Fisheries New Zealand
Tini a Tangaroa

Recent literature on the ecosystem effects of aquaculture (2013 to 2024)

New Zealand Aquatic Environment and Biodiversity Report No. 376

E. McGrath, B. Knight, D. Elvines, D. Clement, L. Bull, R. Sneddon, J. Atalah, K. Hutson, J. Symonds, R. Costilla, M. Scholtens, R. Millar, A. Alder

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PLAIN LANGUAGE SUMMARY

This document presents a summary of recent literature on the ecological effects of aquaculture, to provide context for the 2026 update of the *Overview of Ecological Effects of Aquaculture* (the Overview), first published in 2013.

While the original scientific literature review has not been comprehensively revised, this update includes new information on changes in aquaculture policy, regulation, technology, monitoring and research relevant to understanding environmental effects in New Zealand. The document draws mainly on New Zealand studies where available and uses international research where local information is limited.

EXECUTIVE SUMMARY

McGrath, E.[1]; Knight, B.[1]; Elvines, D.[1]; Clement, D.[1]; Bull, L.[2]; Sneddon, R.[1]; Atalah, J.[1]; Hutson, K.[1]; Symonds, J.[1]; Costilla, R.[1]; Scholtens, M.[1]; Millar, R.[1]; Alder, A.[1] (2026). Recent literature on the ecosystem effects of aquaculture (2013 to 2024).

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This document presents a summary of recent literature on the ecological effects of aquaculture, to provide context for the 2026 update of the *Overview of Ecological Effects of Aquaculture* (the Overview), first published in 2013.

Although the underlying literature review has not been comprehensively revised, the update incorporates developments in aquaculture policy, regulation, technology, monitoring and scientific understanding relevant to ecological effects in New Zealand. The document draws primarily on New Zealand research, supported by international literature where relevant, and is intended as a strategic overview rather than a comprehensive evidence review. It comprises a bibliography summarising the principal additions to the original review, alongside an abbreviated list of references most relevant to those updates.

Since 2013, New Zealand's aquaculture sector has undergone substantial strategic and regulatory change. Government production targets have increased from $1 billion by 2025 to $3 billion by 2035 under the Aquaculture Development Plan, with expansion into open ocean environments and diversification into new species identified as key pathways for growth. The updated Overview reflects corresponding changes in regulatory and management frameworks, including recent national policy instruments and evolving environmental management approaches.

Major advances in understanding ecological effects associated with aquaculture are highlighted, including benthic processes, hydrodynamics, marine wildlife interactions, biosecurity, cumulative effects and climate-related pressures. Developments in environmental monitoring and predictive modelling, including eDNA techniques, remote sensing and adaptive management frameworks, have improved the capacity to assess and manage ecological risk. However, significant uncertainty remains, particularly for open ocean aquaculture, cumulative effects, climate change interactions and emerging industries where empirical data are limited.

The revised Overview also recognises increasing interest in restorative aquaculture and the potential for some aquaculture activities to provide ecosystem services alongside food production. Shellfish and seaweed farming may contribute to habitat provision, nutrient cycling and water filtration under some conditions, although outcomes remain highly site- and context-specific. Overall, the revised Overview emphasises that ecological effects are strongly influenced by farm location, scale, design and management practices, reinforcing the importance of monitoring, adaptive management and continued research to support sustainable aquaculture development in New Zealand.

[1] Cawthron Institute.
[2] BlueGreen Ecology Ltd.

1. INTRODUCTION

The *Literature Review of Ecological Effects of Aquaculture* was compiled in 2013 by two of New Zealand's main science providers in aquaculture – the National Institute of Water and Atmospheric Research (NIWA) and Cawthron Institute (Cawthron). The review brought together existing scientific knowledge on the main potential ecological effects of aquaculture in New Zealand and identified uncertainties and knowledge gaps.

The 2013 *Overview of Ecological Effects of Aquaculture* (the Overview) summarised the key potential ecological effects of aquaculture in New Zealand, provided commentary on their likely significance, and outlined management and mitigation options. It was intended to communicate the key technical details of the literature review in an accessible format.

