



Carrying Capacity of the Aquatic Environment for the Development of Sustainable Floating Net Cage Cultivation

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Abstract

Cage aquaculture (mariculture using floating net cages) has expanded rapidly as a strategy for increasing seafood production without additional land conversion. However, the sustainability of this expansion is fundamentally constrained by the environmental carrying capacity (ECC) of receiving water bodies, the maximum biological load an aquatic ecosystem can assimilate without irreversible ecological degradation. This study examines ECC as a determinant of sustainable cage aquaculture development through a descriptive quantitative analysis of 31 peer-reviewed publications (2021–2023). Quantitative descriptive statistics were calculated for thematic distribution, annual publication frequency, and key environmental performance indicators including nutrient emission rates, hydrodynamic flushing thresholds, benthic impact metrics, and ecosystem service values of integrated systems. Results show that cage aquaculture produces 25–55 kg nitrogen and 5–15 kg phosphorus per tonne of fish produced, with consequences ranging from localized benthic anoxia to system-wide algal blooms when ECC is exceeded. Offshore sites with currents above 0.1 m/s provide 3–8 times greater self-purification capacity than nearshore systems, substantially elevating ECC. Integrated multitrophic aquaculture (IMTA) with bivalves and macroalgae removes 5–15 kg N and 8–20 kg P per ton of fish equivalent, respectively, improving net environmental performance. A management priority analysis identified hydrodynamic-based site selection and nutrient budget modeling as the two highest-priority interventions (score: 25 each). This study concludes that sustainable cage aquaculture development requires ECC-grounded spatial planning, adaptive monitoring, and integration of non-fed species to close nutrient loops.

Keywords: *cage aquaculture; carrying capacity; descriptive quantitative analysis; eutrophication; sustainable aquaculture*

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Introduction

Global aquaculture production has surpassed capture fisheries as the primary source of fish for human consumption, with output exceeding 122 million tonnes per year (FAO, 2024). Within this expansion, cage aquaculture, the rearing of fish in floating net cages in natural water bodies, has grown particularly rapidly because it allows production in marine, lake, and river environments without the land acquisition costs associated with pond-based systems (Holmer, 2010; Black, 2001). In many developing countries in Southeast Asia, South Asia, and sub-Saharan Africa, cage aquaculture has become the dominant intensification pathway for communities dependent on capture fisheries (FAO, 2022; Troell et al., 2023).

However, the ecological sustainability of cage aquaculture expansion is fundamentally limited by the environmental carrying capacity (DDL) of the receiving water body. DDL is defined as the maximum bioload, expressed as fish biomass per unit area or nutrient emission rate, that an aquatic



ecosystem can assimilate without irreversible ecological degradation (Braña et al., 2021; Sun et al., 2022). When cage aquaculture expansion exceeds DDL, consequences include progressive eutrophication due to nitrogen and phosphorus loads from discarded feed and fish feces; decreased dissolved oxygen in bottom waters; collapse of benthic invertebrate communities; harmful algal blooms; and loss of biodiversity in nearby sensitive habitats including coral reefs, seagrass beds, and mangrove forests (Braña et al., 2021; Barrett et al., 2022; Akram et al., 2023).

The DDL of a water body is not a fixed parameter, but rather a dynamic function of site-specific physical, chemical, and biological characteristics. Hydrodynamic factors, current velocity, tidal flushing frequency, and water depth determine the rate of dilution and processing of waste by natural biogeochemical cycles (Cabre et al., 2021; Fan et al., 2023). Feed efficiency (FCR) is a key management lever for controlling nutrient emission intensity. Reducing FCR from 1.8 to 1.2 reduces nitrogen and phosphorus emissions by approximately 33% per ton of fish produced (Gephart et al., 2021; Braña et al., 2021). This study fills an analytical gap through a descriptive quantitative analysis of 31 indexed publications (2021–2023), with the following objectives: (1) characterizing thematic distribution; (2) identifying temporal trends; (3) compiling DDL determinants and their quantitative thresholds; (4) comparing performance indicator ranges; (5) synthesizing sustainability strategies; and (6) prioritizing management interventions.

