UNIVERSITY of TASMANIA

IMAS

Institute for Marine and Antarctic Studies

Aquaculture Environment Review Series

Ecological effects of finfish aquaculture on shallow temperate reef ecosystems

White CA, Hartog M, Bush F, Elvines DM & Ross DJ

May 2025

Institute for Marine and Antarctic Studies,
University of Tasmania,
Private Bag 49, Hobart TAS 7001

Enquires should be directed to:

Dr Camille White
Institute for Marine and Antarctic Studies
University of Tasmania
Private Bag 49, Hobart, Tasmania, 7001, Australia

Camille.White@utas.edu.au

Ph: (03) 6226 8377

Contents

1 Introduction

This is the third in a series of independent literature reviews about marine farming interactions and the environment.

The Department of Natural Resources and Environment Tasmania (DNRE Tas) commissioned the University of Tasmania's Institute for Marine and Antarctic Studies (IMAS) to perform these reviews to support the planning and regulation of marine farming in Tasmania, and to provide a reference source for people with an interest in Tasmanian aquaculture. It is intended to cover all forms of existing or proposed marine-based aquaculture within Tasmanian state waters and will be regularly updated and revised to consider new scientific information. This review will focus on the interaction between shallow temperate reef ecosystems and finfish aquaculture.

In temperate coastal waters, rocky reef ecosystems are a foundation for a wide range of ecological, recreational and commercial services of local and global importance. Typically, rocky reef ecosystems are highly productive and support significant levels of biodiversity and endemic species (Campbell et al. 2014, Smale et al. 2016, Coleman & Wernberg 2017, Teagle et al. 2017).

In shallow coastal waters where environmental conditions allow, rocky reef habitats will be dominated by macroalgae (seaweeds; Wernberg et al. 2009). These macroalgal communities dominate the hard-substrate, provide multi-dimensional habitat for fish and invertebrate species and are critical for healthy functioning of temperate reef ecosystems (Stuart-Smith et al. 2008, Nichol et al. 2009, Krumhansl et al. 2016, Teagle et al. 2017). Reef habitats occur at all depth-strata, but for this review, the shallow water reef communities found in nearshore coastal zones are the focus.

Temperate reefs are generally dominated by one or two canopy-forming species of macroalgae, most typically kelps. Canopy-forming macroalgae creates an environment that functions like terrestrial forests, so are often referred to as 'kelp forests'. A wide array of sub-canopy and substrate species are found beneath the canopy, including algae and sessile invertebrates. The species composition of reef communities are often determined by the dominant canopy-forming species, along with environmental factors such as light attenuation, sedimentation, wave exposure and abrasion by kelp (Gorman et al. 2013, Smale 2013, Teagle et al. 2017).

A range of epiphytic and ephemeral algal species are also observed within the reef community. These species respond to ambient environmental conditions, growing rapidly when nutrients and light are both in high abundance (Steneck et al. 2002, Wernberg & Goldberg 2008, Smale et al. 2020). Both macroalgae and sessile invertebrate communities provide a source of food and shelter to a wide range of fish and invertebrate species.

As most human activity is concentrated in the inshore coastal zone, macroalgae-dominated temperate reefs are often exposed to significant anthropogenic pressure (Vitousek et al. 1997, Halpern et al. 2008, Crain et al. 2009). Anthropogenic pressures, such as increased urbanisation, coastal industry, catchment activities and finfish aquaculture may interact with these habitats directly, while global environmental stressors such as climate change may indirectly put pressure on these ecosystems (Ross et al. 2021). Indirect and direct pressures can also work together to cause greater effects than either in isolation (Steneck et al. 2002, Wernberg et al. 2011, Strain et al. 2014).

In Tasmania, there has been growing concern around the ecological effects that finfish aquaculture may have in the coastal environment. Finfish farming (feed-added aquaculture) has the potential to interact with temperate reefs through the release of nutrients and organic material into the environment. This occurs via the discharge of waste products such as urea, ammonium, uneaten fish feed and fish faeces (Strain & Hargrave 2005).

The purpose of this review is to explore and establish the current state of knowledge of interactions between temperate reef ecosystems and finfish aquaculture, both globally and locally. For this review, the focus will be on coastal reef communities dominated by macroalgae. The term 'nutrient enrichment' will be used generically to cover all the pathways and processes relating to the increase of nutrients and organic material in the water column associated with an anthropogenic nutrient source. Information provided by studies relating to nutrient enrichment caused by general anthropogenic pressures, along with those specifically addressing finfish farming activities, are examined. Methods used to monitor ecological effects, along with mitigation and management strategies are also discussed.

Figure 1: Examples of dominant canopy-forming macroalgae on rocky reefs in Tasmania

a) Ecklonia radiata

b) Macrocystis pyrifera

c) Phyllospora comosa

d) Durvillaea potatorum

2 Effects on temperate rocky reefs

Finfish aquaculture can interact with shallow reef ecosystems through numerous pathways. The current state of knowledge of these interactions, along with associated environmental effects are discussed in this section.

Nutrient enrichment of temperate reef ecosystems can occur directly through either dissolved or particulate inputs, or indirectly through changes to the productivity of marine food webs. These ecosystem processes are seldom independent and will trigger a range of different ecosystem responses (Figure 2).

Increases in dissolved nutrients like nitrogen tend to boost productivity at the base of the food web. Increases in particulate loads onto reef ecosystems can also influence primary productivity, potentially shading algae and smothering encrusting flora and fauna (Krause-Jensen et al. 2008, 2009).

Dissolved and particulate enrichment pathways are not independent, as elevated dissolved nutrients can contribute to increased sedimentation of organic material by boosting water column productivity via increased phytoplankton growth (Irving & Connell 2002, Strain & Hargrave 2005, Balata et al. 2015). This can in turn influence light penetration with negative feedback to the primary productivity of reef ecosystems (Diehl 2002, Guinder et al. 2009).

Consequently, both dissolved and particulate inputs have the capacity to drive community change on temperate rocky reefs, albeit through different but interlinked pathways. Particulate enrichment sources can also increase food resources to opportunistic invertebrates and fish, potentially causing top-down effects (Dempster et al. 2009, White et al. 2018).

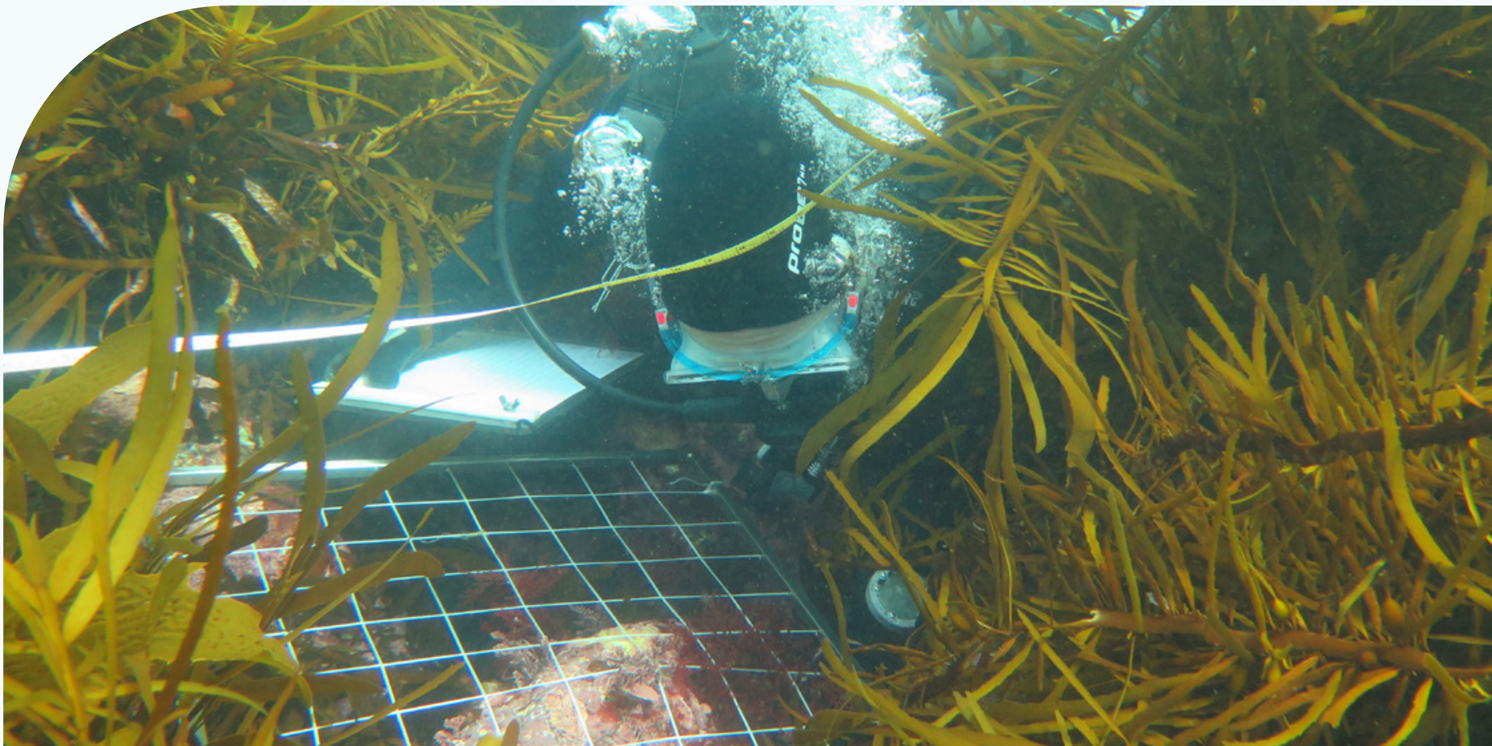
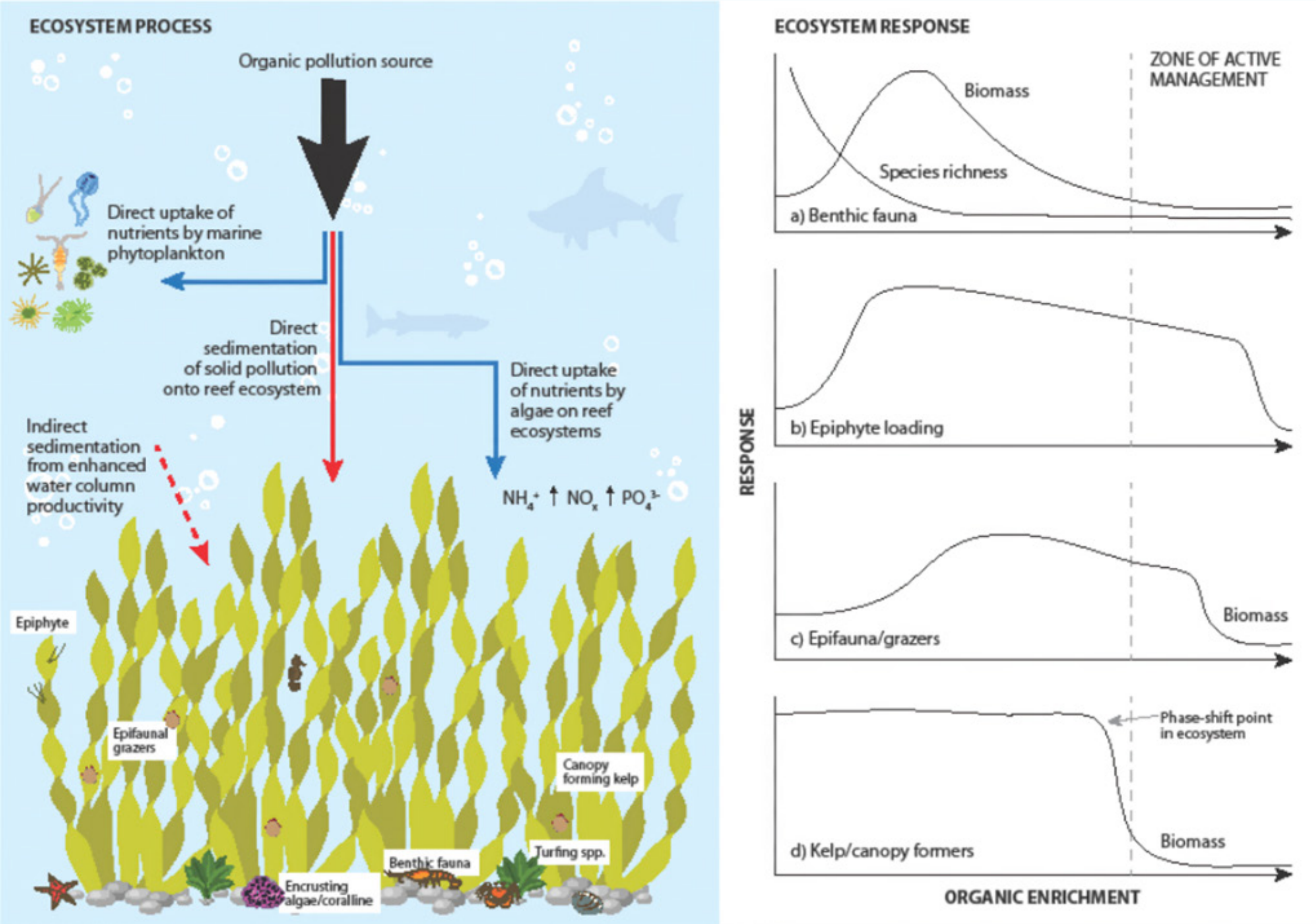


