cycling.

Seaweeds and shellfish fully offset both N and P release from sewage, with net P removal increasing over time. This stems from reduced sewage P discharge (e.g., via P-free detergent use and P-rich wastewater treatment) and elevated N discharge (Chen et al., 2022; Yu et al., 2019), leading to high sewage N:P ratios (Table 1). When combining fish and sewage pollution, mariculture still achieved net N removal but could not fully mitigate P release, highlighting the need to select species with higher P removal capacity.

4.3. Comparative nutrient removal capacity between seaweeds and shellfish

Over the past five years, seaweeds and shellfish removed similar N amounts, but seaweeds removed 50 % more P—likely due to shellfish having higher N:P ratios (Table 1). Seaweeds exhibited substantially higher maximum N (363 %) and P (699 %) removal capacities than shellfish, driven by superior growth rates and productivity (Gao et al., 2020a). As autotrophs, seaweeds photosynthesize throughout their thalli, enabling faster growth than shellfish, whose energy is allocated to shell production (e.g., mussels allocate 67 % of assimilated energy to shells) and anti-predator defenses (Sanders et al., 2018).

Gracilaria lemaneiformis showed the highest N removal capacity, not due to N content but its prolonged culture period (up to 10+ months/year in Ningde, Fujian), facilitated by thermotolerant strain improvements (Cao et al., 2024). *Saccharina japonica* exhibited the highest P removal capacity, attributed to its elevated P content (Gao et al., 2021). Among shellfish, mussels and oysters had the highest N and P removal capacities, respectively, due to a combination of high productivity, soft tissue/shell N/P content, and fast growth with high culture density (Peng et al., 2021; Zhong et al., 2022). It is important to note that the calculations of nutrient removal capacity presented in this study were derived from national average data. Given the inherent variations in environmental conditions, operational parameters, and regional characteristics across different areas, significant regional differences in actual nutrient removal performance are likely to exist. Therefore, when applying these findings to specific regional contexts or formulating region-specific strategies, additional targeted studies that account for local factors (e.g., temperature, water quality, and system design) are strongly recommended to obtain more accurate and contextually relevant results.

4.4. Implications for eutrophication mitigation

Fish mariculture is commonly conducted within 20 km offshore. With the development of far-offshore aquaculture, it has been extended to distances of up to 50 km from the coast (Mo et al., 2025). This expansion has shifted is pollution sources from nearshore to offshore regions, which may support the occurrences of algal blooms in mariculture zones and posing risks to both aquaculture itself and marine ecosystems (Kang et al., 2021). Notably, seaweed and shellfish mariculture can effectively absorb the released N and P from fish mariculture, thereby mitigating the incidence of harmful algal blooms (HABs). Consequently, optimizing the spatial configuration of multi-trophic mariculture is critical to minimizing eutrophication impacts associated with finfish aquaculture.

It is worth noting that although seaweed and shellfish culture can neutralize N release by fish culture and sewage. There is a long distance for them to neutralize N and P loads by rivers. For instance, the N input from rivers into China's marginal seas in 2010 was estimated to be 11.62 Tg (Wang et al., 2020), around 60-fold higher than what seaweed and shellfish mariculture can remove. The use of nutrient-rich synthetic fertilizers together with the planting of N-fixing crops and their runoff into waterways, elevates N:P in rivers (Dai et al., 2023; Peñuelas and Sardans, 2022). Therefore, in addition to expanding seaweed and shellfish culture, reducing anthropogenic discharge and promoting sewage treatment are essential to mitigate coastal eutrophication.