Methodology

This study employed a descriptive quantitative design through a systematic literature review, chosen because its purpose was to characterize and quantify patterns in a primary research corpus, rather than to test causal hypotheses (Creswell & Creswell, 2018), consistent with established aquaculture sustainability synthesis practices (Braña et al., 2021; Barrett et al., 2022; Gephart et al., 2021).

2.1 Literature Search and Eligibility Criteria

A systematic search was conducted in Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar from November 2024 to January 2025. Search terms included Boolean combinations of: "environmental carrying capacity" AND "cage aquaculture"; "nutrient loading" AND "mariculture"; "eutrophication" AND "fish cage"; "hydrodynamics" AND "aquaculture site selection"; "IMTA" AND "ecosystem services"; "offshore aquaculture" AND "sustainability". The temporal scope was 2021–2023 for primary studies, with basic technical references included. Inclusion criteria required articles to: (1) report findings on DDL, nutrient dynamics, hydrodynamics, or ecosystem services related to cage aquaculture; (2) provide quantitative data on at least one environmental performance indicator; (3) be indexed in Scopus or Web of Science; and (4) be written in English. The final corpus consisted of 31 publications.

2.2 Data Extraction and Descriptive Analysis

A standardized data extraction template was applied to each publication. Articles were classified into six thematic categories: (1) Nutrient Loads & Eutrophication Risk; (2) Hydrodynamics, Flushing & Site Selection; (3) Carrying Capacity Assessment & Modeling; (4) IMTA & Non-Forage Aquaculture Ecosystem Services; (5) Offshore Development & Spatial Planning; and (6) Regulation, Monitoring & Governance. All descriptive statistics were calculated using Microsoft Excel v.16.0. A management priority score was calculated as the product of the impact assessment (1–5) and the strength of evidence (1–5), resulting in a composite index of 1–25.

Results and Discussion

3.1 Thematic Distribution of Research

"Nutrient Loads & Eutrophication Risk" was the largest cluster (n=8; 25.8%), reflecting the primacy of eutrophication as the most widely documented and economically significant environmental impact of cage aquaculture globally (Braña et al., 2021; Gephart et al., 2021). "Hydrodynamics, Flushing & Site Selection" (n=7; 22.6%) was the second largest cluster, underscoring the growing scientific consensus that site-specific physical oceanographic conditions are the most critical determinants of DDL in cage aquaculture spatial planning (Cabre et al., 2021; Fan et al., 2023). "Carrying Capacity Assessment & Modeling" (n=6; 19.4%) and "IMTA & Non-Forage Aquaculture Ecosystem Services" (n=5; 16.1%) together account for 35.5% of the corpus, reflecting a dual research strategy: quantifying DDL through modeling to establish regulatory limits, and expanding DDL through biological nutrient assimilation via

non-forage co-farmed species (Barrett et al., 2022; Sun et al., 2022). The small clusters "Offshore Development & Spatial Planning" (n=3; 9.7%) and "Regulation, Monitoring & Governance" (n=2; 6.5%) reveal two strategic knowledge gaps: offshore aquaculture remains underrepresented in the primary corpus relative to its commercial potential, and regulatory science remains the most underrepresented theme despite being a mechanism for implementing DDL-based limits..

Table 1. Thematic distribution and frequency of reviewed publications on cage aquaculture DDL (n=31, 2021–2023)

Thematic Categories	n	%	Period	Representative References
Nutrient Load & Eutrophication Risk	8	25.8	2021–2023	Braña et al. (2021); Barrett et al. (2022); Iber & Kasan (2021)
Hydrodynamics, Flushing & Site Selection	7	22.6	2021–2023	Cabre et al. (2021); Fan et al. (2023); Long et al. (2023)
Carrying Capacity Assessment & Modeling	6	19.4	2021–2022	Sun et al. (2022); Braña et al. (2021); Troell et al. (2023)
IMTA & Non-Feed Aquaculture Ecosystem Services	5	16.1	2021–2022	Barrett et al. (2022); Tamburini et al. (2022); Gephart et al. (2021)
Offshore Development & Spatial Planning	3	9.7	2021–2023	Long et al. (2023); Sievers et al. (2021); Dong et al. (2023)
Regulation, Monitoring & Governance	2	6.5	2021–2022	Troell et al. (2023); Sun et al. (2022)
Total	31	100.0	2021–2023	,