Figure 2: Summary of the interaction pathways of organic pollution on rocky reefs (from Ross et al. 2021)



The process pane (left) outlines the direct and indirect pathways of organic enrichment of temperate reef ecosystems. The response pane (right) highlights the complexity of response in a multi-level ecosystem, with a) an adaptation of the standard Pearson and Rosenberg (1978) model for organic enrichment for benthic infauna; and b–d) representing the hypothetical response of different functional groups in a three-dimensional/multi-trophic temperate reef system.

While conceptually the process of nutrient enrichment onto rocky reefs is well understood, establishing direct links between finfish farming activities and reef community response is difficult, particularly over broader spatial scales (Roberts et al. 2014, Oh et al. 2015, Valentine et al. 2016, Fowles et al. 2018a, Fowles et al. 2018b, Fowles et al. 2018c, Haugland 2019).

This is largely due to a range of anthropogenic and natural factors, which often contribute to the nutrient status of coastal waters and catchments where finfish aquaculture is active. Therefore, methods to attribute causal mechanisms remains an area of active research in locations where this interaction is likely to occur.

2.1 Effects on primary productivity

Bottom-up effects of nutrient enrichment can be defined as the stimulation of productivity at the base of the food chain (i.e. in the primary producers) with flow-on effects throughout the rest of the ecosystem. Of all the interactions between temperate rocky reefs and nutrient enrichment, bottom-up effects on the macroalgae communities are the most widely reported and understood.

Changes to the natural balance of dissolved nutrients within the environment have the potential to directly affect the growth of algae on rocky reefs (Fowles et al. 2018a, Fowles et al. 2018b, Fowles et al. 2018c, Haugland 2019). A significant body of research has now gone into characterising the bottom-up response of rocky reefs to nutrient enrichment and subsequent alterations to the algal communities (Ross et al. 2021; page 12; Table 1). In this section, interactions between finfish aquaculture and reef systems are discussed broadly, acknowledging that the location and magnitude of any effect will be scenario-specific.

Nutrient enrichment associated with urbanisation has been linked to regional-scale losses of canopy-forming perennial brown macroalgae, and its replacement with fast growing turfing or filamentous species (Benedetti-Cecchi 2001, Eriksson et al. 2002, Connell et al. 2008). This shift from canopy-dominated to turf-dominated reefs will often be initiated after an acute disturbance, such as a storm event, which removes large patches of the canopy-forming algae. The enhanced nutrient conditions will then support persistent growth of opportunistic algae, which inhibits regrowth of the canopy-forming species (Gorgula & Connell 2004, Connell et al. 2008, Alestra & Schiel 2015). In the absence of disturbance, forests of macroalgae have been shown to be quite resilient to nutrient enrichment. For example, in southern Tasmania where salmon farms operate at a high density, Oh et al. (2015) observed consistent nutrient-associated increases in epiphytic and ephemeral algae, but the foundation species that formed macroalgal canopies were largely unaffected by the presence of the farms.

Reef ecosystems are known to be efficient at assimilating excess dissolved nutrients by increasing productivity at the base of the food web. Certain species are biologically adapted to utilise pulses of nutrients and increases in productivity are mostly seen in these opportunistic species (Oh et al. 2015, Haugland et al. 2021). Specifically, indications of early stage nutrient enrichment include increased biomass of opportunistic macroalgae like *Undaria* spp. (Carnell & Keough 2014), *Ulva* spp. (Fowles et al. 2018b), turfing species (Connell et al. 2008, Falkenberg et al. 2012), epiphytic species (Oh et al. 2015, Haugland 2019) and filamentous green algae (Connell et al. 2008, Oh et al. 2015, Fowles et al. 2018a, Haugland 2019; Figure 3, Appendix A). However, there is little understanding presently around nutrient thresholds where tipping points in ecosystem function can be expected (Bokn et al. 2003).

Early indicators of nutrient enrichment will not necessarily impact the structure or function of the macroalgal canopy. However, where elevated nutrient concentrations are prolonged, a sustained increase in the biomass of opportunistic species can destabilise canopy-forming macroalgae through smothering, shading and restriction of water movement. This will leave the canopy vulnerable to the effects of other environmental stressors, including storm damage, grazing by range-extending or introduced species, and climate change. While canopy loss may occur gradually over time under enriched conditions, these same factors may also cause sudden loss of macroalgal canopy (Connell et al. 2008, Johnson et al. 2011).

The widespread loss of canopy-forming species caused by nutrient enrichment can result in a long-term shift to ecosystems dominated by turfing algal species, with subsequent changes to total biomass, benthic fauna diversity, epifauna and grazing species, and ecosystem services (Connell et al. 2008, Smale et al. 2013, Wernberg et al. 2013, Teagle et al. 2017; Figure 2).

As nutrient enrichment within the water column preferentially supports the recolonization of available substrate by fast growing species, opportunistic algal cover takes the place of juvenile canopy-forming species (Falkenberg et al. 2012). For some canopy-forming species (e.g. *Ecklonia radiata*), re-establishment is thought to be further inhibited by the absence of adult plants, which results in the loss of suitable recruitment environments for juveniles (Layton et al. 2019).

Increases in sedimentation associated with nutrient enrichment will also shape recovery dynamics, as opportunistic turfing species enhance sediment retention, inhibiting recovery to the more complex ecosystem dominated by canopy-forming macroalgae (Airoldi et al. 1995, Connell et al. 2008, Bulleri et al. 2010, Balata et al. 2015, Bulleri et al. 2018). As such, the loss of canopy-forming species can have long-term effects, with natural regeneration to original canopy-dominated ecosystems being unlikely or very slow, spanning years or decades (Campbell et al. 2014), particularly in the face of sustained nutrient enrichment or other environmental stressors.

Figure 3: Examples of algae that indicate nutrient enrichment via bottom-up effects

a) filamentous algae

b) epiphytic algae

c) Chaetomorpha billardieri

d) Ulva sp.

e) Asparagopsis armata

2.2 Effects on secondary productivity

Nutrient enrichment can stimulate productivity at higher trophic levels in the food web (i.e. secondary consumers or scavengers) with flow on effects to primary producers and lower-order consumers. In aquaculture, this can occur through the presence of deposited organic material from finfish farms (uneaten feed, faeces, and biofouling drop-off) directly under the cage which provides a food source to marine organisms (Woodcock et al. 2018). This has the potential to attract aggregations of scavengers to the area (Fernandez-Jover et al. 2011, Sanz-Lázaro et al. 2011, White et al. 2017, White et al. 2018).

As there are no farms presently sited over hard substrate in Tasmania, the risk of these interactions is low, but studies overseas have demonstrated the potential for interactions at greater distances from finfish aquaculture leases than directly underneath cages. For example, in Norway the influence of fish farm waste as a food source has been identified up to 1 km from farms in brittle stars and crabs on hard or mixed substrate, with more localised effects on urchins (Woodcock et al. 2018).

In several Norwegian fjords, urchins (*Gracilechinus acutus*) have been found to aggregate on hard substrate within 400 metres of aquaculture sites – and the top-down effects are demonstrated in localised urchin barrens forming, where urchins graze on both aquaculture waste and natural food sources (White et al. 2018).

Enhanced top-down grazing due to aggregations of scavengers, particularly of omnivorous species, may alleviate some effects of nutrient enrichment by consuming the increased biomass of epiphytes (Haugland et al. 2019). While large populations of opportunistic scavengers may lead to problems on a local scale, in lower densities they can be highly efficient at mitigating effects from aquaculture nutrient outputs. This can occur both directly through consumption of aquaculture organic waste, and indirectly through consumption of blooms of epiphytic or filamentous algae caused by excess nitrogen (Figure 4).

Figure 4: Aggregations of sea urchins and sea stars on reef habitat adjacent to salmon farms in Norway (White et al. 2018)

Farms can also provide extensive artificial substrate that is available for colonisation of biofouling species onto neighbouring naturally occurring hard-substrate environments, including reefs (Fitridge et al. 2012, Mineur et al. 2012, Simkanin et al. 2012, Bloecher et al. 2015). The spread of unwanted species to healthy reef ecosystems is thought to be relatively low risk, as the biofouling species are at a competitive disadvantage on natural substrates due to lack of free space (Tyrrell & Byers 2007, Simkanin et al. 2012).

The risk of interactions is likely to increase when rocky reef communities are already affected by other environmental stressors (Mack et al. 2000). In Tasmania, increased incidence of unwanted sessile species on hard substrate has been observed in association with anthropogenic point sources of pollution such as marinas and sewage outfalls but has not been directly linked to enrichment from finfish aquaculture (Fowles et al. 2018b).

Globally, there have been fewer studies on top-down interactions compared to bottom-up interactions between finfish aquaculture and temperate rocky reefs. Where top-down effects do occur, they manifest due to a set of distinct circumstances that tend to be highly site-specific, whereas bottom-up interactions through stimulated productivity at the base of the food web is generally evident to varying extents in all receiving environments.

2.3 Factors affecting scale and magnitude of interactions

Proximity to the source of nutrient enrichment and the level of nutrient enrichment are the primary factors in determining the magnitude of local scale interactions between aquaculture and temperate reefs. For example, in Canada where farms are sited over hard substrate, effects under the cage and up to 10 m distant are particularly profound, with hard substrate covered by flocculent matter, *Beggiatoa*-like mats and opportunistic polychaete species (Hamoutene et al. 2016). Increases in farm nutrient outputs will increase these acute effects.