Since publication of the 2013 *Overview of Ecological Effects of Aquaculture* (the Overview), the New Zealand government has increased its aquaculture production targets from $1 billion by 2025 to $3 billion by 2035 under the Aquaculture Development Plan. This plan identifies aquaculture extension into the open ocean as a key pathway to meet these production goals, alongside diversification of aquaculture species as a strategic priority. An updated version of the Overview to reflect the new direction has therefore been prepared and is available as (McGrath et al. 2026)[3].

This literature review document highlights these updates and lists new references that have become available since 2013, and is hence a summary of recent literature on the ecosystem effects of aquaculture and an addendum to the 2013 *Literature Review of Ecological Effects of Aquaculture*

One of the most significant changes since the 2013 Overview is that the list of marine aquaculture species in New Zealand has been updated to reflect interest in diversification, with the inclusion of pāua, snapper, flat oysters and native seaweed species. Hāpuku has been removed from the updated Overview.

Climate change influences on the ecological effects of aquaculture are complex, poorly understood and highly location-specific, so while available information is incorporated in the updated Overview document where possible, substantial knowledge gaps remain and further national and international research is needed.

Since 2013, New Zealand's regulatory framework for aquaculture has evolved to provide additional national direction and alternative approval pathways, while retaining the Resource Management Act 1991 (RMA) as the primary statute for managing activities in the coastal marine area. The National Environmental Standards for Marine Aquaculture (NES-MA) provide nationally consistent rules for the replacement, extension and reconsenting of existing marine farms and support plan changes to enable aquaculture in suitable areas. The Fast-track Approvals Act 2024 introduces an alternative approvals pathway for projects with significant regional or national benefits, providing a streamlined consenting process in certain circumstances. In addition, the Resource Management (Extended Duration of Coastal Permits for Marine Farms) Amendment Act 2024 extends the duration of coastal permits for aquaculture activities by up to 20 years, with expiry dates not exceeding 2050.

Policy developments also emphasise sustainable sector growth and diversification of species and production systems. Strategies such as the Aquaculture Development Plan identify opportunities for expansion into offshore environments and support the development of emerging sectors such as seaweed aquaculture alongside established mussel, salmon and oyster industries. Consistent with

[3]McGrath, E.; Knight, B.; Elvines, D.; Clement, D.; Bull, L.; Sneddon, R.; Hutson, K.; Symonds, J.; Costilla, R.; Scholtens, M.; Millar, R.; Alder, A. (2026). *2026 Overview of Ecological Effects of Aquaculture*. New Zealand Aquatic Environment and Biodiversity Report No. 375. 100 p.

these objectives, New Zealand has recently consented its first open ocean aquaculture development, while additional offshore proposals are currently undergoing the approvals process.

Management responsibilities remain shared across multiple agencies: regional councils administer coastal permits and environmental assessments under the RMA, while Fisheries New Zealand (MPI) undertakes the statutory undue adverse effects (UAE) assessment under the Fisheries Act 1996 to evaluate potential impacts on commercial, recreational and customary fishing. Biosecurity risks are managed under the Biosecurity Act 1993, with oversight through regional pest management plans and on-farm industry practices.

1.1 Key references (list not exhaustive)

- Cook, K.M.; Dunn, M.R.; Behrens, E.; Pinkerton, M.H.; Law, C.S.; Cummings, V.J. (2025). The impacts of marine heatwaves on ecosystems and fisheries in Aotearoa New Zealand. *New Zealand Journal of Marine and Freshwater Research 59(5)*: 1530–1560.
- New Zealand Aquaculture Development Plan https://www.mpi.govt.nz/dmsdocument/67776-NZ-Aquaculture-Development-Plan-2025-2030

2. ECOLOGICAL EFFECTS OF FARMING SHELLFISH

2.1 Introduction

There are no significant additions to this section.

2.1.1 Key reference (list not exhaustive)

- Gallardi, D. (2014). Effects of bivalve aquaculture on the environment and their possible mitigation: a review. *Fisheries and Aquaculture Journal*. 5.

