Marine Pollution Bulletin 80 (2014) 250–262

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Spatial and temporal dynamics in macrobenthos during recovery from salmon farm induced organic enrichment: When is recovery complete?

Nigel B. Keeley [a,b,*], Catriona K. Macleod [b], Grant A. Hopkins [a], Barrie M. Forrest [a]

[a] Cawthron Institute, Nelson 7010, New Zealand
[b] Tasmanian Aquaculture and Fisheries Institute, University of Tasmania, Taroona, Tasmania, Australia

ARTICLE INFO

Keywords:
Benthic ecology
Fallowing
Aquaculture
Remediation
Parallelism
BACI

ABSTRACT

This study documents eight years of benthic recovery at a highly impacted salmon farm. Substantial recovery occurred in the first 2 years, and was assessed to be complete after ~5 years. However, minor differences were still evident, along with some on-going benthic instability, attributable to medium-scale spatial movements and successional patterns of macrobenthos. Quantifying the endpoint of 'recovery' proved challenging due to: lack of a widely accepted definition, inherent variability in recovering sediments, differing trajectories of impact and reference sites, and statistical challenges. More complex biotic indices and metrics incorporating multiple variables were the most robust indicators. Statistical tests for 'parallelism' in the trajectories of Cage and Reference sites proved useful, but results were contingent upon how the method was applied, and should therefore be used in conjunction with data-visualisation methods. The study highlights the importance of a predetermined recovery endpoint, and using multiple indicators and a weight-of-evidence assessment approach.

1. Introduction

In marine benthic systems, impacts associated with organic enrichment are common and widespread, due to the prevalence of diffuse (e.g. land runoff, Diaz and Rosenberg, 2011) and point source (e.g. outfalls, Cardell et al., 1999; Taylor et al., 1998) discharges of anthropogenic wastes. Two considerations that are critical to evaluating the degree of impact on the environment are spatial scale and 'reversibility' of effects. Strong gradients of ecological succession are common, and the fundamental biological and chemical changes are generally well described (Gray et al., 1979; Kalantzi and Karakassis, 2006; Pearson and Rosenberg, 1978). However, there is less certainty associated with delineating the outer extent of enrichment effects, and the point in time at which a given location can be considered to have recovered from adverse effects; in part this uncertainty reflects natural variability (in both time and space) in environmental conditions (e.g. Hewit and Thrush, 2007; Hewitt et al., 1997; Thrush, 1991) and often a lack of understanding around what constitutes 'natural' conditions.

Finfish aquaculture is a significant point source of organic matter (via waste feed and fish faeces) to the marine environment. The primary discharges of waste feed and faeces typically result in highly enriched conditions in the immediate vicinity of the culture site (Brooks et al., 2002; Karakassis et al., 2000). In extreme cases, conditions immediately beneath the stocked cages can become anoxic, and virtually azoic (no animal life present), representing 'worst-case' conditions in terms of the duration of the pathway to recovery from impact (Keeley et al., 2012a; Pearson and Rosenberg, 1978). Such situations provide a good case study for understanding benthic enrichment and recovery processes (Keeley et al., 2012a). Additionally, the practice of site fallowing (temporarily retiring a site), that is often used for management purposes, provides a commercial incentive to better understand recovery, as the relative time-scales and processes of recovery and re-impact influence fallowing efficacy.

A wide range of farming conditions can be encountered in finfish aquaculture (i.e. differing farm type, farming intensity and age), which can occur across a range of environments. This situation means there will be a variation in the severity of impact at the start of fallowing (e.g. Borja et al., 2009), and variation in the capacity of a given site to recover from adverse effects. For example, it is generally accepted that high energy sites will recovery faster than low energy sites (Borja et al., 2010). Thus, it is not surprising that estimates of benthic recovery times vary greatly, ranging from weeks (Ritz et al., 1989) to >11 years (Wan Hussin et al., 2012). Several studies, especially those undertaken around smaller fish farms, have suggested that complete recovery (biological and chemical) can occur within 6 months of fallowing (Brooks et al., 2003), and in some cases within periods as short as 7–14 weeks (Brooks et al., 2003, cited in Brooks et al., 2004; Ritz

---

* Corresponding author at: Cawthron Institute, Nelson 7010, New Zealand. Tel.: +64 3 5393257; fax: +64 3 5469464.
E-mail address: nigel.keeley@cawthron.org.nz (N.B. Keeley).

0025-326X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.marpolbul.2013.12.008

et al., 1989). The general consensus from studies conducted over the medium-term (i.e. up to 3 years), is that marked improvement occurs in the first 6–12 months, but that recovery generally remained incomplete (Karakassis et al., 1999; Lin and Bailey-Brock, 2008; Macleod et al., 2008; Pereira et al., 2004; Villnas et al., 2011). Long-term (i.e. >3 years) studies of recovery are scarce; one that was conducted over 7 years estimated full chemical remediation would take 5.3 years and that biological remediation may take much longer (Brooks et al., 2004).

While the spread of these estimates will in part be attributable to the levels of impact at the point of fallowing and varying underlying environmental conditions, there are also multiple definitions of 'recovery' that are likely to contribute to the variances. Brooks et al. (2003) distinguished biological and chemical remediation; highlighting characteristically different recovery pathways, and providing specific criteria for recovery in each case. Other studies have emphasised differences between species-based, community recovery, and 'functional recovery' (Macleod et al., 2008); i.e. the point at which ecosystem function is re-established, but not necessarily with the same communities that were present pre-impact. It is generally assumed, that once functional recovery is achieved, an 'equilibrium state' will ensue (Macleod et al., 2008; Young et al., 2001). The concept of 'sustainable ecological succession', indicated by consistent presence and abundances of a limited number of species, has also been proposed as a measure of recovery (Ellis, 2003).