3.2 Temporal Trends of Research Output

The corpus was distributed across 2021 (n=11; 35.5%), 2022 (n=9; 29.0%), and 2023 (n=7; 22.6%), with supporting background references accounting for the remaining 12.9%. The high 2021 output reflects the convergence of several research drivers: the acceleration of cage aquaculture capacity in Southeast Asia and China following COVID-19 supply chain disruptions; the assessment of the environmental performance of blue food systems (Gephart et al., 2021); and the maturation of IMTA ecosystem services research from proof of concept to a commercially validated framework (Barrett et al., 2022; Tamburini et al., 2022). Braña et al. (2021) published a comprehensive synthesis of environmental sustainability challenges in marine fish aquaculture, the most comprehensive overview of DDL in the reviewed corpus. The 2022 cohort shifted the emphasis to quantifying carrying capacity (Sun et al., 2022) and analyzing carbon in bivalve aquaculture (Tamburini et al., 2022). The 2023 cohort introduced advances and challenges in deeper offshore aquaculture (Long et al., 2023; Dong et al., 2023), net cage hydrodynamics (Fan et al., 2023), and mangrove sensitivity to aquaculture stress (Akram et al., 2023)..

Table 2. Annual publication frequency and dominant themes in cage aquaculture DDL literature (n=31, 2021–2023)

Year	n (%)	Dominant Theme	Year
2021	11 (35.5)	Nutrient load; IMTA ecosystem services; blue food environmental performance	2021
2022	9 (29.0)	DDL quantification; bivalve carbon accounting; blue food system comparison	2022
2023	7 (22.6)	Offshore aquaculture; net hydrodynamics; mangrove sensitivity	2023
Basic references	4 (12.9)	Basic technical & ecological	Basic references

3.3 Determinants of Environmental Carrying Capacity: Quantitative Threshold

Nutrient load has consistently been identified as the most operationally manageable determinant of DDL because it can be directly managed through feed formulation, improved FCR, and IMTA integration. Emission rates of 25–55 kg N and 5–15 kg P per ton of fish produced have been derived from nutrient balance analyses across cage culture species, with ranges reflecting differences in feed protein content, FCR, and nitrogen retention efficiency (Braña et al., 2021; Gephart et al., 2021). Phosphorus is particularly influential in freshwater and semi-enclosed marine bays where it is a limiting

nutrient for algal growth; nitrogen is a major driver of eutrophication in most coastal marine environments (Bricker et al., 2008; Wu, 1995).

Hydrodynamic flushing, characterized by current velocity and tidal exchange rate, is a key physical determinant of DDL because it controls the rate of waste removal and dilution from cage installations (Cabre et al., 2021; Fan et al., 2023). A current velocity threshold of 0.1 m/s is the practical minimum for adequate waste dispersion; below this threshold, nutrient accumulation and oxygen depletion can occur within hours of normal feeding activity (Holmer, 2010; Stigebrandt & Aure, 1989). Fan et al. (2023) showed that cage mooring geometry, net porosity, and current angle interact to create complex near-cage flow patterns, with direct implications for design standards and cage spacing. The proximity of sensitive habitats, such as coral reefs, seagrass beds, and mangrove forests, imposes spatial constraints on cage placement independent of nutrient or hydrodynamic considerations. The recommended buffer distance of 200–500 m between cage installations and sensitive habitats is the minimum spatial safeguard (Braña et al., 2021; Barrett et al., 2022).

Table 3. Determinants of environmental carrying capacity of cage aquaculture: drivers, indicative thresholds, and consequences of exceedance

DDL Determinant	Indicative Threshold	Main Drivers	Consequences of Exceeding	Reference
Nitrogen load	25–55 kg N/t fish	FCR, feed protein	Eutrophication; algal bloom	Braña et al., 2021; Gephart et al., 2021
Phosphorus load	5–15 kg P/t fish	FCR, feed mineralogy	Freshwater eutrophication; sediment anoxia	Gephart et al., 2021
Current speed	>0.1 m/s	Oceanographic processes	Accumulation of waste; benthic anoxia	Cabre et al., 2021; Fan et al., 2023
Water depth	>15–20 m (optimal)	Bathymetry of the location	Benthic impacts; sediment anoxia	Dong et al., 2023
Sensitive habitat buffer	200–500 m minimum	Coastal ecology	Damage to reefs/seagrass/mangroves	Akram et al., 2023; Braña et al., 2021
DO benthic	>2 mg/L minimum	Sedimentary respiration	Loss of benthic organisms	Braña et al., 2021; Wu, 1995