2.2 Water column effects

Several updates have been made to the section on the assessment of water column effects from shellfish aquaculture. These include the incorporation of more recent studies and monitoring data, providing a clearer and more detailed understanding of phytoplankton depletion processes, including observed changes in biomass and size structure in some high-intensity farming areas, and potential interactions with larger particles such as zooplankton and fish eggs. The evidence base has been expanded through the inclusion of longer-term datasets (e.g. satellite time-series) alongside field surveys, and interpretations of monitoring results have been refined to emphasise generally minor effects from shellfish aquaculture in New Zealand.

Additional context has also been provided for oyster farming, nutrient dynamics (including the potential for shellfish to reduce algal bloom intensity) and the functional role of biofouling communities. The updated section further introduces the consideration of farm scale and intensity, highlights the importance of maintaining effects within ecological limits, and includes new discussion on potential climate change influences. Minor refinements to management guidance have also been made, including greater emphasis on farm design and orientation, and the use of modelling as a key tool for assessing and managing water column effects.

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- Zeldis, J.; Robinson, K.; Ross, A.; Hayden, B. (2004). First observations of predation by New Zealand Greenshell mussels (*Perna canaliculus*) on zooplankton. *Journal of Experimental Marine Biology and Ecology 311(2)*: 287–299.

2.3 Benthic effects

Key advances in understanding the benthic effects of shellfish farming primarily relate to the positive ecological outcomes, or 'restorative' effects, that these farms can have on the benthos (covered in the newly added Section 7: Restorative Aquaculture). Advances have also been made in monitoring techniques, but these are covered in Section 6 (Monitoring the effects of aquaculture). Understanding of recovery timeframes from shellfish farming was previously identified as a knowledge gap; there are now several studies focusing on this (listed below).

2.3.1 Key references (list not exhaustive)

- Cao, Y.; Shi, R.; Han, T.; Liu, H.; Huang, H.; Qi, Z. (2023). Shell accumulation on seabed due to suspended coastal oyster farming and effects on burrowing capacity of the polychaete *Perinereis aibuhitensis*. *Frontiers in Marine Science 10*: 1219184.
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2.4 Marine mammal interactions

Several new studies and reviews aimed at understanding marine mammal use of habitats near or around shellfish farms and subsequent interactions have been completed since the previous version of the Overview document. International and national reviews on marine mammal and aquaculture interactions have also provided information on the causes and outcomes of marine mammal

entanglements, which can inform future farm management and mitigation measures. Aquaculture New Zealand (AQNZ) has developed the A+ Sustainable Management Framework guidelines for the mussel, salmon and oyster industries, which provide operational standards and, importantly, recommend establishing monitoring programmes for understanding how marine wildlife interacts with farms. More information on underwater noise and factors associated with vessel strikes is now available. However, there are still knowledge gaps and uncertainty around how marine mammals will perceive open ocean farm structures visually and acoustically and the results of their reactions to such large farms in association with multiple large farm blocks.

2.4.1 Key references (list not exhaustive)

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- Aquaculture Stewardship Council. (2019). ASC Bivalve Standard version 1.1. March 2019. www.asc-aqua.org
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2.5 Effects on wild fish

Recent research and meta-analyses indicate that off-bottom shellfish aquaculture can enhance habitat complexity through the introduction of hard substrate from shell fall-off and debris, creating structured benthic environments that support a diversity of fish and invertebrate species. However, these benefits are not uniform and may favour some species while disadvantaging others (e.g. infaunal communities) and can influence trophic dynamics. In some cases, shellfish farms may also act as "stepping stones" for invasive species. Evidence suggests that oyster farms can support fish species that are associated with natural oyster habitats, although outcomes depend on farming method. Overall, these effects are typically localised, spatially constrained and generally of low magnitude, with variability driven by farm type, location and environmental conditions.

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2.6 Effects on seabirds

Prior to 2013, knowledge of the effects of shellfish farming on seabirds was largely theoretical due to the lack of any New Zealand studies on potential impacts. Since 2013, there has been increasing photographic and tracking evidence of the use of shellfish structures (mussels and oysters) as roosting sites by several species, including terns, gulls and shags (including king shags). Tracking data have also documented subsequent foraging in and around farms by roosting king shags, as well as preferential foraging in mussel farms by some individual birds. AQNZ has developed guidelines for mussel, salmon and oyster industry, the A+ Sustainable Management Framework, which provides operational standards and, importantly, recommends establishing monitoring programmes for understanding how marine wildlife interacts with farms.