In Tasmania, there are presently no finfish aquaculture operations situated directly over hard substrate, so the acute impacts of excess sedimentation and subsequent smothering are unlikely to be observed on Tasmanian reef environments. Near-field impacts are more likely to be detected on fringing reefs between the farm and the coast, and manifest as bottom-up impacts from nutrient exposure in algal communities (Oh et al. 2015). In southern Tasmania, Oh et al. (2015) identified the effects of nutrient enrichment from finfish farms on rocky reefs up to 1 km from active farms, with the most pronounced effects at 100 m. These effects were mainly evident in the increase in epiphytic and filamentous algae (Oh et al. 2015). More recently, White et al. (2022) documented a similar influence of nutrient enrichment from the salmon lease in Port Arthur, southern Tasmania, on the adjacent reef ecosystem, with the most pronounced effects out to the 100 m sites. Low to moderate effects of nutrient enrichment were evident at the 400 and 1000 m sites in the form of elevated abundances of epiphytic and filamentous algae, along with altered nitrogen isotope ratios.

However, the influence of wave exposure and other nutrient inputs at these greater distances from the lease made attribution of ecological change to salmon farming alone difficult (White et al. 2022).

The mode of delivery of nutrients into the system will also affect the magnitude of interactions on both near and intermediate spatial scales and across various temporal scales. Coastal ecosystems are adapted to assimilate pulses of additional nutrients associated with natural environmental phenomena, such as the spring bloom or high rainfall and runoff events (Worm & Sommer 2000, Yang et al. 2008). In this scenario, opportunistic species such as ephemeral algae will likely experience a large pulse of productivity, resulting in short-term increases in biomass, then subsiding again as the nutrient stimulation decreases (Worm & Sommer 2000, McSkimming et al. 2015). However, if the nutrient input is sustained as is often the case with anthropogenic inputs, then the magnitude of the response is likely to be greater and to persist for as long as the exposure to the elevated nutrients occurs (Gillanders & Kingsford 2002).

Interactions between rocky reef communities and nutrient enrichment will vary depending on the prevailing environmental conditions of the receiving environment and the species present within these communities (Airoldi 2003, Gorgula & Connell 2004, Balata et al. 2007, Russell & Connell 2007, Krause-Jensen et al. 2008, Alestra & Schiel 2015, Dunmore et al. 2015, Oh et al. 2015, Muth et al. 2017). Localised hydrodynamics will play a large role in how reef systems will interact with nearby finfish aquaculture sites (Ross et al. 2021). Where there is high water movement, the magnitude of effects from nutrient enrichment on temperate reefs is likely to be less acute due to greater dilution, but effects may be observed at a much greater distance from the source or be altered in the way they manifest (Keeley et al. 2019).

In Tasmania, the species assemblage of opportunistic algae may be different depending on wave and wind exposure (Oh et al. 2015) and hence local knowledge is important in assessing any potential interaction.

Existing ambient nutrient concentrations can also affect the way finfish farming interacts with rocky reefs. High anthropogenic inputs into nutrient-poor (oligotrophic) systems are likely to have the most extreme results (Russell et al. 2005, Connell & Irving 2008, Gorman et al. 2009). For example, Gorman et al. (2009) found the distribution and extent of turfing algae on South Australian coasts was largely dependent on the inherent nutrient availability, with the most severe effects recorded where the difference between nutrient input and existing nutrient concentrations was the greatest.

Finally, the scale and magnitude of interactions between rocky reefs and finfish farming is likely to be affected by cumulative impacts. In coastal waters, it is common for multiple nutrient enrichment sources to exist within one system, with riverine inputs, urbanisation, marinas and other industrial inputs all likely to happen at the same time as finfish aquaculture. In this scenario, cumulative system-wide impacts may occur, as nutrients from multiple sources are transported and mixed (Ban et al. 2010, Fowles et al. 2018b).

Cumulative nutrient enrichment across a large spatial scale is likely to be subtle but spatially widespread, with the potential to gradually shift baselines as additional sources of organic enrichment are introduced (Connell et al. 2008, Keeley et al. 2019). As a result, attributing impacts on coastal reef ecosystems to one source of nutrient enrichment alone is likely to be challenging.

Summary of potential interactions between finfish farming and temperate rocky reefs, and key management practices to mitigate these interactions

Potential ecological interactions

The ecological interactions between finfish aquaculture and temperate reef ecosystems are tightly linked to nutrient enrichment. Change in reef ecosystems due to nutrient enrichment can occur directly through either dissolved or particulate inputs, or indirectly through trophic effects or changes to the productivity of marine food webs.

Effects of nutrient enrichment on primary productivity (bottom-up interactions)

- Changes in dissolved nutrients can increase primary productivity in the water column, altering light and sedimentation regimes.
- An indication of early-stage nutrient enrichment includes increased biomass via the rapid growth of opportunistic macroalgae, including turfing species, epiphytic species and filamentous algae that are well adapted to assimilate the excess nutrient loads.
- Sustained nutrient loadings may cause smothering, shading and restrictions to water flow that limit canopy productivity.
- These processes make reefs vulnerable to the effects of other environmental stressors, including storm damage, over-grazing and climate change, all of which can also cause loss of macroalgal canopy.
- Canopy loss can result in a phase shift in reef productivity, altering total biomass, biodiversity, epifauna and grazing species, along with the ecosystem services provided.
- Opportunistic turfing species enhance sediment retention, inhibiting recovery to a more complex ecosystem dominated by canopy-forming macroalgae under increased sedimentation rates.
- Once gone, natural regeneration to original canopy dominated ecosystems is unlikely or very slow, spanning years or decades.

Effects of nutrient enrichment on secondary productivity (top-down interactions)

- The presence of deposited organic material from finfish farms (uneaten feed, faeces and biofouling drop-off) can attract scavengers, which can form localised aggregations.

- Aggregations of omnivorous scavengers can reduce the impact of nutrient enrichment by grazing on epiphytic algae or particulate waste. This grazing may also mitigate these bottom-up nutrient enrichment symptoms.
- Top-down effects are less predictable but can alter ecosystem dynamics if populations of keystone species (e.g. urchins) are changed.

These ecosystem processes are seldom independent and will trigger a range of different ecosystem responses, and the magnitude of these are scenario specific.

Spatial scales

The spatial scale of impact will be governed by the proximity of the reef to the farm, the level of farm outputs, the inherent sensitivity/resilience of reef ecosystems, coupled with the receiving environment and hydrodynamics. The energy of the environment is an important consideration affecting spatial scale of interaction. Low energy environments may observe a greater acute local impact, while in dynamic higher energy environments there may be more diffuse interactions over a larger area (spatial scale). Cumulative effects with other sources of nutrient enrichment will also influence the spatial scale of interactions.

Management and mitigation

Management actions to mitigate the effects of nutrient enrichment include:

- appropriate site selection – not situating farms over or near hard substrate, accounting for cumulative effects within a system
- baseline environmental monitoring before farming commences
- system and/or site-specific limits on farming via limits on feed inputs or biomass
- local and broadscale environmental monitoring to inform farm management, such as fallowing requirements.

Knowledge gaps

Resilience thresholds remain largely unknown, notably tipping points relating to epiphyte loads that will lead to canopy loss, and how much canopy loss can occur before there is a long-term shift in ecosystem function. Attribution of change to finfish inputs relative to other natural and anthropogenic influences remains challenging. As such, the further development of aquaculture specific tracers remains an important area to address.

3 Mitigation and management of impacts

As aquaculture expands globally, many jurisdictions are examining the interaction between finfish aquaculture and reef ecosystems, with the development of management strategies to limit potential effects.

There are very few direct examples in the global literature of implemented management strategies to mitigate potential interactions between finfish aquaculture and shallow rocky reefs. However, the Tasmanian Government recently introduced a framework for assessing shallow reef systems as part of finfish farming compliance monitoring, along with introducing reef monitoring into environmental licences for a number of growing regions. There are also several key principles applicable to general nutrient enrichment on reef environments, which can be applied to potential enrichment from finfish aquaculture. These include:

- Proximity – the distance between farms and rocky reefs
- Hydrodynamics – the transport of farm-derived outputs and dilution within the environment
- Intensity and methods of farming – the volume of nutrients and organic material discharged into the environment
- Cumulative or synergistic effects – proximity to other anthropogenic organic pollutant sources, such as sewage outlets or farm runoff.

Proximity and hydrodynamics can be managed through site selection. A key mitigation measure widely cited in the aquaculture literature is the movement of farms from sheltered environments into more dispersive locations, to decrease the magnitude of local scale impacts (Woodcock et al. 2018, Keeley et al. 2019). While there will be greater dilution of waste in highly dispersive environments, nutrients from farm waste will also travel much greater distances. For example, in Norway, farm waste has been detected on reef ecosystems up to 1.2 km from farms in highly dispersive environments (Woodcock et al. 2018, Keeley et al. 2019). However, associated ecological effects are less likely to be evident, becoming more subtle or non-existent as the nutrient loadings that reefs are exposed to decline. As a result, with increasing distance and dilution, detecting differences between anthropogenically driven change and natural processes becomes increasingly difficult (Bannister et al. 2016, Broch et al. 2017, Keeley et al. 2019).

Where there has been widespread loss of canopy due to nutrient enrichment more generally, some mitigation measures have largely focused on abating nutrient inputs and replanting canopy-forming species. For example, attempts to replant these species in areas of loss has been trialled in New South Wales, Australia, with some success once sources of nutrient enrichment were reduced (Campbell et al. 2014). However, such programs are unlikely to be a realistic option at a large scale, particularly where nutrient enrichment within the environment persists. Substantial loss of canopy attributable to finfish farming or other nutrient enrichment sources has not been reported in Tasmania. Best practice management is to avoid or mitigate nutrient enrichment before loss of canopy can occur.

One concept that has gained traction in recent years around mitigation and management of finfish aquaculture is the implementation of restorative aquaculture, or integrated multi-trophic aquaculture (IMTA). These forms of aquaculture generally involve the production of one or more extractive species, such as seaweeds or shellfish, alongside finfish aquaculture (Chopin 2013, Sickander & Filgueira 2022, Mizuta et al. 2023). One of the potential benefits of these forms of aquaculture is nitrogen remediation (Mizuta et al. 2023). This concept is presently being trialled in several salmon growing regions in Norway and Chile, though few examples exist of this occurring widely at a commercial scale (Sickander & Filgueira 2022). While there is promise for the future, issues of economic viability, logistics of scale and increased biofouling of the cultured product remain key hurdles for these forms of regenerative aquaculture or IMTA.

Overall, for management to be most effective, a more comprehensive understanding of the ways nutrient enrichment will affect temperate reef ecosystems is needed, in particular how local biotic and abiotic factors might interact to enhance or mitigate these effects (Ross et al. 2021). Understanding how nutrient enrichment interacts with temperate reefs is critical to establishing the sensitivity or resilience of these ecosystems and, by extension, to defining threshold values for key indicator parameters. This understanding is an essential prerequisite to developing risk-appropriate management strategies and monitoring programs at relevant local and regional scales.

3.1 Environmental performance frameworks

3.1.1 Environmental requirements

Finfish farming in Tasmania primarily occurs in coastal areas covered by a marine farming development plan, and within a marine farming lease area (DNRET 2023a). A marine farming licence is required to operate within a lease area, and an environmental licence to farm finfish is also required. Environmental licences require ongoing environmental monitoring and compliance against environmental conditions. The Environmental Standards (DNRET 2023b) include managing rocky reef condition related to changes in overall canopy cover and epiphytic loadings (see below).