4.5. Potential impacts of climate change on nutrient removal capacity by seaweeds and shellfish

The capacities of maricultured seaweeds and shellfish to remove nitrogen (N) and phosphorus (P) are inherently sensitive to environmental conditions, which are increasingly altered by climate change. Warming seawater temperatures usually enhance N and P removal capacities of seaweeds and shellfish within tolerable limits via accelerating their nutrient uptake rates and growth (Gao et al., 2020b). Yet once thermal thresholds are crossed, elevated temperatures could reduce N/P removal capacity, particularly for cold-water species. For instance, nitrate uptake rates of the kelp *Saccharina latissima* were severely impaired at higher temperatures (e.g., 24.5 °C), even releasing nitrate under thermal stress (Ding et al., 2025). Ocean acidification (OA), driven by elevated CO_2, could commonly stimulate N and P removal capacities of seaweeds. For instance, increased pCO_2 (1000 μatm) enhanced the nitrate uptake rate of *Sargassum muticum* by 68 % compared to the ambient pCO_2 level (400 μatm) (Xu et al., 2017). However, OA can directly impair key physiological processes in bivalves that underpin their nutrient removal capacity. It has shown that reduced pH disrupts intestinal homeostasis in the noble scallop (*Chlamys nobilis*), promoting pathogenic bacteria (e.g., *Mycoplasma*) and inducing oxidative stress and inflammation. This compromises digestive efficiency and nutrient assimilation (Liu et al., 2026).

Extreme climate events (e.g., heatwaves, storms, and hypoxia) pose additional risks. Heatwaves may accelerate algal respiration over photosynthesis, reducing net nutrient uptake, while storms can damage seaweed and shellfish mariculture and their nutrient removal function (Jiang et al., 2022; Veenhof et al., 2024). Hypoxic events, exacerbated by warming and eutrophication, may suppress shellfish survival and nutrient sequestration function (Gobler et al., 2014). These factors collectively threaten the stability of mariculture-based nutrient management.

To address these uncertainties, we recommend integrating a climate-sensitivity analysis into future studies. This could involve: (1) Modeling scenarios combining IPCC climate projections with nutrient uptake kinetics (e.g., temperature-dependent functions for algae and acidification effects on shellfish); (2) Assessing adaptive strategies such as selecting thermally resilient species or optimizing cultivation timing to align with optimal climatic windows; (3) Quantifying compound impacts through multi-stressor experiments, particularly for interactions between warming, acidification, and extreme events. Such analysis would enhance predictive accuracy and inform climate-resilient mariculture practices.

5. Conclusions

To address the rising eutrophication in coastal waters, this study assesses the contribution of seaweed and shellfish mariculture in China to N and P release removal during the past 20 years. The findings reveal that such mariculture can completely neutralize nitrogen release from fish mariculture but not phosphorus release, with net phosphorus release increasing over time due to the higher nitrogen-to-phosphorus ratios in seaweed and shellfish compared to fish and the rising fish production. In contrast, seaweed and shellfish mariculture fully offsets both nitrogen and phosphorus release from sewage discharge, with net nitrogen and phosphorus removal increasing as mariculture expands and sewage discharge decreases. When combining fish mariculture and sewage pollution, mariculture still achieves net nitrogen removal but cannot fully mitigate phosphorus release. Comparative analysis shows that seaweeds have significantly higher nitrogen and phosphorus removal capacities than shellfish, with *G. lemaneiformis* and *Saccharina japonica* demonstrating the highest nitrogen and phosphorus removal capacities among seaweeds, respectively, and mussels and oysters excelling in nitrogen and phosphorus removal among shellfish. These findings highlight the potential of seaweed and shellfish culture in mitigating coastal eutrophication, provide insights for selecting optimal species to enhance nutrient removal efficiency, and are helpful for addressing escalating eutrophication challenges in coastal waters.

CRediT authorship contribution statement

Yuling Yang: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Yonglong Xiong:** Writing – review & editing, Methodology, Investigation, Data curation. **Tengteng Wang:** Writing – review & editing, Methodology, Investigation. **Junxiao Zhang:** Writing – review & editing, Methodology, Investigation. **Lan Feng:** Writing – review & editing, Methodology. **Guang Gao:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.118793.

Data availability

Data will be made available on request.