2.6.1 Key references (list not exhaustive)

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2.7 Biosecurity

Since the 2013 Overview, several new pests and diseases have emerged in New Zealand's shellfish aquaculture sector, including World Organisation for Animal Health–notifiable parasitic diseases affecting mussels and oysters. Industry-led biosecurity frameworks, such as AQNZ's A+ guidelines for mussels and oysters, have been widely adopted to support disease prevention and management. Additionally, MPI has enhanced its biosecurity hotline, introducing online reporting options alongside phone reporting, and maintains a national database tracking shellfish pests and aquatic diseases.

2.7.1 Key references (list not exhaustive)

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- Lane, H.S.; Duncan, J.; Webb, S.C. (2016). *Bonamia ostreae* in the New Zealand oyster *Ostrea chilensis*: a new host and geographic record for this haplosporidian parasite. *Diseases of Aquatic Organisms 118*: 55–63.
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2.8 Escapee and genetic effects

This section has been updated to highlight new research elucidating the role of farm-derived larvae and hatchery-reared spat in contributing to local recruitment of wild mussel populations, with connectivity varying between regions. Movement of spat and stock is now recognised as a pathway for pathogen transmission, particularly for oysters and OsHV-1, with selective breeding for disease resistance increasingly applied. Expanded selective breeding programmes and hatchery production for green-lipped mussels and Pacific oysters raise considerations for domestication selection, effective population size and potential genetic drift, which may influence wild populations if gene flow occurs. For Pacific oysters, the ecological effects of feral populations are better understood, including their role as ecosystem engineers and potential impacts on benthic communities, with climate change likely to influence larval dispersal, reproductive timing and relative fitness. Management and mitigation measures now emphasise genetic monitoring, biosecurity and breeding strategies to reduce pathogen and genetic risks, alongside continued regulatory oversight of transgenic or gene-edited organisms under Environmental Protection Authority (EPA) and upcoming Gene Technology Bill 2024 frameworks.

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2.9 Effects from additives

The effects of plastics released from aquaculture has been added to this section.

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2.10 Hydrodynamic alteration of flows

This section has been updated to reflect new knowledge surrounding how mussel and oyster farms influence water movement, stratification and wave dynamics. New information highlights that farms can sometimes affect currents at locations beyond the immediate farm area, and that vertical mixing varies with farm type – for example, longline mussel structures generally do not reach the seabed,

while oyster farms may. The potential for wave dampening has also been refined, noting that modern floating oyster structures may reduce previously observed effects. These refinements, alongside updated guidance on modelling and monitoring – including consideration of cumulative effects and associated changes in circulation, temperature and salinity – enhance the ability to predict hydrodynamic changes and inform future farm design and management decisions.

2.10.1 Key reference (list not exhaustive)

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3. ECOLOGICAL EFFECTS OF FARMING FINFISH

3.1 Introduction

There has been growing interest in expanding New Zealand's finfish aquaculture sector into novel areas capable of dispersing farm-derived organic waste. These areas include more exposed or open locations characterised by deeper, higher-current environments than inshore locations where fish farming currently operates.

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3.2 Water column effects

This section has been updated to reflect several recent studies that have refined understanding of water column effects associated with finfish farming. New evidence highlights the potential for farm-derived nutrients to interact with increasing coastal nutrient inputs and climate-driven changes in nutrient availability, potentially influencing phytoplankton composition and the occurrence of harmful species. Advances in farm management, including improved automated feeding, higher-quality feed and enhanced feed conversion ratios (FCRs), are increasingly recognised as effective at reducing nutrient inputs and limiting impacts on both water quality and wild fish populations. The role of farm siting, including depth, current regimes and oxygen supplementation, as well as design factors such as cage orientation and biofouling management, has also been emphasised. Furthermore, the introduction of longer-term and higher-resolution monitoring, including satellite-derived surface chlorophyll and turbidity, is highlighted as an emerging tool for assessing regional and farm-scale water column changes and for supporting adaptive management and multitrophic aquaculture approaches.

