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Comparison of three potential methods for accelerating seabed recovery beneath salmon farms

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ABSTRACT

Fish production from sea-cages is a globally significant and expanding industry, but farm production can be constrained due to localised but extreme seabed enrichment, which requires the farm to be rested for extended periods. This study compares the effectiveness of three potential techniques for accelerating seabed recovery in highly enriched sediments. Benthic changes induced by in-situ 'harrowing' (heavy raking of the seabed), 'irrigation' with oxygenated surface-water, and simulated sediment 'removal' are described in relation to passive recovery. Treatment effectiveness was assessed after four months based on physico-chemical and biological analyses of sediments, changes in benthic respiration in mesocosm experiments, and an assessment of the instantaneous water column effects induced during treatment. Results indicated significant sediment plumes associated with reduced dissolved oxygen levels, particularly during 'removal', but the magnitude and duration of the changes were negligible in an ecological effects context. Two treatments, 'harrowing' (HA) and 'irrigation' (IR), had little impact on seabed condition, particularly when compared with the natural recovery that occurred over the study period. Whereas, the 'removal' (RE) treatment (exposing the underlying sediment) significantly improved the physico-chemical and biological properties, and appeared to facilitate benthic recolonization. These findings suggest that, removal of degraded surface sediments has the potential to accelerate seabed recovery and can be a useful management strategy where trace metal concentrations (e.g. copper and zinc) have become unacceptably elevated. However, commercial-scale implementation would be contingent upon: i) further evaluation of water column effects associated with larger-scale treatments, and ii) the ability to safely dispose of the sediments.

1. Introduction

Sea-cage production of fish can be encumbered by undesirable levels of localised seabed enrichment due to the deposition of organic-rich particles, primarily comprising fish faeces (Buschmann et al., 2006; Gowen and Bradbury, 1987). In extreme cases, sediments immediately beneath a farm can become anoxic, defaunated, and may release toxic gases (e.g. hydrogen sulphide), which can also adversely impact the overlying water body (Brooks and Mahnken, 2003a). Farmed fish, which are unable to avoid the farm area, can become stressed, their health and growth may be impaired, and in extreme cases, mortalities may occur (Black et al., 1996; Kiemer et al., 1995). Degraded seabed conditions can also result in breaches of environmental standards (Wilson et al., 2009), requiring the farm to be removed or destocked for a prolonged period. In some cases, farmers opt to routinely shift the cages to rest the site in between cohorts (i.e. 'fallowing') to help ensure operational sustainability (Carroll et al., 2003). Such events can adversely impact production and profitability as well as industry reputations.

It is therefore clearly advantageous if the environmental goals could be achieved more rapidly, and in doing so, allow the farms to be restocked sooner. This is particularly pertinent in countries where permitted space for salmon farming is very limited (e.g., New Zealand; Banta and Gibbs, 2009) and having alternate sites to shift to is not an option. Hence, emphasis naturally shifts to potential mechanisms for enhancing the natural recovery process. The basic premise being that recovery may be accelerated by increasing both oxygen penetration into the sediments and carbon assimilation rates by reinstating the nitrification and denitrification processes, which are shut down when the sediment becomes anoxic (Bianchi, 2007). Several potential methods have been proposed that can be broadly classified as either physical

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(e.g. harrowing, re-suspension and removal), biological (e.g. the addition of detritivores) or chemical (e.g. oxygenation). Yet, surprisingly, there are very few studies that have tested the effectiveness of possible remediation approaches.

The physical approach of in-situ harrowing, has been tested, and has the potential to improve sediment quality, and with that, farm productivity (O'Connor et al., 1993). A subsequent review also identified the following methods as having potential: i) increasing oxygen penetration by drawing surface water through the sediments, ii) 'harrowing' the sediments, and iii) carbon capture by intercepting the particles with a subsurface structure before they reach the seabed (Eriksen et al., 2011). In lab-based mesocosm trials Eriksen et al. (2012) demonstrated the potential to increase oxygen penetration to the sediments, reduce the variability in sediment quality, and provided evidence to suggest that harrowing may improve the recovery process over a longer timeframe. These processes may be further enhanced in-situ, where oxygen exchange occurs naturally (with local hydrodynamics and large connected water body) and, importantly, biological recruitment and therefore bioirrigation and remediation is occurring, and not precluded as it is with incubation cores that can be effectively defaunated to begin with.

The effectiveness of any seabed remediation techniques should necessarily be considered in conjunction with the potential for the method itself to induce adverse environmental effects. For example, remediation techniques that involve disturbing large areas of seabed are likely to resuspend the enriched sediment, and in doing so, rapidly release a large flux of anaerobic organic material and associated contaminants (e.g., antifoulants or chemical therapeutants; Brooks and Mahnken, 2003b). This can adversely impact local water quality, and potentially, the wider ecology of the bay, and the farmed fish themselves (Burridge et al., 2008; Eriksen et al., 2011). Methods which are less likely to disturb the sediments have been trialled, such as in-situ bioremediation using micro-organisms (Vezzulli et al., 2004), opportunistic polychaetes (Kunihiro et al., 2008) and detritivorous fish (Katz et al., 2002). Some of which show clear remediation potential, however, there are obvious logistical and financial issues associated with up-scaling for commercial application (Eriksen et al., 2011).