Reef Habitat Ecological Standards

Managing rocky reef condition with regard to finfish aquaculture is referenced in the Environmental Standards (DNRET 2023b). The Reef Habitat Ecological Standard states that:

1. The licence holder must ensure that at any reef compliance site, when compared with reference conditions, there is no:
   a) significant and persistent increase in the presence of opportunistic algae; or
   b) significant change in canopy cover; or
   c) significant change in abundance and composition of key taxa; or
   d) significant change in composition of reef communities.

Previously in Tasmania, key mitigation and management aspects have included site selection, limits on feed inputs and performance-based management, which includes environmental monitoring that feeds back into management actions as necessary (Wu 1995, EPA 2022). However, until the development of the new Environmental Standards, rocky reefs have not been subject to environmental condition requirements (DNRET 2023b, DNRET 2023c). The Environmental Standards provide compliance requirements for reef habitat monitoring that will be applied across all marine farming regions where these habitats are present (DNRET 2023b, DNRET 2023c).

The key mechanism for assessing environmental impacts on reef ecosystems will be to compare measurements of relevant reef health indicators at compliance sites close to the farm and at more distant reference sites that are not likely to be impacted by marine finfish farming. Additionally, reef health may be assessed at compliance sites both when farm inputs are present (e.g. during maximum stocking density) and alternate times when such inputs are absent (i.e. after destocking or during fallowing). At the reef compliance sites, licence holders must undertake reef surveys and conduct an assessment against the reef habitat ecological standards (see page 15).

More detailed monitoring, assessment, reporting and data management requirements for assessing environmental performance against the Environmental Standards will be provided in the Technical Standards, which are still under development by Tasmania's Environment Protection Authority (EPA). These standards are being informed by a significant body of research over recent years that has developed methodology and tested performance indicators across multiple regions subject to different natural (e.g. wave exposure) and anthropogenic influences (Ross et al. 2021, White et al. 2021, White et al. 2022, Strain et al. 2023).

In Tasmania, there are also broader environment and ecosystem monitoring requirements where the lease/s are situated, known as Broadscale Environmental Monitoring Programs (BEMPs). Exceedance of any prescribed environmental performance requirements may result in management actions being taken by the EPA at the regional level (Ross et al. 2022). Presently, reef monitoring is included in the BEMPs for several, but not all, growing regions within Tasmania.

Environmental requirements for the broader ecosystem are mostly established for water quality, while assessment of reef condition at the broadscale generally relies on expert opinion around temporal changes. A technical standard for the BEMP that will set out reef monitoring, assessment, reporting and data management requirements for assessing environmental performance at the broadscale is being developed by the EPA.

3.1.2 Operational practices

Operational practices are typically focused on managing soft sediment and water column effects from marine finfish farming, but they are also applicable to mitigating and managing rocky reef effects and are discussed in this context below.

Biomass and dissolved nitrogen output limits (feed-N input limit)

Farmed biomass and feed caps (via the total permissible dissolved nitrogen output, TPDNO) are the common management measures used to limit the scale of marine farming activities across a region. They are also an important way to control the staged development of farming in new areas, while information on environmental impacts and their management is still being developed (Giles et al. 2021). In Norway, biomass limits continue to be used (Oppedal et al. 2011), but in New Zealand, total feed input limits are the primary way inputs are regulated, sometimes in conjunction with nitrogen-feed limits (CBOI 2013, MDC 2016).

Maximum permissible biomass is a fixed limit on farmed biomass in the system at any one time, set for a Marine Farming Development Plan (MFDP) area, and/or a specific area within. This was a common way to regulate the scale of finfish farming activity in Tasmania in the past, although biomass limits have now been superseded by TPDNO across most leases in Tasmania.

TPDNO limits the amount of nitrogen that may be released via feed inputs (primarily for management of water column eutrophication) into a defined area over a specified time (i.e. a 12-month rolling period; EPA 2022). As a tool for managing and mitigating effects of finfish aquaculture onto shallow reef systems, TPDNO limits have recently been applied in Port Arthur (south-east Tasmania) in response to an IMAS inshore reef study (White et al. 2022) and water quality monitoring results, to reduce the current annual finfish feed inputs by approximately 20% compared to average levels across the period from 2019 to 2023.

Fallowing

Short-term, regular fallowing (removal of fish) of farm sites is a widely used practice to sustainably manage seabed organic enrichment in many countries (Hansen et al. 2001, Chang et al. 2014). Fallowing is also a strategy used to help manage fish health issues, such as parasites and disease (Chang et al. 2014).

In Tasmania, fallowing is typically performed if sediment conditions after harvest are not acceptable for immediate restocking. So far, fallowing has not been used as a response for managing shallow reef conditions in Tasmania.

4 Methods for monitoring

While there are many established methods for determining overall reef health, methods that examine the interaction between finfish aquaculture and rocky reefs are relatively novel and still developing as our knowledge of this interactions increases.

Methods available for monitoring change on rocky reefs are largely based on quantitative and qualitative visual analysis, either performed by divers in-situ or by analysing photographic or video images after field surveys (Roberts et al. 2014). Remotely operated vehicles (ROVs) or towed cameras are now widely used to capture data on reef health (Buscher et al. 2020, Davis et al. 2020).

Visual survey approaches can adopt a wide range of techniques, from a full underwater visual census model where the focus is capturing data on biodiversity, to targeting functional groups and indicator species that respond to early stages of nutrient enrichment (Ross et al. 2021).

4.1 Biodiversity surveys

Biodiversity surveys provide an important ecological baseline for the area of interest, documenting the abundance and diversity of all fish, invertebrates and algae. Once a baseline is established, biodiversity surveys can detect changes in population numbers and size-structure, cascading ecosystems effects associated with disturbance, and long-term change and variability in temperate reef assemblages (Edgar & Barrett 1997, Edgar et al. 1997, 1999).

This method involves a comprehensive visual census by a diver along a 200 m transect line, divided into 4 x 50 m sub-sections. All fish species on both sides of the line, within 5 m of the transect, are counted and their size visually estimated. Invertebrates and cryptic fish species within 1 m of the transect line are counted, and commercially or ecologically important invertebrate species are also measured. Algal diversity is assessed by point-count using a 0.25 m2 quadrat placed every 10 m along the transect line (Edgar et al. 1997, 1999).

This survey method has been consistently implemented across both Tasmania and southern Australia for nearly 30 years. The high-resolution taxonomic detail allows for unanticipated impacts on coastal reef communities to be examined and offers an invaluable reference to measure future change (Valentine et al. 2016). As the method has widespread application, it is also possible to compare local results with a broader database, to separate out changes due to local stressors like finfish farming from more regional or broader-scale stressors (i.e. climate change).

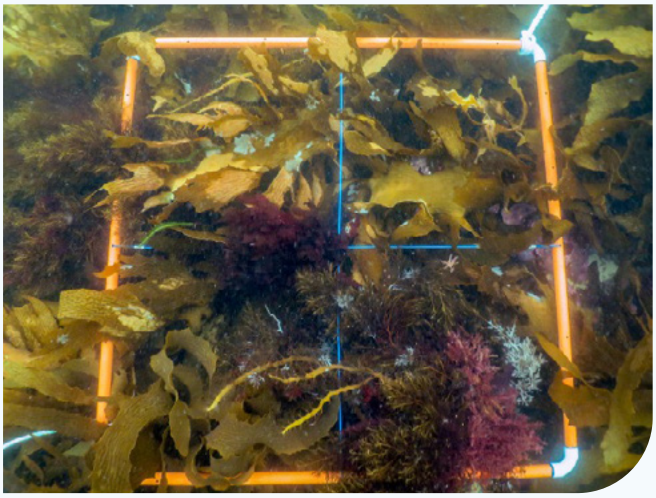
4.2 Targeted assessments

Targeted assessments aim to detect a loss of ecosystem resilience due to nutrient enrichment, before widespread loss of canopy occurs (Valentine et al. 2016). In Tasmania, a targeted Rapid Visual Assessment (RVA) has been designed to complement biodiversity surveys. This provides a faster way to assess functional change and loss of resilience due to nutrient enrichment (Ross et al. 2021). Broad functional categories include canopy, sub-canopy (red, green, brown algae), epiphytic algae, filamentous algae and opportunistic algae species (e.g. *Chaetomorpha billardieri*, *Ulva* spp., *Asparagopsis armata*) associated with organic enrichment in the region (Figure 3).

Survey sites are assessed using 12 x 1 m2 quadrats haphazardly placed along a 50 m fixed transect (Ross et al. 2021, White et al. 2022). This technique is designed so that shifts across several functional parameters, such as loss in canopy combined with increases in species/groups that indicate enrichment, can be detected simultaneously. The data provides a more complete picture of the enrichment status of a reef than achieved by examining a single parameter. The survey is designed to be undertaken biannually, so that prolonged growth of indicator species associated with nutrient enrichment can be separated from acute ecosystem responses to natural nutrient pulses that occur seasonally, or with rainfall events (Ross et al. 2021, White & Brasier 2021).

Figure 5: Reef survey methods

a) 1x1 m quadrat used in a Rapid Visual Assessment (RVA) of Tasmanian rocky reefs



b) scuba diver records biodiversity data

4.3 Remote assessments

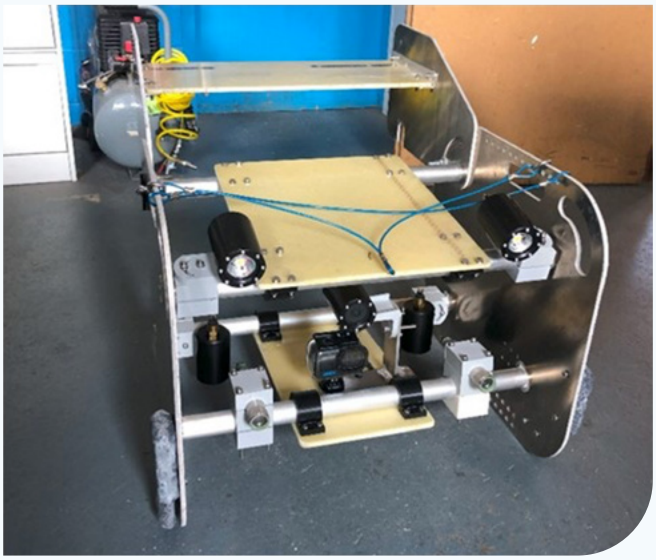
ROVs, Autonomous Underwater Vehicles (AUVs) or towed camera systems offer robust survey tools for quantifying temperate reef habitat that are not constrained by diving limitations such as depth or bottom time (Sward et al. 2019, Sward et al. 2022). When connected to a positioning system, seabed imagery can be geo-referenced to a collection location (Monk et al. 2018).

These systems can be used to capture both video and still images, and are useful to quantitatively assess fish, invertebrate and algae/substrate communities on temperate reefs (Sward et al. 2022). ROVs and towed camera systems can be operated live, enabling increased control in navigation, while AUVs tend to follow pre-programmed routes.