3.2.1 Key references (list not exhaustive)

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3.3 Benthic effects

Since 2013, additional literature documenting deposition and / or benthic responses from "dispersive" farming areas has emerged, along with a review of Norwegian farming impacts according to various environmental and operational factors. These studies are aligned with our current understanding of factors influencing benthic organic enrichment, and have reinforced the importance of increased flushing and dilution on waste transport, benthic community resilience and, ultimately, ecological carrying capacity. However, the drive for expansion of "open ocean" fish farms into more dynamic and exposed coastal areas has highlighted the lack of understanding of how non-soft sediment habitats (e.g. structured habitats such as temperate reefs and shellfish or maerl beds) and epifauna will respond to, or tolerate, organic enrichment from fish farming. Although this remains a critical gap in knowledge, species-specific interactions between epifauna and fish farm organic wastes is gradually becoming documented, with the subject of these studies most often guided by site- and species-specific ecological risk profiles. In a New Zealand–specific context, readers are referred to New Zealand Aquatic Environment and Biodiversity Reports (AEBRs; McMullin & McGrath (2023) and McMullin et al. 2025a; b in the accompanying reference list) which were commissioned by MPI as part of a project to define environmental health measures related to open ocean aquaculture. These AEBRs address some of the information gaps around interactions of proposed open ocean fish farms on some of the most at-risk benthic species, with consideration of potential tipping points.

New literature since 2013 has also highlighted some of the complex factors governing organic waste deposition from fish farms. Fortunately, modelling tools for predicting organic waste deposition have become substantially more advanced to include different faecal pellet sizes, more realistic resuspension dynamics, and the decay of organic matter over time. These advancements ultimately improve predictions of benthic ecological risks from proposed developments in dynamic and dispersive systems. In addition, substantial technological advances have been made in benthic monitoring techniques, central to which is the evolution of environmental DNA (eDNA) analysis for monitoring benthic health and non-soft sediment habitats (described in Section 6). Further context and specific guidance for monitoring and managing benthic effects is provided in two other MPI-driven

AEBRs, one focusing on open ocean finfish farms and the other specific to the Marlborough Sounds (see Giles et al. 2021 and Fletcher et al. 2022 in the below reference list, respectively).

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3.4 Marine mammal interactions

Several new studies aimed at understanding marine mammal interactions with finfish farms have been completed since the previous Overview document was released. International and national reviews have also provided information on the causes and outcomes of marine mammal entanglements, which can help inform future farm management and mitigation measures. The level of entanglement has become clearer since the aquaculture industry began regularly recording and reporting marine mammal entanglements with inshore farms in the Marlborough Sounds. These reviews were subsequently used as the basis for developing Fisheries New Zealand's Open Ocean Guidelines for Marine Mammals. AQNZ has also developed guidelines for the mussel, salmon and oyster industries, the A+ Sustainable Management Framework, which provides operational standards and, importantly, recommends establishing monitoring programmes for understanding how marine wildlife interacts with farms. These recommendations align with several overseas aquaculture certification programmes. More information on underwater noise and factors associated with vessel strikes is also now available. It is acknowledged that there are still knowledge gaps and uncertainty around how marine mammals will perceive open ocean farm structures visually and acoustically and the results of their reactions to such large farms in association with multiple large farm blocks.

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3.5 Wild fish interactions

There is limited information on interactions between wild fish and finfish aquaculture in New Zealand, particularly in relation to offshore developments and their interaction with pelagic species particularly in novel habitats. International research indicates that finfish farms can influence wild fish through habitat modification, attraction to farm structures and the availability of waste feed. These interactions may result in both positive and negative effects, including localised increases in fish abundance and condition, as well as changes in behaviour, distribution, and potential exposure to contaminants or disease. However, the magnitude and ecological significance of these effects are not well understood in the New Zealand context and are likely to be site-specific, influenced by farm location, environmental conditions and operational practices.