References

Akinnawo, S.O., 2023. Eutrophication: Causes, consequences, physical, chemical and biological techniques for mitigation strategies. Environ. Chall. 12, 100733.
Aniebone, V., Imo, D., Shonde, O., 2024. Nutrients pollution of the coastal marine ecosystems. Int. J. Innov. Agric. Biol. Res. 12, 82–95.
Baffour, B., King, T., Valente, P., 2013. The modern census: evolution, examples and evaluation. Int. Stat. Rev. 81, 407–425.
Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81, 169–193.
Bouwman, L., Beusen, A., Glibert, P.M., Overbeek, C., Pawlowski, M., Herrera, J., Mulsow, S., Yu, R., Zhou, M., 2013. Mariculture: significant and expanding cause of coastal nutrient enrichment. Environ. Res. Lett. 8, 044026.
Boyd, C.E., McNevin, A.A., Davis, R.P., 2022. The contribution of fisheries and aquaculture to the global protein supply. Food Secur. 14, 805–827.
Cao, M., Zhang, J., Li, P., Wang, J., Mi, P., Sui, Z., 2024. Review on recent advances of *Gracilariopsis lemaneiformis* (Rhodophyta). Algal Res. 79, 103453.
Chen, X., Wang, Y., Bai, Z., Ma, L., Strokal, M., Kroeze, C., Chen, X., Zhang, F., Shi, X., 2022. Mitigating phosphorus pollution from detergents in the surface waters of China. Sci. Total Environ. 804, 150125.
Clements, J.C., Comeau, L.A., 2019. Nitrogen removal potential of shellfish aquaculture harvests in eastern Canada: A comparison of culture methods. Aquacult. Rep. 13, 100183.
Dai, M., Zhao, Y., Chai, F., Chen, M., Chen, N., Chen, Y., Cheng, D., Gan, J., Guan, D., Hong, Y., 2023. Persistent eutrophication and hypoxia in the coastal ocean. Cambridge Prisms: Coastal Futures 1, e19.
Ding, X., Soetaert, K., Timmermans, K., 2025. Effect of temperature on growth and nitrate and phosphate uptake kinetics of juvenile *Saccharina latissima* sporophytes (Phaeophyceae). J. Appl. Phycol. 37, 1277–1287.
Dong, S.L., Dong, Y.W., Huang, L.Y., Zhou, Y.G., Cao, L., Tian, X.L., Han, L.M., Li, D.H., 2024. Advancements and hurdles of deeper-offshore aquaculture in China. Rev. Aquacult. 16, 644–655.
Dvarskas, A., Bricker, S.B., Wikfors, G.H., Bohorquez, J.J., Dixon, M.S., Rose, J.M., 2020. Quantification and valuation of nitrogen removal services provided by commercial shellfish aquaculture at the subwatershed scale. Environ. Sci. Technol. 54, 16156–16165.
Feng, Y., Xiong, Y., Hall-Spencer, J.M., Liu, K., Beardall, J., Gao, K., Ge, J., Xu, J., Gao, G., 2024. Shift in algal blooms from micro-to macroalgae around China with increasing eutrophication and climate change. Glob. Chang. Biol. 30, e17018.
Gao, G., Beardall, J., Bao, M., Wang, C., Ren, W., Xu, J., 2018. Ocean acidification and nutrient limitation synergistically reduce growth and photosynthetic performances of a green tide alga *Ulva linza*. Biogeosciences 15, 3409–3420.
Gao, G., Burgess, J.G., Wu, M., Wang, S., Gao, K., 2020a. Using macroalgae as biofuel: current opportunities and challenges. Bot. Mar. 63, 355–370.
Gao, G., Gao, L., Fu, Q., Li, X., Xu, J., 2022. Coculture of the Pacific white shrimp *Litopenaeus vannamei* and the macroalga *Ulva linza* enhances their growth rates and functional properties. J. Clean. Prod. 349, 131407.
Gao, G., Gao, L., Jiang, M., Jian, A., He, L., 2021. The potential of seaweed cultivation to achieve carbon neutrality and mitigate deoxygenation and eutrophication. Environ. Res. Lett. 17, 014018.