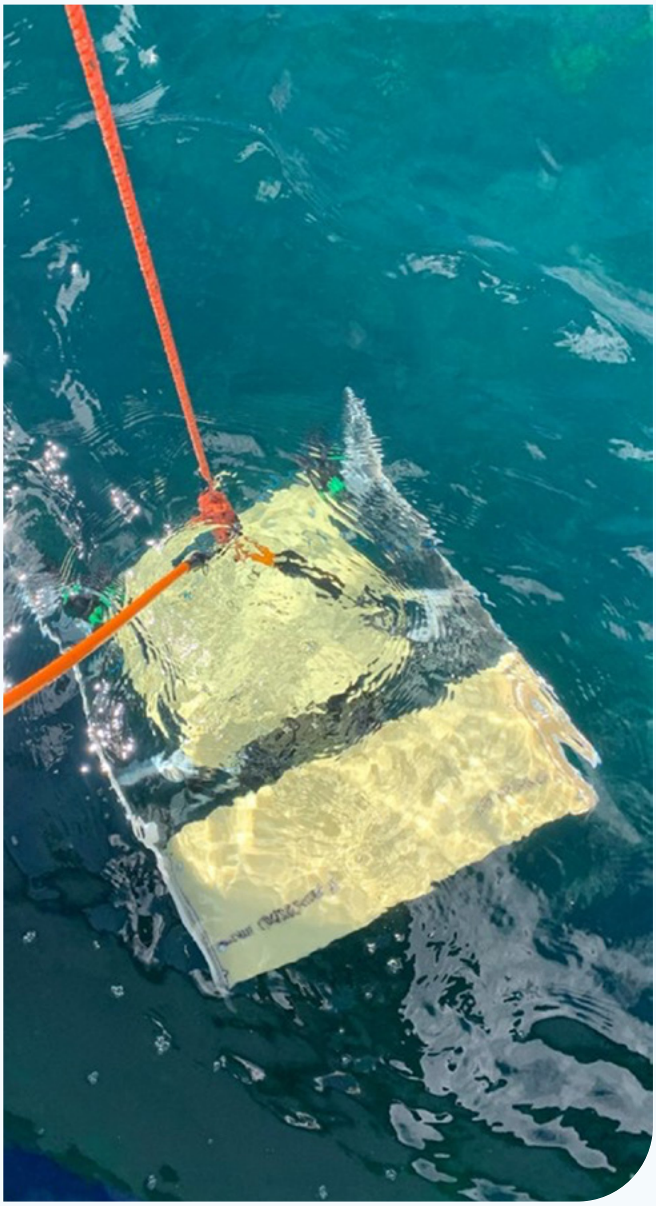
Figure 6: Equipment used for remote assessments

a) remotely operated vehicle (ROV)

b) towed camera system



c) towed camera system in action



The main advantage of remote survey platforms is the dramatic increase in the spatial area and depth that can be covered in a survey, while reducing dive time and providing a permanent record of the sampling (Parravicini et al. 2009, Guinda et al. 2014).

However, there are also disadvantages to working with remote platforms. In shallow-water systems for example, working in exposed locations can be particularly difficult, with entanglement, equipment damage and difficulty piloting all potential problems. Compared to diver-based surveys there is also a loss of taxonomic resolution and reduced capacity for consistent species identification (Guinda et al. 2014). The ability to identify cryptic or highly mobile species, or individuals masked by canopy-forming macroalgae is reduced, as identification relies on photographs or videos alone (Ross et al. 2021). Substantial time and expertise are needed to undertake image analysis consistently and accurately. Despite these drawbacks, technological advances may help to overcome several of these issues, and it is expected that the use of remote platforms for temperate reef monitoring will increase into the future.

4.4 Monitoring design

Although the monitoring of shallow rocky reefs is a relatively new addition to regulatory requirements, the design for regulatory monitoring is consistent with that developed for soft sediments and the water column, where assessment is focused on two spatial scales. Local (lease) scale monitoring assesses direct effects from nutrient emissions from a particular lease and broadscale monitoring assesses environmental change and the potential for cumulative effects across a region that may include multiple leases.

An inherent challenge in monitoring shallow reefs owes to their patchiness which can often constrain the ability to have a balanced sampling design. A sampling program that can best account for background spatial and temporal variability is imperative when trying to quantify the potential effects of finfish aquaculture on reef habitats. Reference conditions for assessing the effects of individual leases are best captured during pre-farming baseline surveys at both farm and reference sites, and then at reference sites during active farming.

This will not only capture pre-farming conditions but also capture changes over time in response to non-aquaculture related drivers, both natural and anthropogenic. Similarly, broadscale surveys conducted prior to active farming across the region are critical to assess the potential for the cumulative effects of aquaculture in the context of natural variability.

In Tasmania, baseline surveys are typically a requirement before marine farming activities commence and/or when there is a variation to a lease area (EPA 2022). Once farming commences, the environmental licences require lease scale monitoring at compliance and reference sites, along with broadscale monitoring of sites encompassing the region. The new Environmental Standards now provide compliance requirements for reef habitat monitoring that will be applied across all marine farming regions where these habitats are present. As baseline information on reefs is lacking in several growing areas, most notably the D'Entrecasteaux Channel in southern Tasmania, there will be challenges in establishing robust baseline conditions for these areas.

5 Summary

Shallow reef systems interact with finfish aquaculture through nutrient enrichment of the water column and deposition of organic wastes onto the substrate.

- Sustained environmental pressure through nutrient enrichment on inshore temperate rocky reefs can cause an increase in opportunistic species and a loss of macroalgal canopy, with potential ramifications for the broader food web.
- Inputs from finfish farming in Tasmania have the potential to interact with rocky reefs,although with no farms situated directly above hard substrate, effects are more likely to be from interactions with dissolved nutrients in the water column, rather than deposition of organic material onto the substrate.

- Effects of nutrient enrichment in the form of increased abundance of epiphytic and filamentous algae have been observed on reef ecosystems in Tasmania, with changes observed up to 1000 m from finfish farms.
- At a broad spatial scale, determining the effects of nutrients derived from finfish aquaculture as opposed to nutrients from other anthropogenic and natural sources is difficult.
- Effective monitoring of rocky reefs helps provide early warning signs of nutrient enrichment related stress, which in turn helps manage the risk of canopy loss.
- Effective management is informed by:
  - An understanding of how reefs respond to nutrient enrichment at local and regional scales
  - How ecological and environmental factors, such as hydrodynamics, might interact with nutrient enrichment to enhance or mitigate effects at local and regional scales.
  - Baseline information on reef condition prior to the introduction of finfish aquaculture into a system.
- Targeted research and ongoing monitoring will provide a better understanding of the sensitivity to nutrient enrichment and the long-term resilience of coastal reef systems in Tasmania.

6 Glossary and acronyms

BEMP

Broadscale Environmental Monitoring Program. A monitoring program within Tasmania to understand potential aquaculture effects within a larger spatial context.

Canopy

The tallest layer of macroalgae (seaweed) that can form dense underwater forests, providing structure and shaping the ecology of temperate reef environments in the photic zone.

Encrusting algae

A type of algae that tightly adheres to hard substrate, spreading out in thin layers or crusts. These are often calcified.

Epiphytic algae

A type of algae that grows on the surface of other algae.

Environmental Licence

Environmental licences to operate salmon farms in Tasmania are issued by the Environment Protection Authority under the *Environmental Management and Pollution Control Act 1994*.

EPA

Environment Protection Authority. Tasmania's principal environmental regulatory body, established as an independent statutory authority under the *Environmental Management and Pollution Control Act 1994*.

Filamentous algae

A group of algae characterised by long threadlike structures that can form dense mats or tufts in marine environments. They may be free floating or attached to rock or other algae (epiphytic).

Hydrodynamics

The movement of fluids (in this case, seawater) and the subsequent movement of material or bodies immersed in fluids, such as organic waste.

Nuisance species

A functional category of opportunistic algae that can threaten the diversity or abundance of other species, ecosystem functioning and ecosystem services.

Nutrient enrichment

An increase in the nutrients that can drive excessive primary production and lead to increased anaerobic microbial activity.

Opportunistic species

Generally fast-growing and highly fecund species, adapted to exploit newly available, polluted, transient and variable habitats.

ROV

Remotely Operated Vehicle. A vehicle used to survey marine habitats, while tethered to a vessel.

RVA

Rapid Visual Assessment. A survey method used to rapidly assess functional change and loss of resilience due to organic enrichment on rocky reefs.

Scavenger species

An animal that feeds on dead material.

Shallow reef

A hard-substrate ecosystem in the shallow photic zone where macroalgae communities dominate.

Sub-canopy

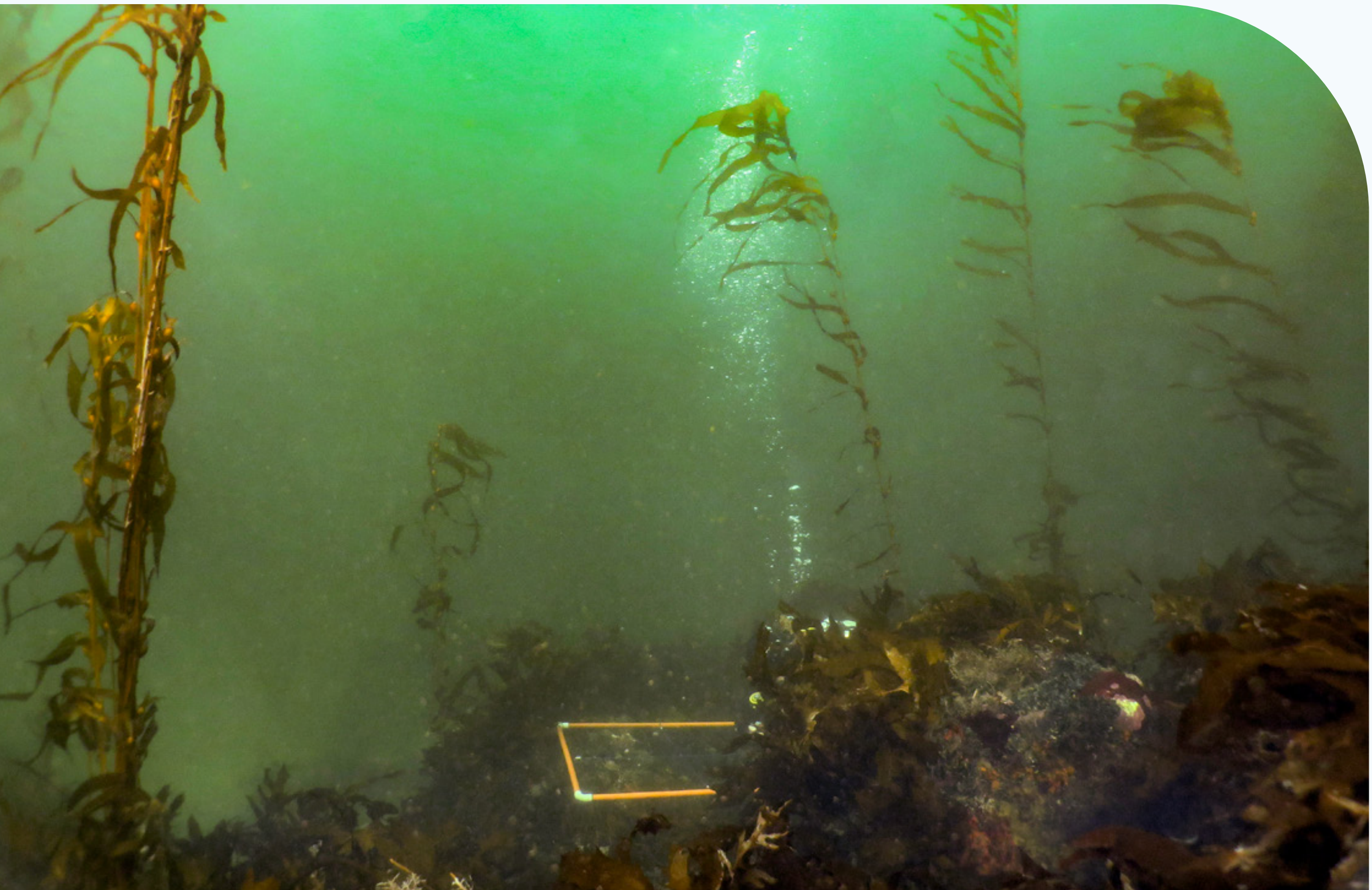
Algal species growing below the canopy.