As aquaculture expands into more exposed offshore environments, interactions with pelagic predators, particularly sharks, may become more likely. Farm structures and associated prey aggregation can attract species from higher trophic levels, with international studies documenting shark interactions at finfish farms, including occasional net entanglement. In New Zealand, species such as the white shark (*Carcharodon carcharias*) are protected, and available evidence suggests that they are typically transient rather than resident around farms. The likelihood and the nature of the interactions are expected to vary by location, reflecting local species distributions and ecological conditions. Management measures, including careful site selection, minimisation of feed waste and fish mortality, and implementation of monitoring and predator management strategies are important to reduce potential interactions and associated ecological risks.

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3.6 Effects on seabirds

Knowledge of the effects of finfish farming on seabirds is similar to that for shellfish farming – largely theoretical due to the lack of any New Zealand studies focused on such impacts. The perceived negative effects of finfish aquaculture also centre on entanglement (resulting in birds being injured and / or drowning) and habitat exclusion / displacement from feeding grounds. The frequency of entanglement has become clearer since the aquaculture industry began regularly recording and reporting seabird entanglement with inshore farms in the Marlborough Sounds. Records demonstrate that several species of seabird (e.g. red-billed gull / tarāpunga, southern black-backed gull / karoro, pied shag / kāruhiruhi) are prone to entanglement in finfish farm structures, particularly flexible nets made of soft materials (e.g. predator nets) and with wide mesh gaps.

Similar to shellfish farms, there is now photographic and tracking evidence of some seabird species (including yellow-eyed penguin / hoiho) foraging near and around finfish farms, and indicating that farms may provide some positive benefits (e.g. roosting and foraging opportunities) for particular species. However, the effects of siting farms near nesting areas and / or any indirect effects of farms on prey changes, artificial lighting and ingestion of marine litter are less well studied and still fairly unknown.

In 2021, national guidelines to minimise and mitigate seabird interactions with open ocean finfish aquaculture were developed based on international and national reviews and extensive expert, government and industry discussions. AQNZ has also developed new guidelines for the mussel, salmon and oyster industries, the A+ Sustainable Management Framework, which provides operational standards and, importantly, recommends establishing monitoring programmes for understanding how marine wildlife interacts with farms. These recommendations support marine wildlife standard requirements of several overseas aquaculture certification programmes.

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3.7 Biosecurity

Since the 2013 Overview, new disease threats have been identified in New Zealand's finfish aquaculture industry, notably globally distributed bacterial pathogens affecting Chinook salmon. Marine farm infrastructure and aquaculture vessel movements may also provide potential pathways for the spread of terrestrial pests (e.g. rodents and stoats) capable of swimming to nearby islands.

Land-based fish marine fish farming has been implemented for yellowtail kingfish, presenting a high degree of control on effluent, and subsequently an opportunity to reduce biosecurity risk. AQNZ's A+ biosecurity frameworks for salmon have been implemented widely across the sector to support proactive disease management. MPI has also upgraded its biosecurity hotline, providing online reporting in addition to phone options, and continues to manage a national database on finfish pests and aquatic diseases.

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3.8 Escapee and genetic effects

This section expands on potential effects of escapees in New Zealand finfish aquaculture, including competition with wild populations, pathogen transfer and altered genetic structure. New content emphasises life stage–specific risks, including gamete release from broadcast-spawning species and mitigations such as monosex stocks, light and temperature control, and selective use of triploidy. The causes of escapes now include climate-driven extreme oceanic events and deliberate sabotage, in addition to net failure. Species-specific management is highlighted, with detailed discussion of Chinook salmon (introduced, selectively bred, all-female production) and kingfish (native, with emerging marine pen farming and genomic diversity management).

The section also incorporates proactive biosecurity, disease-resistant stock and ongoing genomic monitoring to reduce genetic risks. Legal and regulatory context is clarified regarding transgenic or gene-edited fish under the current law and the proposed Gene Technology Bill 2024. Management and mitigation measures are expanded to include adaptive siting, structural resilience, staff training, monitoring, reproductive control, and long-term genetic diversity strategies using SNP-based genotyping and cryopreservation. Overall, the updates strengthen species-specific risk assessment, integrate climate and operational considerations, and emphasise precautionary monitoring and management.