Gao, G., Li, G., Xu, J., Feng, Y., Hall-Spencer, J.M., 2025. Coastal restoration policy needs to consider seaweed diversity. Nat. Ecol. Evol. 9, 740–742.
Gao, K., Gao, G., Wang, Y., Dupont, S., 2020b. Impacts of ocean acidification under multiple stressors on typical organisms and ecological processes. Mar Life Sci Technol 2, 279–291.
Gobler, C.J., DePasquale, E.L., Griffith, A.W., Baumann, H., 2014. Hypoxia and acidification have additive and synergistic negative effects on the growth, survival, and metamorphosis of early life stage bivalves. PLoS One 9, e83648.
He, J., Zhu, Z., Yan, X., 2025. The legend continues: The critical evidence showing the bivalve farmingis a carbon sink with a novel budget framework. Rev. Aquacult. 17, e70001.
Herath, S., Satoh, S., 2015. Environmental impact of phosphorus and nitrogen from aquaculture. In: Feed and Feeding Practices in Aquaculture. Woodhead Publishing, pp. 369–386.
Jiang, M., Gao, L., Huang, R., Lin, X., Gao, G., 2022. Differential responses of bloom-forming *Ulva intestinalis* and economically important *Gracilariopsis lemaneiformis* to marine heatwaves under changing nitrate conditions. Sci. Total Environ. 840, 156591.
Kang, Y., Kim, H.-J., Moon, C.-H., 2021. Eutrophication driven by aquaculture fish farms controls phytoplankton and dinoflagellate cyst abundance in the southern coastal waters of Korea. J. Mar. Sci. Eng. 9, 362.
Kumar, A., Hanjabam, M.D., Kishore, P., Uchoi, D., Panda, S.K., Mohan, C.O., Chatterjee, N.S., Zynudheen, A.A., Ravishankar, C.N., 2023. Exploitation of seaweed functionality for the development of food products. Food and Bioprocess Tech. 16, 1873–1903.
Lazzari, R., Baldisserotto, B., 2008. Nitrogen and phosphorus waste in fish farming. Bol. Inst. Pesca 34, 591–600.
Li, W., Chen, J., Feng, Y., Li, X., Gao, G., 2024. Production and ecological function of fucoidans from marine algae in a changing ocean. Int. J. Biol. Macromol. 283, 137944.
Liu, M., Guo, X., Han, L., Zhao, Y., Ge, C., 2026. Effects of ocean acidification on intestinal homeostasis and organismal performance in a marine bivalve: From microbial shifts to physiological suppression. Mar. Pollut. Bull. 222, 118704.
Marinho-Soriano, E., Nunes, S., Carneiro, M., Pereira, D., 2009. Nutrients' removal from aquaculture wastewater using the macroalgae *Gracilaria birdiae*. Biomass Bioenerg. 33, 327–331.
Mo, Z., Chen, Y., Zhang, X., Wang, Z., Zhang, Q., 2025. Spatiotemporal trends and zoning geospatial assessment in China's offshore mariculture (2018–2022). Remote Sensing 17, 1227.
Peng, D., Zhang, S., Zhang, H., Pang, D., Yang, Q., Jiang, R., Lin, Y., Mu, Y., Zhu, Y., 2021. The oyster fishery in China: Trend, concerns and solutions. Mar. Policy 129, 104524.
Peñuelas, J., Sardans, J., 2022. The global nitrogen-phosphorus imbalance. Science 375, 266–267.
Pontius, J., McIntosh, A., 2024. Gulf of Mexico dead zone. In: Environmental Problem Solving in an Age of Climate Change: Volume One: Basic Tools and Techniques. Springer International Publishing, Cham, pp. 45–56.
Qu, L., Feng, P., Cong, P., Tao, G., Liu, H., Duan, W., 2025. Spatial-temporal distribution of nitrogen and phosphorus nutrients and potential eutrophication assessment in Bohai Bay. China. Ocean Coast. Manage. 267, 107741.