TPDNO

Total Permissible Dissolved Nitrogen Output. A regulatory metric which limits the amount of dissolved inorganic nitrogen that can be released via feed inputs into a defined area over a specified time. The TPDNO is based on estimated dissolved nitrogen released through waste outputs from farmed fish (EPA 2022).

Turfing species

Generally 'short' (0.5 to 3 cm) or 'low lying' algae growing under the canopy.



7 References

Agatsuma Y, Endo H, Yoshida S, Ikemori C, Takeuchi Y, Fujishima H, Nakajima K, Sano M, Kanezaki N, Imai H, Yamamoto N, Kanahama H, Matsubara T, Takahashi S, Isogai T, Taniguchi K (2014) Enhancement of *Saccharina* kelp production by nutrient supply in the Sea of Japan off southwestern Hokkaido, Japan. J Appl Phycol 26:1845-1852

Airoldi L (2003) The effects of sedimentation on rocky coast assemblages. In: Gibson RN, Atkinson RJA (eds) Oceanography and Marine Biology: an Annual Review, Volume 41. CRC Press, London, p 161-236

Airoldi L, Cinelli F (1997) Effects of sedimentation on subtidal macroalgal assemblages: An experimental study from a Mediterranean rocky shore. J Exp Mar Biol Ecol 215:269-288

Airoldi L, Fabiano M, Cinelli F (1996) Sediment deposition and movement over a turf assemblage in a shallow rocky coastal area of the Ligurian Sea. Mar Ecol Prog Ser 133:241-251

Airoldi L, Rindi F, Cinelli F (1995) Structure, seasonal dynamics and reproductive phenology of a filamentous turf assemblage on a sediment influenced, rocky subtidal shore. Bot Mar 38:227-237

Alestra T, Schiel DR (2015) Non-trophic responses of algal communities to nutrient enrichment: interactions among coralline turfs, ephemeral algae and perennial fucoids. Mar Ecol Prog Ser 538:145-156

Balata D, Piazzi L, Bulleri F (2015) Sediment deposition dampens positive effects of substratum complexity on the diversity of macroalgal assemblages. J Exp Mar Biol Ecol 467:45-51

Balata D, Piazzi L, Cinelli F (2007) Increase of sedimentation in a subtidal system: Effects on the structure and diversity of macroalgal assemblages. J Exp Mar Biol Ecol 351:73-82

Ban NC, Alidina HM, Ardron JA (2010) Cumulative impact mapping: Advances, relevance and limitations to marine management and conservation, using Canada's Pacific waters as a case study. Mar Policy 34:876-886

Bannister RJ, Johnsen IA, Hansen PK, Kutti T, Asplin L (2016) Near- and far-field dispersal modelling of organic waste from Atlantic salmon aquaculture in fjord systems. ICES J Mar Sci 73:2408-2419

Benedetti-Cecchi L (2001) Beyond BACI: Optimization of environmental sampling designs through monitoring and simulation. Ecol Appl 11:783-799

Bloecher N, Floerl O, Sunde LM (2015) Amplified recruitment pressure of biofouling organisms in commercial salmon farms: potential causes and implications for farm management. Biofouling 31:163-172

Bokn TL, Duarte CM, Pedersen MF, Marba N, Moy FE, Barrón C, Bjerkeng B, Borum J, Christie H, Engelbert S, Fotel FL, Hoell EE, Karez R, Kersting K, Kraufvelin P, Lindblad C, Olsen M, Sanderud KA, Sommer U, Sørensen K (2003) The response of experimental rocky shore communities to nutrient additions. Ecosystems 6:577-594

Broch OJ, Daae RL, Ellingsen IH, Nepstad R, Bendiksen EÅ, Reed JL, Senneset G (2017) Spatiotemporal dispersal and deposition of fish farm wastes: A model study from Central Norway. Front Mar Sci 4:199

Bulleri F, Balata D, Bertocci I, Tamburello L, Benedetti-Cecchi L (2010) The seaweed *Caulerpa racemosa* on Mediterranean rocky reefs: from passenger to driver of ecological change. Ecology 91:2205-2212

Bulleri F, Cucco A, Dal Bello M, Maggi E, Ravaglioli C, Benedetti-Cecchi L (2018) The role of wave-exposure and human impacts in regulating the distribution of alternative habitats on NW Mediterranean rocky reefs. Estuar Coast Shelf Sci 201:114-122

Buscher E, Mathews DL, Bryce C, Bryce K, Joseph D, Ban NC (2020) Applying a low cost, mini Remotely Operated Vehicle (ROV) to assess an ecological baseline of an Indigenous seascape in Canada. Front Mar Sci 7:669

Campbell AH, Marzinelli EM, Vergés A, Coleman MA, Steinberg PD (2014) Towards restoration of missing underwater forests. PLOS ONE 9:e84106

Carnell PE, Keough MJ (2014) Spatially variable synergistic effects of disturbance and additional nutrients on kelp recruitment and recovery. Oecologia 175:409-416

CBOI (2013) Final Conditions as amended by Addendum dated 13 March 2013; Resource Consent for Richmond [Kopaua] issued to New Zealand King Salmon, Coastal Permit under the Resource Management Act 1991. Notice by the Chairman of The Board of Inquiry (CBOI), Auckland, NZ

Chang BD, Coombs KA, Page FH (2014) The development of the salmon aquaculture industry in southwestern New Brunswick, Bay of Fundy, including steps toward integrated coastal zone management. Aquacult Econ Manage 18:1-27

Chopin T (2013) Integrated multi-trophic aquaculture. Ancient, adaptable concept focuses on ecological integration. Global Aquaculture Advocate 16:16-19

Claudet J, Fraschetti S (2010) Human-driven impacts on marine habitats: A regional meta-analysis in the Mediterranean Sea. Biol Conserv 143:2195-2206

Coleman MA, Kelaher BP, Steinberg PD, Millar AJK (2008) Absence of a large brown macroalga on urbanized rocky reefs around Sydney, Australia, and evidence for historical decline. J Phycol 44:897-901

Coleman MA, Wernberg T (2017) Forgotten underwater forests: The key role of fucoids on Australian temperate reefs. Ecol Evol 7:8406-8418

Connell SD, Irving AD (2008) Integrating ecology with biogeography using landscape characteristics: a case study of subtidal habitat across continental Australia. J Biogeogr 35:1608-1621

Connell SD, Russell BD, Turner DJ, Shepherd SA, Kildea T, Miller D, Airoldi L, Cheshire A (2008) Recovering a lost baseline: missing kelp forests from a metropolitan coast. Mar Ecol Prog Ser 360:63-72

Crain CM, Halpern BS, Beck MW, Kappel CV (2009) Understanding and managing human threats to the coastal marine environment. Ann N Y Acad Sci 1162:39-62

Davis TR, Cadiou G, Williams J, Coleman MA (2020) Costs and benefits of towed videos and remotely operated vehicles for sampling shallow reef habitats and fish. Aust J Mar Freshwater Res 71:953-961

Dempster T, Uglem I, Sanchez-Jerez P, Fernandez-Jover D, Bayle-Sempere J, Nilsen R, Bjørn PA (2009) Coastal salmon farms attract large and persistent aggregations of wild fish: an ecosystem effect. Mar Ecol Prog Ser 385:1-14

Diehl S (2002) Phytoplankton, light, and nutrients in a gradient of mixing depths: theory. Ecology 83:386-398

DNRET (2023a) Tasmanian Regulatory Framework for Finfish Aquaculture. Department of Natural Resources and Environment Tasmania, Hobart

DNRET (2023b) Environmental Standards for Tasmanian Marine Finfish Farming 2023. Environment Strategic Business Unit, Department of Natural Resources and Environment Tasmania, Hobart

DNRET (2023c) Companion Paper – Environmental Standards for Tasmanian Marine Finfish Farming 2023. Environment Strategic Business Unit, Department of Natural Resources and Environment Tasmania, Hobart

Dunmore R, Keeley N, Peacock L (2015) Reef environmental monitoring results for the Clay Point and Te Pangu salmon farms: 2014 (Cawthron Report No. 2687). Cawthron Institute, Nelson

Echavarri-Erasun B, Juanes JA, García-Castrillo G, Revilla JA (2007) Medium-term responses of rocky bottoms to sewage discharges from a deepwater outfall in the NE Atlantic. Mar Pollut Bull 54:941-954

Edgar GJ, Barrett NS (1997) Short term monitoring of biotic change in Tasmanian marine reserves. J Exp Mar Biol Ecol 213:261-279

Edgar GJ, Barrett NS, Graddon DJ (1999) A classification of Tasmanian estuaries and assessment of their conservation significance using ecological and physical attributes, population and land use. Tasmanian Aquaculture and Fisheries Institute, Hobart

Edgar GJ, Moverley J, Barrett NS, Peters D, Reed C (1997) The conservation-related benefits of a systematic marine biological sampling programme: the Tasmanian reef bioregionalisation as a case study. Biol Conserv 79:227-240

EPA (2022) Review of Tasmanian and International Regulatory Requirements for Salmonid Aquacultre. Environment Protection Authority, Hobart

Eriksson BK, Johansson G, Snoeijs P (2002) Long-term changes in the macroalgal vegetation of the inner Gullmar Fjord, Swedish Skagerrak coast. J Phycol 38:284-296

Falkenberg LJ, Connell SD, Russell BD (2014) Herbivory mediates the expansion of an algal habitat under nutrient and CO2 enrichment. Mar Ecol Prog Ser 497:87-92

Falkenberg LJ, Russell BD, Connell SD (2012) Stability of strong species interactions resist the synergistic effects of local and global pollution in kelp forests. PLOS ONE 7:e33841

Fernandez-Jover D, Martinez-Rubio L, Sanchez-Jerez P, Bayle-Sempere JT, Jimenez JAL, Lopez FJM, Bjørn P-A, Uglem I, Dempster T (2011) Waste feed from coastal fish farms: A trophic subsidy with compositional side-effects for wild gadoids. Estuar Coast Shelf Sci 91:559-568

Fernandez-Jover D, Sanchez-Jerez P, Bayle-Sempere JT, Valle C, Dempster T (2008) Seasonal patterns and diets of wild fish assemblages associated with Mediterranean coastal fish farms. ICES J Mar Sci 65:1153-1160

Fitridge I, Dempster T, Guenther J, de Nys R (2012) The impact and control of biofouling in marine aquaculture: a review. Biofouling 28:649-669

Fowles AE, Edgar GJ, Hill N, Stuart-Smith RD, Kirkpatrick JB (2018a) An experimental assessment of impacts of pollution sources on sessile biota in a temperate urbanised estuary. Mar Pollut Bull 133:209-217

Fowles AE, Edgar GJ, Stuart-Smith RD, Kirkpatrick JB, Hill N, Thomson RJ, Strain EMA (2018b) Effects of pollution from anthropogenic point sources on the recruitment of sessile estuarine reef biota. Front Mar Sci 5:417