3.8.1 Key references (list not exhaustive)

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3.9 Effects from additives

The updated review provides a more detailed discussion of chemical substances and treatments associated with finfish aquaculture, including metals associated with antifouling coatings (e.g. copper and zinc), fish feed additives and therapeutants. The review notes that the use of copper-containing antifouling coatings in New Zealand finfish aquaculture has declined, and that the only approved therapeutant in New Zealand is the isoeugenol-based anaesthetic AQUI-S. It elaborates on release pathways, local accumulation and factors affecting bioavailability and toxicity, and highlights that while ecological risks from therapeutant use are currently minimal, this may change in response to increasing animal welfare and disease management challenges associated with warming marine environments and climate change. The expanded guidance reflects current best practice, including adherence to the industry-backed A+ standards, optimised feed strategies, alternative antifouling approaches, proactive disease control, and monitoring and mitigation measures to minimise environmental effects while maintaining fish health.

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3.10 Hydrodynamic alteration of flows

Recent updates indicate that finfish farms can influence currents, stratification and wave energy beyond the immediate farm area, consistent with findings from shellfish farm models. Small-scale local changes in currents are almost certain, while embayment-scale circulation changes may occur in bays with multiple farms, with ecological significance dependent on the magnitude of modification. Hydrodynamic effects persist only while structures remain in place, although indirect impacts on seabed habitats and associated communities may last longer. Potential effects can be predicted and

managed through modelling, monitoring, and adjustments to cage design, layout, flexibility and net porosity, with staged development monitoring recommended to capture a range of environmental conditions.

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4. ECOLOGICAL EFFECTS OF FARMING SEAWEEDS AND SEA CUCUMBERS

There is growing interest in diversification of aquaculture species in New Zealand, particularly in the development of seaweed aquaculture. A wide range of native macroalgal species, including kelps (*Macrocystis pyrifera*, *Ecklonia radiata*, *Lessonia variegata*), sea moss (*Gracilaria* spp.), fucoids (*Hormosira banksii*, *Cystophora retroflexa*, *Cystophora scalaris*, *Landsburgia quercifolia*, *Carpophyllum maschalocarpum*, *Xiphophora chondrophylla*), red seaweeds (*Asparagopsis armata*, *Pterocladiella capillacea*, karengo [*Pyropia* spp.; *Porphyra* spp.]) and green seaweeds (*Ulva* cf. *lactuca*, *Codium fragile*), have been identified as having cultivation potential. Despite this interest, the domestic seaweed sector remains at an early stage, with most production reliant on wild harvest rather than cultivation. Hatchery and nursery infrastructure is limited, and sea-based farming remains largely at trial scale. Key issues identified in recent literature include the need for reliable seedstock supply, sustainable management of wild harvest, improved understanding of genetic interactions with wild populations, and development of regulatory settings and environmental guidance to support industry expansion. Ecologically, seaweed farming is generally expected to have relatively minor effects on the seabed and water column compared with fed aquaculture, although interactions such as shading, nutrient uptake, hydrodynamic modification and the release of propagules may occur and remain poorly quantified in the New Zealand context.

Progress in commercial farming of *Undaria pinnatifida* (*Undaria*) and sea cucumbers in New Zealand has been limited since earlier reviews. Sea cucumber aquaculture, including potential use in integrated multitrophic aquaculture (IMTA) systems due to its consumption and processing of organic matter, remineralisation process enhancement and promotion of surface sediment oxygenation, remains largely conceptual or experimental, with limited information available on environmental effects under New Zealand conditions. For *Undaria*, which is an introduced species classified as an unwanted organism under the Biosecurity Act 1993, recent work highlights biosecurity considerations associated with cultivation. Potential risks relate to the spread of vegetative material and propagules, the transfer of pests, pathogens or parasites through the movement of stock, equipment and vessels, and the possibility that large quantities of farm-derived propagules could influence the distribution or genetic structure of feral populations. While ecological effects associated with the cultivation structures themselves are expected to be broadly comparable to other suspended aquaculture systems, the literature highlights the need for precautionary management, spatial restrictions to areas of existing infestation and robust monitoring and biosecurity controls if cultivation were to expand.