Reusch, T.B.H., Dierking, J., Andersson, H.C., Bonsdorff, E., Carstensen, J., Casini, M., Czajkowski, M., Hasler, B., Hinsby, K., Hyytiäinen, K., Johannesson, K., Jomaa, S., Jormalainen, V., Kuosa, H., Kurland, S., Laikre, L., MacKenzie, B.R., Margonski, P., Melzner, F., Oesterwind, D., Ojaveer, H., Refsgaard, J.C., Sandström, A., Schwarz, G., Tonderski, K., Winder, M., Zandersen, M., 2018. The Baltic Sea as a time machine for the future coastal ocean. Sci. Adv. 4, eaar8195.
Sanders, T., Schmittmann, L., Nascimento-Schulze, J.C., Melzner, F., 2018. High calcification costs limit mussel growth at low salinity. Front. Mar. Sci. 5, 352.
Simcock, A., Halpern, B., Ramalingam Kirubagaran, M.M., Polette, M., Smith, E., Wang, J., Kelley, J., Malone, T., Rasoanaina, J., 2016. Coastal, riverine and atmospheric inputs from land. In: Inniss .A,.S., L (Ed.), First global integrated marine assessment, pp. 1–93. UN-DoLAS.
Solórzano, L., Sharp, J.H., 1980. Determination of total dissolved phosphorus and particulate phosphorus in natural waters. Limnol. Oceanogr. 25, 754–758.
Song, C., Xiong, Y., Jin, P., Sun, Y., Zhang, Q., Ma, Z., Gao, G., 2023. Mariculture structure adjustment to achieve China's carbon neutrality and mitigate climate change. Sci. Total Environ. 895, 164986.
Veenhof, R.J., Burrows, M.T., Hughes, A.D., Michalek, K., Ross, M.E., Thomson, A.I., Fedenko, J., Stanley, M.S., 2024. Sustainable seaweed aquaculture and climate change in the North Atlantic: challenges and opportunities. Front. Mar. Sci. 11, 1483330.
Vymazal, J., 2020. Removal of nutrients in constructed wetlands for wastewater treatment through plant harvesting–biomass and load matter the most. Ecol. Eng. 155, 105962.
Wang, J., Beusen, A.H., Liu, X., Van Dingenen, R., Dentener, F., Yao, Q., Xu, B., Ran, X., Yu, Z., Bouwman, A.F., 2020. Spatially explicit inventory of sources of nitrogen inputs to the Yellow Sea, East China Sea, and South China Sea for the period 1970–2010. Earth's Future 8 e2020EF001516.
Wu, Y., Zhou, Z., Pan, Y., Zhao, J., Bai, H., Chen, B., Zhang, X., Pu, F., Chen, J., Xu, P., 2021. GWAS identified candidate variants and genes associated with acute heat tolerance of large yellow croaker. Aquaculture 540, 736696.
Xiong, Y., Gao, L., Qu, L., Xu, J., Ma, Z., Gao, G., 2023. The contribution of fish and seaweed mariculture to the coastal fluxes of biogenic elements in two important aquaculture areas. China. Sci. Total Environ. 856, 159056.
Xu, Z., Gao, G., Xu, J., Wu, H., 2017. Physiological response of a golden tide alga (*Sargassum muticum)* to the interaction of ocean acidification and phosphorus enrichment. Biogeosciences 14, 671–681.
Xu, Z., Lin, X., Lin, Q., Yang, Y., Wang, Y., 2007. Nitrogen, phosphorus, and energy waste outputs of four marine cage-cultured fish fed with trash fish. Aquaculture 263, 130–141.
Yanez, J.M., Barria, A., Lopez, M.E., Moen, T., Garcia, B.F., Yoshida, G.M., Xu, P., 2023. Genome-wide association and genomic selection in aquaculture. Rev. Aquacult. 15, 645–675.
Yu, C., Huang, X., Chen, H., Godfray, H.C.J., Wright, J.S., Hall, J.W., Gong, P., Ni, S., Qiao, S., Huang, G., 2019. Managing nitrogen to restore water quality in China. Nature 567, 516–520.
Zhao, F., Wu, J., 2024. The role of shellfish aquaculture in coastal habitat restoration. Int. J. Mar. Sci. 14, 275.
Zhong, W., Lin, J., Zou, Q., Wen, Y., Yang, W., Yang, G., 2022. Hydrodynamic effects of large-scale suspended mussel farms: Field observations and numerical simulations. Front. Mar. Sci. 9, 973155.