Fowles AE, Stuart-Smith RD, Hill NA, Thomson RJ, Strain EMA, Alexander TJ, Kirkpatrick J, Edgar GJ (2018c) Interactive responses of primary producers and grazers to pollution on temperate rocky reefs. Environ Pollut 237:388-395

Giles H, Baxter A, Taylor D, Elvines D, Neale D, Jorgensen E, James M, Bunce M, Broekhuizen N, Wade O, Ford R, Cumming S, O’Connell-Milne S, Hart S-R, Hampton B (2021) Best practice guidelines for benthic and water quality monitoring of open ocean finfish culture in New Zealand (New Zealand Aquatic Environment and Biodiversity Report No. 278). Fisheries New Zealand, Ministry for Primary Industries, Wellington

Gillanders BM, Kingsford MJ (2002) Impact of changes in flow of freshwater on estuarine and open coastal habitats and the associated organisms. Oceanogr Mar Biol Annu Rev 40:233-309

Gorgula SK, Connell SD (2004) Expansive covers of turf-forming algae on human-dominated coast: the relative effects of increasing nutrient and sediment loads. Mar Biol 145:613-619

Gorman D, Bajjouk T, Populus J, Vasquez M, Ehrhold A (2013) Modeling kelp forest distribution and biomass along temperate rocky coastlines. Mar Biol 160:309-325

Gorman D, Russell BD, Connell SD (2009) Land-to-sea connectivity: linking human-derived terrestrial subsidies to subtidal habitat change on open rocky coasts. Ecol Appl 19:1114-1126

Guidetti P, Terlizzi A, Fraschetti S, Boero F (2003) Changes in Mediterranean rocky-reef fish assemblages exposed to sewage pollution. Mar Ecol Prog Ser 253:269-278

Guinda X, Gracia A, Puente A, Juanes JA, Rzhanov Y, Mayer L (2014) Application of landscape mosaics for the assessment of subtidal macroalgae communities using the CFR index. Deep Sea Res II 106:207-215

Guinder VA, Popovich CA, Perillo GME (2009) Particulate suspended matter concentrations in the Bahía Blanca Estuary, Argentina: Implication for the development of phytoplankton blooms. Estuar Coast Shelf Sci 85:157-165

Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, Bruno JF, Casey KS, Ebert C, Fox HE, Fujita F, Heinemann D, Lenihan HS, Madin EMP, Perry MT, Selig ER, Spalding M, Steneck R, Watson R (2008) A global map of human impact on marine ecosystems. Science 319:948-952

Hamoutene D, Salvo F, Donnet S, Dufour SC (2016) The usage of visual indicators in regulatory monitoring at hard-bottom finfish aquaculture sites in Newfoundland (Canada). Mar Pollut Bull 108:232-241

Hansen PK, Ervik A, Schaanning M, Johannessen P, Aure J, Jahnsen T, Stigebrand A (2001) Regulating the local environmental impact of intensive, marine fish farming II. The monitoring programme of the MOM system (Modelling-Ongrowing fish farms-Monitoring). Aquaculture 194:75-92

Haugland BT (2019) Effects of fish farm effluents on kelp forest ecosystems. PhD dissertation, University of Oslo, Oslo, Norway

Haugland BT, Armitage CS, Kutti T, Husa V, Skogen MD, Bekkby T, Carvajalino-Fernández MA, Bannister RJ, White CA, Norderhaug KM, Fredriksen S (2021) Large-scale salmon farming in Norway impacts the epiphytic community of *Laminaria hyperborea*. Aquacult Environ Interact 13:81-100

Haugland BT, Rastrick SPS, Agnalt A-L, Husa V, Kutti T, Samuelsen OB (2019) Mortality and reduced photosynthetic performance in sugar kelp *Saccharina latissima* caused by the salmon-lice therapeutant hydrogen peroxide. Aquacult Environ Interact 11:1-17

Hernández-Carmona G, Robledo D, Serviere-Zaragoza E (2001) Effect of nutrient availability on *Macrocystis pyrifera* recruitment and survival near its southern limit off Baja California. Bot Mar 44:221-229

Hillebrand H, Worm B, Lotze HK (2000) Marine microbenthic community structure regulated by nitrogen loading and grazing pressure. Mar Ecol Prog Ser 204:27-38

Irving AD, Connell SD (2002) Sedimentation and light penetration interact to maintain heterogeneity of subtidal habitats: algal versus invertebrate dominated assemblages. Mar Ecol Prog Ser 245:83-91

Johnson CR, Banks SC, Barrett NS, Cazassus F, Dunstan PK, Edgar GJ, Frusher SD, Gardner C, Haddon M, Helidoniotis F, Hill KL, Holbrook NJ, Hosie GW, Last PR, Ling SD, Melbourne-Thomas J, Miller K, Pecl GT, Richardson AJ, Ridgway KR, Rintoul SR, Ritz DA, Ross DJ, Sanderson JC, Shepherd SA, Slotwinski A, Swadling KM, Taw N (2011) Climate change cascades: Shifts in oceanography, species' ranges and subtidal marine community dynamics in eastern Tasmania. J Exp Mar Biol Ecol 400:17-32

Keeley N, Valdemarsen T, Woodcock S, Holmer M, Husa V, Bannister R (2019) Resilience of dynamic coastal benthic ecosystems in response to large-scale finfish farming. Aquacult Environ Interact 11:161-179

Krause-Jensen D, Carstensen J, Dahl K, Bäck S, Neuvonen S (2009) Testing relationships between macroalgal cover and Secchi depth in the Baltic Sea. Ecol Indic 9:1284-1287

Krause-Jensen D, Sagert S, Schubert H, Boström C (2008) Empirical relationships linking distribution and abundance of marine vegetation to eutrophication. Ecol Indic 8:515-529

Krumhansl KA, Okamoto DK, Rassweiler A, Novak M, Bolton JJ, Cavanaugh KC, Connell SD, Johnson CR, Konar B, Ling SD, Micheli F, Norderhaug KM, Pérez-Matus A, Sousa-Pinto I, Reed DC, Salomon AK, Shears NT, Wernberg T, Anderson RJ, Barrett NS, Buschmann AH, Carr MH, Caselle JE, Derrien-Courtel S, Edgar GJ, Edwards M, Estes JA, Goodwin C, Kenner MC, Kushner DJ, Moy FE, Nunn J, Steneck RS, Vásquez J, Watson J, Witman JD, Byrnes JEK (2016) Global patterns of kelp forest change over the past half-century. Proc Natl Acad Sci USA 113:13785-13790

Layton C, Shelamoff V, Cameron MJ, Tatsumi M, Wright JT, Johnson CR (2019) Resilience and stability of kelp forests: The importance of patch dynamics and environment-engineer feedbacks. PLOS ONE 14:e0210220

Ling SD, Davey A, Reeves SE, Gaylard S, Davies PL, Stuart-Smith RD, Edgar GJ (2018) Pollution signature for temperate reef biodiversity is short and simple. Mar Pollut Bull 130:159-169

Lotze HK, Worm B, Sommer U (2001) Strong bottom-up and top-down control of early life stages of macroalgae. Limnol Oceanogr 46:749-757

Mack RN, Simberloff D, Lonsdale WM, Evans H, Clout M, Bazzaz FA (2000) Biotic invasions: Causes, epidemiology, global consequences, and control. Ecol Appl 10:689-710

Mancuso FP, Strain EMA, Piccioni E, De Clerck O, Sarà G, Airoldi L (2018) Status of vulnerable *Cystoseira* populations along the Italian infralittoral fringe, and relationships with environmental and anthropogenic variables. Mar Pollut Bull 129:762-771

McKinley A, Johnston EL (2010) Impacts of contaminant sources on marine fish abundance and species richness: a review and meta-analysis of evidence from the field. Mar Ecol Prog Ser 420:175-191

McSkimming C, Tanner JE, Russell BD, Connell SD (2015) Compensation of nutrient pollution by herbivores in seagrass meadows. J Exp Mar Biol Ecol 471:112-118

MDC (2016) Certificate of Resource Consent; Number U150081; Te Pangu Bay, Tory Channel. Decision of Marlborough District Council (MDC) under the Resource Management Act 1991 for The New Zealand King Salmon Company Limited. Marlborough District Council, Blenheim

Mineur F, Cook EJ, Minchin D, Bohn K, MacLeod A, Maggs CA (2012) Changing coasts: Marine aliens and artificial structures. Oceanogr Mar Biol Annu Rev 50:189-234

Mizuta DD, Froehlich HE, Wilson JR (2023) The changing role and definitions of aquaculture for environmental purposes. Rev Aquacult 15:130-141

Monk J, Barrett N, Bridge T, Carroll A, Friedman A, Hill N, Ierodiaconou D, Jordan A, Kendrick G, Lucieer V (2018) Marine sampling field manual for AUVs (autonomous underwater vehicles). In: Przeslawski R, Foster S (eds) Field Manuals for Marine Sampling to Monitor Australian Waters. Marine Biodiversity Hub, National Environmental Science Programme, p 65-81

Muth AF, Henríquez-Tejo EA, Buschmann AH (2017) Influence of sedimentation in the absence of macrograzers on recruitment of an annual population of *Macrocystis pyrifera* in Metri Bay, Chile. Austral Ecol 42:783-789

Nichol SL, Anderson TJ, McArthur M, Barrett N, Heap AD, Siwabessy PJW, Brooke B (2009) Southeast Tasmania temperate reef survey. Post-survey report (Record 2009/43). Geoscience Australia, Canberra

Oh ES, Edgar GJ, Kirkpatrick JB, Stuart-Smith RD, Barrett NS (2015) Broad-scale impacts of salmon farms on temperate macroalgal assemblages on rocky reefs. Mar Pollut Bull 98:201-209

Oppedal F, Dempster T, Stien LH (2011) Environmental drivers of Atlantic salmon behaviour in sea-cages: A review. Aquaculture 311:1-18

Parravicini V, Morri C, Ciribilli G, Montefalcone M, Albertelli G, Bianchi CN (2009) Size matters more than method: Visual quadrats *vs* photography in measuring human impact on Mediterranean rocky reef communities. Estuar Coast Shelf Sci 81:359-367

Pearson TH, Rosenberg R (1978) Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Oceanogr Mar Biol Annu Rev 16:229-311

Roberts CA, Telfer TC, Johnson I, Honey DJ, Miller FM, Aldous E, Tillin HM, Hull SC (2014) Impact of salmonid pen aquaculture on hard substrates. ABP Marine Environmental Research Ltd, Southampton

Ross J, Macleod C, White C, Hadley S, Moreno D, Bush F, Barrett N (2021) Managing ecosystem interactions across differing environments: building flexibility and risk assurance into environmental management strategies. FRDC Project No. 2015/024. Institute for Marine and Antarctic Studies, University of Tasmania, Hobart

Ross J, Moreno D, Bell J, Mardones J, Beard J (2022) Assessment of the Macquarie Harbour Broadscale Environmental Monitoring Program (BEMP) data from 2011-2020. Institute for Marine and Antarctic Studies, University of Tasmania, Hobart

Russell BD, Connell SD (2005) A novel interaction between nutrients and grazers alters relative dominance of marine habitats. Mar Ecol Prog Ser 289:5-11

Russell BD, Connell SD (2007) Response of grazers to sudden nutrient pulses in oligotrophic versus eutrophic conditions. Mar Ecol Prog Ser 349:73-80

Russell BD, Elsdon TS, Gillanders BM, Connell SD (2005) Nutrients increase epiphyte loads: broad-scale observations and an experimental assessment. Mar Biol 147:551-558