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5. CUMULATIVE EFFECTS ASSOCIATED WITH AQUACULTURE

This section has been updated to reflect that cumulative ecological effects can arise over time through the incremental and interacting effects of an aquaculture activity in combination with other anthropogenic stressors and foreseeable environmental change. Cumulative effects also include the combined environmental changes arising from multiple aquaculture operations within a defined geographic area, which may manifest as a range of impacts and are particularly important to consider as aquaculture expands in production effort and location (e.g. into open ocean and dispersive sites). Nutrient and organic matter additions from finfish farms, plankton removal by shellfish and nutrient uptake by seaweed can interact with other anthropogenic and natural stressors, potentially affecting phytoplankton dynamics, benthic conditions and broader ecosystem processes.

Evidence from long-term monitoring suggests that effects on plankton communities are generally low at current shellfish and seaweed farm densities, while finfish-derived nutrient enrichment may lead to localised organic accumulation and, in extreme cases, low-oxygen conditions. Mitigation of cumulative effects is achievable through good farm practices, including considered farm placement, feed management, stocking densities and IMTA, as well as restorative approaches using co-cultured species such as mussels, seaweeds and sea cucumbers. Adaptive management (using the Blue Endeavour salmon farm as an example), informed site selection, and staged development underpinned by baseline monitoring and modelling of nutrient dynamics and carrying capacity, are recommended to minimise impacts and ensure environmentally sustainable expansion.

5.1.1 Key reference (list not exhaustive)

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6. MONITORING THE EFFECTS OF AQUACULTURE

This section has been updated to reflect the importance of appropriate monitoring of aquaculture effects at a level and frequency sufficient to ensure sustainable operation and adaptive management, particularly as aquaculture expands into areas with limited prior data, or involves new species or large-scale or offshore farms. Baseline monitoring is essential to establish existing conditions, including benthic habitats, water quality (supplemented with satellite-derived surface parameters), hydrodynamics and local marine wildlife.

Offshore siting considerations and examples of best management practices, such as the Best Management Practice Guidelines for Open Ocean Aquaculture and the Siting and Management Guidelines for Open Ocean Aquaculture, provide guidance on standardised, flexible and adaptive monitoring and management approaches. Monitoring should integrate individual farm consent requirements with regional state of the environment (SoE) programmes to assess both localised and cumulative effects, including those on seabed communities that may not be captured by standard SoE monitoring. The *Best Management Practice Guidelines for Salmon Farms in the Marlborough Sounds* is cited as an example of a "living" document, where guidelines are periodically reviewed to include emerging technologies and practices, such as the recent inclusion of eDNA for improved detection and monitoring of farm-derived impacts on the seabed. Data accessibility, coordination across farms and councils, and staged monitoring are recommended to capture temporal and spatial variation, inform adaptive management and support robust regional-scale assessments of cumulative ecological effects. The Tasmanian Broadscale Environmental Monitoring Programme (BEMP) provides an example of a standardised monitoring framework designed to support consistent data collection and regional-scale assessment of aquaculture effects[4].

6.1.1 Key references (list not exhaustive)

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7. RESTORATIVE AQUACULTURE

Since MPI's Ecological Effects of Aquaculture chapter series was developed in 2013, interest has steadily grown in understanding ecosystem functions and services and the role aquaculture plays in providing these benefits. To reflect this progress, we have included an overview section on restorative aquaculture that highlights work undertaken internationally and within New Zealand, while also identifying key knowledge gaps.

Restorative aquaculture refers to farming practices that generate measurable ecological benefits alongside food production, such as habitat creation, improved water quality and enhanced coastal resilience. In New Zealand, shellfish farms provide the strongest evidence for these positive effects through filtration, habitat formation and nutrient cycling. While benefits may be immediate or long term, they remain highly context-dependent, and finfish farming provides fewer restorative outcomes due to well-documented environmental risks. This section also highlights substantial knowledge gaps, particularly around the quantification and monitoring of restorative effects, the need for standardised indicators, and the absence of a national framework to guide consistent implementation across New Zealand, all of which currently limit the sector's ability to scale ecological, social and cultural benefits.

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8. ACKNOWLEDGEMENTS

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