The ability to accelerate seabed recovery also has broader social and environmental implications, as it may provide a means to shorten the pathway to full recovery after farming has ceased. While the benthic effects from organic enrichment have been shown to recover substantially within 1–2 years (Keeley et al., 2015; Macleod et al., 2008; Villnas et al., 2011), reverting to a natural functional state can take much longer (Brooks et al., 2004; Keeley et al., 2014; Pereira et al., 2004). There are also other farm-derived contaminants associated with the sediments that may have even longer recovery profiles. Copper and zinc are commonly found in undesirably elevated concentrations due to their historical use in antifouling on nets and as a fish feed supplement (respectively), and their propensity to bind with organically enriched sediments (Batley and Simpson, 2009). Copper in particular, is considered reasonably conservative once bound in the sediments (Sneddon et al., 2012) and buried (and therefore unable to be transported), and consequently, remediation of those constituents presents its own challenges and is an important adjunct to biological recovery.

In this study three potential remediation methods were selected for in-situ testing: harrowing (akin to terrestrial methods), irrigation of sediment with oxygenated surface waters (both based largely on recommendations of Eriksen et al., 2012) and the simulated removal of surface sediments. The objective was to evaluate the effectiveness of each of the chosen treatments in terms of the potential to: 1) accelerate benthic recovery from a highly enriched state, and 2) whether the approach has the potential to adversely impact the water column (and wider environment) through resuspension. The findings are then used to make management recommendations in relation to sediment remediation, specifically providing guidance on the employment of appropriate approaches for implementation at a commercial scale.

2. Methods

2.1. Study site

The study was conducted at a 1.2 Ha "low-flow" (average current speeds 3.0–3.4 cm s^{-1}) salmon farm situated in the Marlborough Sounds New Zealand. Water depth across the site ranged from 32 m to 34 m and the substrate comprised mud/sand with overlying patches of biofouling (as a result of mussel drop off from the farm). The site was fallowed (unoccupied) for four months prior to commencing the study, following 13 months of relatively intensive use (approx. 160 t feed/month). Annual environmental surveys show that the site was very highly impacted two years' prior, following a period of intensive use (Keeley et al., 2015). At the start of this study, the farm was still in a highly enriched sate with blackened, flocculent organic sediments, a severely impoverished macrofauna and with a white bacterial mat covering much of the sediment surface.

2.2. Remediation treatments and experimental design

Eight experimental field plots (~15 m^2) were haphazardly arranged within the most enriched area (i.e. previously beneath the farm, Fig. 1), and randomly assigned, with duplicates, to each of the four remediation approaches. The treatments were: untreated natural recovery (plots 'UT1, UT2'); repeated irrigation and oxygenation (plots 'IR1, IR2'); repeated harrowing (plots 'HA1, HA2'); and removal of enriched sediment layer by simulated dredging (plots 'RE1, RE2'; Table 1). The RE was a one-off treatment, whereas HA and IR were treated three times: day 0, 42 and 68. Natural un-impacted reference plots (natural reference plots 'Ref1, Ref2') were also established outside of the farmed to allow for assessment of any natural variations in environmental conditions that might influence the outcome. Each plot was individually labelled after the initial treatment: the treated area ('plot') was marked out on the seabed by divers using ropes and stakes and a small mooring block with subsurface and surface floats was placed alongside each plot with GPS coordinates recorded to enable the same area of seabed to be sampled each time.

The harrowing (HA) and irrigation (IR) treatments were selected based primarily on recommendations of Eriksen, Macleod, Ross (2012). The RE treatment was added specifically to consider the effect of removing the upper layer of highly enriched sediments (Table 1). The initial plan was to remove the sediment using a dredge, but significant logistical and compliance issues associated with employing a commercial dredge for such a small-scale trial, and with the subsequent disposal of the dredge spoil, prohibited this option.

The 'pilot-scale' of the treatment plots (approx. 15 m^2) was chosen such that it was large enough to allow: i) the remediation techniques to be practically evaluated in-situ using semi-industrial sized equipment, ii) three sets of replicate cores could be haphazardly collected at each sampling occasion without being compromised by previous sampling events, and ii) the sampling to induce a level of disturbance that would be somewhat indicative of commercial scale activities. These requirements were balanced against the practical and logistical constraints and a requirement that the experimental activities needed to present a low risk and be unlikely to produce bay-wide water column effects during treatment. Resource Consent was obtained from the local regulatory body to carry out the trials. Descriptions of the treatment methods can be found in Table 1.

The initial survey provided the baseline data against which temporal change was assessed. Thirteen near-bottom water column samples were collected from across the site to characterise the conditions (see Day 0, Section 2.4). Triplicate sediment samples were collected from within each of the plots immediately prior to the initial treatment (Day 0). To help account for the significant across-site heterogeneity that was observed during the initial survey, in the final survey (i.e. at the conclusion of the study, Day124) triplicate (3) sediment samples were collected both from within and adjacent to (i.e. 6 samples in total) all