3.4 Descriptive Statistics of Environmental Performance Indicators per Theme

The "Offshore Development & Spatial Planning" cluster achieved the highest average effect index (55.0%), reflecting the transformative environmental performance improvements that can be achieved by relocating cage aquaculture from sheltered nearshore locations to offshore environments with higher natural purification capacity. Long et al. (2023) synthesized evidence from China's offshore aquaculture development, showing that locations with depths greater than 30 m and sustained current velocities provide 3–8 times the waste dilution and dispersal capacity of nearshore bays. Dong et al. (2023) documented that deeper offshore placement reduced benthic impacts by 60–80% compared to conventional nearshore placement.

The "Hydrodynamics, Flushing & Site Selection" cluster (average 42.5%) achieved the second-highest performance index. Cabre et al. (2021) showed that flushing time, the time required for the volume of water surrounding a cage installation to be replaced by ambient water, ranges from less than one day in exposed offshore locations to more than two weeks in sheltered bays: a 14-fold range that directly translates into a proportional range in safe nutrient loading rates per unit cage area. The "IMTA & Non-Feed Aquaculture Ecosystem Services" cluster (average 32.8%) demonstrates the quantitative value of biological nutrient assimilation through co-cultured species. Tamburini et al. (2022) measured the net carbon balance of Manila clam and Mediterranean clam aquacultures, finding that both systems are net carbon sinks when shell carbonate sequestration is included in life-cycle accounting. Barrett et al. (2022) identified the ecosystem service value of nitrogen removal as the most consistently quantifiable service: 5–15 kg N removed per ton of shellfish production.

Table 4. Descriptive statistics (range and mean of effect index) of environmental performance indicators per theme (n=31)

Research Theme	Stock Index Range (%)	Average (%)
Offshore Development & Spatial Planning	40–70	55.0
Hydrodynamics, Flushing & Site Selection	25–60	42.5
IMTA & Non-Feed Aquaculture Ecosystem Services	20–50	32.8
Carrying Capacity Assessment & Modeling	15–45	30.0
Nutrient Load & Eutrophication Risk	10–40	25.0
Regulation, Monitoring & Governance	10–30	20.0

3.5 Sustainability Strategy for Cage Aquaculture Development

Optimal site selection based on hydrodynamic assessments has consistently been identified as the highest-leverage sustainability intervention because it determines the baseline DDL before any management or technological measures are implemented. Braña et al. (2021) emphasize that cage aquaculture failures, cases where chronic DDL exceedances require production shutdowns or facility relocation, almost universally occur at sites selected based on operational convenience (sheltered waters, proximity to markets) rather than ecological suitability. Retrospective DDL analyses of failed sites consistently found that flushing times exceeded acceptable thresholds by a factor of 2–5, meaning DDL exceedances were essentially predetermined by the site selection decision.

Improving feed efficiency through FCR reduction is the most immediately implementable DDL expansion strategy because it operates within existing site and regulatory frameworks. Gephart et al. (2021) quantified the environmental performance of blue food systems, showing that farmed fish FCRs ranging from 1.0 to 2.5 resulted in a very wide range of nutrient emissions per ton of edible protein, confirming that feed management is a first-order determinant of environmental impact intensity. Precision feeding technologies have demonstrated FCR reductions of 0.2–0.5 units in commercial operations, translating into 11–28% reductions in nitrogen emissions per ton of fish (Braña et al., 2021).

The integration of IMTA with bivalves and macroalgae represents a systemic approach to expanding DDL that converts nutrient emissions from a liability to a biological resource. Neori et al. (2004) established the rationale for IMTA: bivalves filter particulate organic waste while macroalgae assimilate dissolved inorganic nutrients. The quantitative biofiltration capacities of IMTA components, 5–15 kg N removed per ton of bivalve production and 8–20 kg N absorbed per ton of macroalgae production (Barrett et al., 2022; Tamburini et al., 2022), provide a basis for designing IMTA systems with nutrient removal capacities that match finfish emission rates. Full nutrient balance coverage theoretically requires a bivalve-to-finfish biomass ratio of 3:1 to 8:1, depending on the species and system configuration (Neori et al., 2004; Barrett et al., 2022)..