Sanz-Lázaro C, Belando MD, Navarrete-Mier F, Marín A (2011) Effects of wild fish and motile epibenthic invertebrates on the benthos below an open water fish farm. Estuar Coast Shelf Sci 91:216-223

Scherner F, Horta PA, de Oliveira EC, Simonassi JC, Hall-Spencer JM, Chow F, Nunes JMC, Pereira SMB (2013) Coastal urbanization leads to remarkable seaweed species loss and community shifts along the SW Atlantic. Mar Pollut Bull 76:106-115

Schönberg CHL (2016) Happy relationships between marine sponges and sediments - a review and some observations from Australia. J Mar Biol Assoc UK 96:493-514

Sickander O, Filgueira R (2022) Factors affecting IMTA (integrated multi-trophic aquaculture) implementation on Atlantic Salmon (*Salmo salar*) farms. Aquaculture 561:738716

Simkanin C, Davidson IC, Dower JF, Jamieson G, Therriault TW (2012) Anthropogenic structures and the infiltration of natural benthos by invasive ascidians. Mar Ecol 33:499-511

Smale DA (2013) Multi-scale patterns of spatial variability in sessile assemblage structure do not alter predictably with development time. Mar Ecol Prog Ser 482:29-41

Smale DA, Burrows MT, Evans AJ, King N, Sayer MDJ, Yunnie ALE, Moore PJ (2016) Linking environmental variables with regional-scale variability in ecological structure and standing stock of carbon within UK kelp forests. Mar Ecol Prog Ser 542:79-95

Smale DA, Burrows MT, Moore P, O'Connor N, Hawkins SJ (2013) Threats and knowledge gaps for ecosystem services provided by kelp forests: a northeast Atlantic perspective. Ecol Evol 3:4016-4038

Smale DA, Pessarrodona A, King N, Burrows MT, Yunnie A, Vance T, Moore P (2020) Environmental factors influencing primary productivity of the forest-forming kelp *Laminaria hyperborea* in the northeast Atlantic. Sci Rep 10:12161

Smith AK, Ajani PA, Roberts DE (1999) Spatial and temporal variation in fish assemblages exposed to sewage and implications for management. Mar Environ Res 47:241-260

Steneck RS, Graham MH, Bourque BJ, Corbett D, Erlandson JM, Estes JA, Tegner MJ (2002) Kelp forest ecosystems: biodiversity, stability, resilience and future. Environ Conserv 29:436-459

Strain E, White C, Hartog M, Hortle J, Coutts A, Brasier M, Hadley S, Ross J (2023) The Storm Bay Observing System: An evaluation of the sampling parameters and design for assessing the performance of salmon aquaculture. FRDC Project No. 2018/131. Institute for Marine and Antarctic Studies, University of Tasmania, Hobart

Strain EMA, Thomson RJ, Micheli F, Mancuso FP, Airoldi L (2014) Identifying the interacting roles of stressors in driving the global loss of canopy-forming to mat-forming algae in marine ecosystems. Glob Change Biol 20:3300-3312

Strain PM, Hargrave BT (2005) Salmon aquaculture, nutrient fluxes and ecosystem processes in southwestern New Brunswick. In: Hargrave BT (ed) Environmental Effects of Marine Finfish Aquaculture. The Handbook of Environmental Chemistry, volume 5M. Springer, Berlin, p 29-57

Stuart-Smith R, Barrett N, Crawford C, Edgar G, Frusher S (2008) Condition of rocky reef communities: A key marine habitat around Tasmania. NRM/NHT Final Report. Tasmanian Aquaculture and Fisheries Institute, Hobart

Stuart-Smith RD, Edgar GJ, Stuart-Smith JF, Barrett NS, Fowles AE, Hill NA, Cooper AT, Myers AP, Oh ES, Pocklington JB, Thomson RJ (2015) Loss of native rocky reef biodiversity in Australian metropolitan embayments. Mar Pollut Bull 95:324-332

Sward D, Monk J, Barrett N (2019) A systematic review of remotely operated vehicle surveys for visually assessing fish assemblages. Front Mar Sci 6:134

Sward D, Monk J, Barrett NS (2022) Regional estimates of a range-extending ecosystem engineer using stereo-imagery from ROV transects collected with an efficient, spatially balanced design. Remote Sens Ecol Conserv 8:105-118

Teagle H, Hawkins SJ, Moore PJ, Smale DA (2017) The role of kelp species as biogenic habitat formers in coastal marine ecosystems. J Exp Mar Biol Ecol 492:81-98

Tyrrell MC, Byers JE (2007) Do artificial substrates favor nonindigenous fouling species over native species? J Exp Mar Biol Ecol 342:54-60

Valentine JP, Jensen M, Ross DJ, Riley S, Ibbott S (2016) Understanding broad scale impacts of salmonid farming on rocky reef communities. FRDC Project No. 2014/042. Fisheries Research and Development Corporation, Canberra

Vitousek PM, Aber JD, Howarth RW, Likens GE, Matson PA, Schindler DW, Schlesinger WH, Tilman DG (1997) Human alteration of the global nitrogen cycle: sources and consequences. Ecol Appl 7:737-750

Wernberg T, Campbell A, Coleman MA, Connell SD, Kendrick GA, Moore PJ, Russell BD, Smale DA, Steinberg PD (2009) Macroalgae and temperate rocky reefs. In: Poloczanska ES, Hobday AJ, Richardson AJ (eds) A Marine Climate Change Impacts and Adaptation Report Card for Australia 2009. NCCARF, Perth, Western Australia

Wernberg T, Goldberg N (2008) Short-term temporal dynamics of algal species in a subtidal kelp bed in relation to changes in environmental conditions and canopy biomass. Estuar Coast Shelf Sci 76:265-272

Wernberg T, Russell BD, Moore PJ, Ling SD, Smale DA, Campbell A, Coleman MA, Steinberg PD, Kendrick GA, Connell SD (2011) Impacts of climate change in a global hotspot for temperate marine biodiversity and ocean warming. J Exp Mar Biol Ecol 400:7-16

Wernberg T, Smale DA, Tuya F, Thomsen MS, Langlois TJ, de Bettignies T, Bennett S, Rousseaux CS (2013) An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. Nat Clim Change 3:78-82

White CA, Bannister RJ, Dworjanyn SA, Husa V, Nichols PD, Dempster T (2018) Aquaculture-derived trophic subsidy boosts populations of an ecosystem engineer. Aquacult Environ Interact 10:279-289

White CA, Bannister RJ, Dworjanyn SA, Husa V, Nichols PD, Kutti T, Dempster T (2017) Consumption of aquaculture waste affects the fatty acid metabolism of a benthic invertebrate. Sci Total Environ 586:1170-1181

White C, Brasier M (2021) Rapid visual assessment surveys on rocky reefs in the Derwent Estuary. Institute for Marine and Antarctic Studies, University of Tasmania, Hobart

White C, Hartog M, Brasier M, Ross J (2022) Rapid visual assessment of rocky reef assemblages in Port Arthur. Institute for Marine and Antarctic Studies, University of Tasmania, Hobart

White C, McAllister J, Johnson O, Mundy C, Ross J (2021) Assessment of reef condition in the southern D'Entrecasteaux Channel. Institute for Marine and Antarctic Studies, University of Tasmania, Hobart

Woodcock SH, Strohmeier T, Strand Ø, Olsen SA, Bannister RJ (2018) Mobile epibenthic fauna consume organic waste from coastal fin-fish aquaculture. Mar Environ Res 137:16-23

Worm B, Lotze HK, Boström C, Engkvist R, Labanauskas V, Sommer U (1999) Marine diversity shift linked to interactions among grazers, nutrients and propagule banks. Mar Ecol Prog Ser 185:309-314

Worm B, Sommer U (2000) Rapid direct and indirect effects of a single nutrient pulse in a seaweed-epiphyte-grazer system. Mar Ecol Prog Ser 202:283-288

Wu RSS (1995) The environmental impact of marine fish culture: Towards a sustainable future. Mar Pollut Bull 31:159-166

Yang LH, Bastow JL, Spence KO, Wright AN (2008) What can we learn from resource pulses? Ecology 89:621-634

Appendix 1

Temperate rocky reef responses to nutrient enrichment and sedimentation

Table 1: Common temperate reef ecosystem responses to organic enrichment and sedimentation (Ross et al. 2021)

Type	Response	Location (reference)
Dissolved nutrient enrichment		
Algae	Increased growth of turfing algae	South Australia (Connell et al. 2008, Falkenberg et al. 2012)
	Increased density of epiphytic cover on macroalgae	SE Australia (Oh et al. 2015), Western Norway (Haugland 2019)
	Increased density of filamentous green algae	Southern Norway (Bokn et al. 2003), Western Norway (Haugland 2019), SE Australia (Oh et al. 2015)
	Loss of perennial/ canopy-forming species	Baltic Sea (Worm et al. 1999), South Australia (Gorman et al. 2009)
	Loss of species diversity	Baltic Sea (Worm et al. 1999), SW Atlantic (Scherner et al. 2013)
	Increased biomass of rapid growth macroalgae	Japan (*Saccharina*, Agatsuma et al. (2014)), SE Australia (*Undaria*, Carnell and Keough (2014)), California (*Macrocystis*, Hernández-Carmona et al. (2001))
Fish & mobile invertebrates	Increases in herbivorous species	Baltic Sea (Hillebrand et al. 2000), NW Atlantic (Lotze et al. 2001), South Australia (Russell & Connell 2005, Falkenberg et al. 2014)

Type	Response	Location (reference)
Sedimentation		
Algae	Inhibition of growth or recruitment of sensitive species	South Australia (Irving & Connell 2002, Connell et al. 2008), Mediterranean (Claudet & Fraschetti 2010), Chile (Muth et al. 2017)
	Mortality through smothering of sensitive species	Western Mediterranean (Airoldi et al. 1995, Airoldi & Cinelli 1997), South Australia (Irving & Connell 2002).
	Trapping of sediment by turf species	Western Mediterranean (Airoldi et al. 1995, Airoldi et al. 1996)
Fish & mobile invertebrates	Increases in opportunistic species	NE Atlantic (Echavarri-Erasun et al. 2007), Mediterranean (Fernandez-Jover et al. 2008), Western Norway (White et al. 2018)
	Community changes in filter feeders	NE Atlantic (Echavarri-Erasun et al. 2007), Australia (Schönberg 2016)
	Community changes in fish species	SE Australia (Smith et al. 1999), Mediterranean (Guidetti et al. 2003), Norway (Dempster et al. 2009)
Combined effects		
Algae	Loss of perennial/canopy-forming macroalgae	NW Mediterranean (Benedetti-Cecchi 2001, Mancuso et al. 2018), Sweden (Eriksson et al. 2002), South Australia (Connell et al. 2008), SE Australia (Coleman et al. 2008), SW Atlantic (Scherner et al. 2013)
	Increases in turfing algae	NW Mediterranean (Benedetti-Cecchi 2001), Sweden (Eriksson et al. 2002), South Australia (Gorgula & Connell 2004, Connell et al. 2008)
Fish & mobile invertebrates	Increases in abundance of smaller, faster growing species	SE Australia (Stuart-Smith et al. 2015, Ling et al. 2018)
	Reduced biomass	SE Australia (Stuart-Smith et al. 2015)
	Reduced species richness	SE Australia (Stuart-Smith et al. 2015), Global b(McKinley & Johnston 2010)

UNIVERSITY of TASMANIA

IMAS

Institute for Marine and Antarctic Studies