The difficulties associated with determining the point of recovery are further exacerbated by problems that arise when attempting to evaluate the question statistically. Many impact studies lack an appropriately defined assessment of pre-impact conditions, against which recovery can be quantitatively compared (Verdonschot et al., 2013). Consequently, recovery is assessed by comparison of conditions against selected spatial reference sites, that may in fact be naturally different, and the opportunity to evaluate the degree of change at a particular site is lost. Another problem with using spatial comparison as the reference point for recovery is that it may not always be appropriate to assume a strict equilibrium (or a single 'stable state') in biological systems (Beisner et al., 2003; Parker and Wiens, 2005). There may instead be a 'dynamic equilibrium' or shifting baseline (Macleod et al., 2008; Parker and Wiens, 2005; Verdonschot et al., 2013) and/or several possible alternative stable states (Beisner et al., 2003). Hence recovery should be assessed against a backdrop of both temporal and spatial variation.

Conventional beyond-BACI designs (e.g., Underwood, 1991, 1992) are considered to be one of the best approaches for monitoring recovery (Verdonschot et al., 2013). However, they tend to be resource intensive, requiring both multiple reference sites, and multiple randomly timed samplings within each specified time window. Few multi-year monitoring programs are initiated with this level of sampling effort in place, and maintaining such a design over a long time-frame is uncommon as the cost can be prohibitive. In addition, although beyond-BACI designs clearly partition the multiple sources of variation, the design is premised upon there being two fixed periods, 'before' and 'after' (e.g., Aguado-Giménez et al., 2012), whereas in most long-term datasets time is often a continuous variable that may have a non-linear response. Therefore, with a beyond-BACI approach it can be difficult to directly address the questions "was recovery complete?" and if so, "when did it occur?".

Recovery can be conceptually defined as occurring when the impacted resource reaches the level at which it would have been, had it not been impacted in the first place. At that point, the influence of impact-related factors will have diminished to a situation where levels of the resource vary temporally in a natural way (Parker and Wiens, 2005 and U.S. Code of Federal Regulation, 2001). The concept of 'varying temporally in a natural' way implies an assumption of 'parallelism', whereby impact and reference sites will begin to respond similarly; for example, to wider oceanographic processes. This is useful statistically, and methods (based on the BACI approach) have been developed accordingly, which were used to assess recovery from the *Exxon Valdez* oil spill (Skalski et al., 2001). These methods appear to have broader applications, which we explore in this paper along with a variety of other indicators and approaches for evaluating the remediation process and exploring the concept of recovery 'end points'. Our analysis is based on a 10 year dataset that provides a baseline characterization of a highly impacted seabed beneath and adjacent to a salmon farm, which was followed by eight years of annual monitoring of the spatial and temporal patterns of recovery.

2. Methods

2.1. Study sites and sampling procedures

This study was conducted at a commercial Chinook salmon (*Oncorhynchus tshawytscha*) farm site located in the outer reaches of the Marlborough Sounds, New Zealand (Fig. 1). The farm was situated in a sheltered embayment over muddy-sand sediments (average mud content = 78–84%), in water depths ranging between 28 and 35 m, with relatively low current speeds (mid-water mean current speed $\approx 3\ \mathrm{cm\ s^{-1}}$).

The farm was fallowed in 2001 after approximately seven years of consistent and relatively intensive use (average feed usage of $\sim$180 mt month^{-1}). Benthic sampling was undertaken in the Austral spring (October/November) as follows: two years prior to fallowing in 1999 (T-2), immediately after the farm was fallowed in 2001 (T0), followed by annual monitoring until 2009 (T8), with the exception of 2008 when no sampling was undertaken. Seabed samples were collected beneath the site previously occupied by the cages ('Cage stations'), at 25 m intervals along a north-western transect ('Gradient' stations) running away from the farm, and at fixed Reference stations (Fig. 1). Not all sampling stations were sampled in every year; most notably, two reference sites were

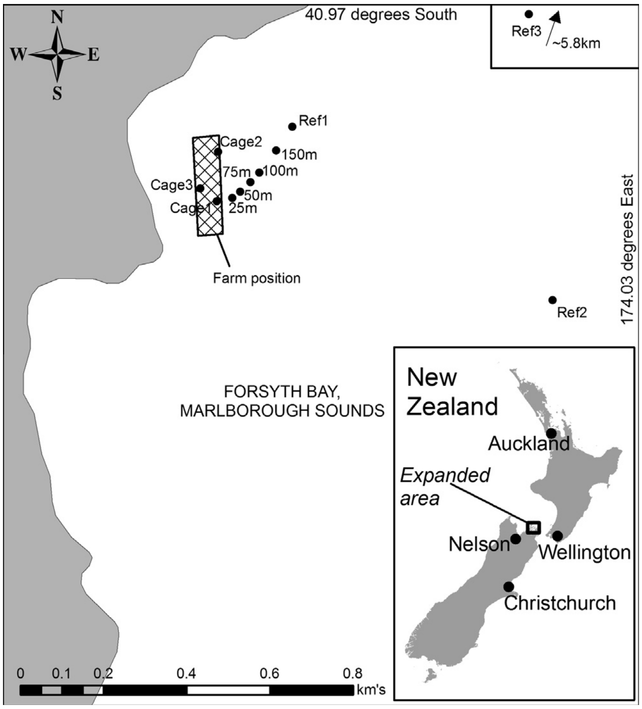

Fig. 1. Location of study site and sampling stations in relation to the farm.