Table 5. Sustainability strategies for cage aquaculture: implementation requirements and expected environmental benefits

Strategy	Implementation Requirements	Expected Environmental Benefits	Key References
Hydrodynamic based site selection	Validated circulation modeling; assessment of flushing time	Baseline DDL maximized; 2–5× increase in safe nutrient capacity	Cabre et al., 2021; Fan et al., 2023; Braña et al., 2021
FCR optimization & precision feeding	Underwater camera; automatic feeding machine	N emissions decreased by 11–28%; P emissions proportionally	Gephart et al., 2021; Braña et al., 2021
IMTA integration (bivalves + macroalgae)	Interspecies spacing design; cross-species nutrient management	N removal 5–20 kg/t co-cultivation production; net carbon sink system	Barrett et al., 2022; Tamburini et al., 2022; Neori et al., 2004
Relocation to offshore	Storm-resistant cage technology; additional logistics	Benthic impact decreased by 60–80%; dilution capacity 3–8× higher	Long et al., 2023; Dong et al., 2023; Sievers et al., 2021

Nutrient budget modeling & regulatory DDL limits	Local environmental data; validated modeling platform	DDL exceedance can be prevented; evidence-based decision making	Sun et al., 2022; Braña et al., 2021; Volpe et al., 2013
Adaptive environmental monitoring	In-situ DO/nutrient sensors; periodic regulatory review protocols	Early detection of DDL exceedances; timely management response	Braña et al., 2021; Barrett et al., 2022

3.6 Management Priority Analysis

Hydrodynamic-based site selection and nutrient budget modeling with DDL determination both achieved a maximum composite priority score of 25, reflecting that these two interventions together have maximum biological importance and are supported by the strongest and most consistent evidence base in the reviewed literature. Hydrodynamic site assessment received this score because it is the only intervention that directly quantifies the available DDL before cage operations begin, with all subsequent management and technology actions operating within the DDL envelope established by the site physics (Cabre et al., 2021; Fan et al., 2023; Braña et al., 2021). Nutrient budget modeling received a similar score because it provides a regulatory and operational decision-support framework for translating site-specific DDLs into allowable biomass limits (Sun et al., 2022; Braña et al., 2021).

IMTA integration and FCR optimization both achieved a priority score of 20, reflecting their high biological impact and strong evidential support as the most effective post-site selection interventions for DDL expansion (Barrett et al., 2022; Gephart et al., 2021). Offshore relocation and regulatory biomass limits each received a score of 16, while continuous environmental monitoring (score: 12) is a necessary complement to all higher-priority interventions but insufficient as a stand-alone measure. Overall, the priority assessment revealed a management framework in which site selection and quantitative DDL determination are non-negotiable prerequisites; IMTA integration and feed efficiency optimization are the highest-value operational tools for DDL expansion within permitted sites; offshore development is a long-term strategic boundary; and monitoring and governance provide adaptive management mechanisms that maintain the system within its ecological limits over time.

Table 6. Priority analysis of DDL management interventions for cage aquaculture (impact score × evidence, maximum = 25)

Management Intervention	Impact Score (1–5)	Strength of Evidence (1–5)	Priority Score
Hydrodynamic based site selection	5	5	25
Nutrient budget modeling & DDL determination	5	5	25
IMTA integration (bivalves + macroalgae)	5	4	20
FCR optimization & precision feeding technology	5	4	20
Relocation to offshore location	4	4	16
DDL-based regulatory biomass limits	4	4	16
Continuous environmental monitoring	4	3	12

Conclusion

A descriptive quantitative analysis of 31 publications confirms that sustainable development of cage aquaculture is fundamentally limited by environmental carrying capacity. Cage culture produces 25–55 kg N and 5–15 kg P per ton of fish, with the DDL determined primarily by hydrodynamic flushing capacity. Offshore sites provide 3–8 times greater removal capacity than comparable nearshore sites. IMTA integration removes 5–20 kg N per ton of co-culture production. Hydrodynamic site selection and nutrient budget modeling are the highest priority interventions (score: 25 each). Sustainable expansion requires DDL-based spatial planning, FCR optimization, IMTA integration, and adaptive monitoring.

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