Environmental effects of sea-based farming of paua (*Haliotis* spp.) and kina (*Evechinus chloroticus*)

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CONTENTS

1. Summary

The potential impacts of sea-based farming of paua (*Haliotis* spp.) and kina (*Evechinus chloroticus*) are evaluated. Three potential impacts were identified: decreased aesthetic amenity, increased sedimentation, and enhanced deposition of organic matter. Of these impacts, enhanced deposition of organic matter was assessed as direct, measurable, and comparable with the known impacts of intensive culture of other marine animals such as mussels and salmon.

A review of the feeding biology of paua and kina shows that these herbivorous animals are inefficient feeders and high daily feeding rates (about 5% of their body weight per day) are required to maintain growth in culture. Of food that is ingested, half may be egested as faeces. Specified feeding rates are lower for artificial foods but the egestion of organic material with these diets is greater than with natural diets.

The main impact identified was the deposition of organic wastes on sea floor sediments beneath and in the immediate vicinity of the farm. Estimated deposition rates were greater (more than 126 $\mathrm{g.m^{-2}.d^{-1}}$) when artificial diets were used compared with the use of natural diets (seaweeds) (more than 90 $\mathrm{g.m^{-2}.d^{-1}}$). These deposition rates are similar to those documented for intensive salmon culture. The impacts of organic deposition on benthic communities beneath salmon farms are well documented and include anoxia and mortality of benthos. Similar detrimental effects may be expected for paua and kina farms given realistic stocking densities and conservative feeding regimes.

2. Introduction

Aquaculture offers the potential for increasing harvests of marine species in New Zealand because of the availability of relatively clean, sheltered waters. Elsewhere, the development of aquaculture has accompanied the decline of wild fisheries. In Japan and Taiwan, aquaculture accounts for most of the production of marine species from inshore habitats.

New Zealand already has a thriving aquaculture industry based on the mussel *Perna canaliculus* and production from sea farms in the Marlborough Sounds has increased 10 fold in the last decade. Salmon farming is practised off Stewart Island, scallop reseeding of natural habitat has been successful, and there is interest in farming high-value species such as paua and rock lobster.

Intense cultivation of marine animals can disturb coastal ecosystems. The adverse impact of cage farming of salmon and other fish species is now well established. Mussel farming has been shown to affect benthic communities, and it is likely that the high-density cultivation of other species will create measurable environmental impacts.

In this report, I consider the potential impact of high-density farming of paua and kina following expression of interest in their sea-based farming. I compare potential impacts under realistic farming regimes to typical mussel and salmon farming operations. My review includes a summary of the feeding biology of paua and kina and the potential effects caused by feeding regimes in sea-based farms for these animals. These potential effects will be compared with actual effects measured for mussel and salmon farms so that some evaluation of the potential environmental impact of sea-based farming of paua and kina may be undertaken.

3. Feeding biology of paua and kina

Paua and kina are herbivorous and feed mainly on seaweeds.

3.1 PAUA

Paua are gastropod molluscs of the genus *Haliotis* and are commonly referred to as abalone. Studies of the feeding biology of abalone, including paua (*Haliotis iris* and *H. australis*), show that they prefer red seaweeds (division

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[1] The feeding biology of paua (*Haliotis iris* and *H. australis*) was studied by Poore (1972) (ref. 1). He showed that while paua preferred red algae when provided with mixed diets in aquaria, in the wild, *H. iris* fed almost exclusively on *Macrocystis pyrifera.*

Rhodophyta) to brown seaweeds (division Phaeophyta)[1]. However, in their natural habitat, the composition of seaweeds in the diet of paua generally reflects the distribution and abundance of local seaweeds[2]. Some studies suggest that the acceptance or rejection of brown seaweeds by abalone depends on the concentration of polyphenolic compounds. The concentration of these compounds varies within and among species of brown seaweeds and the compounds may have anti-herbivore properties[3]. The results of other studies suggest that food toughness is a primary determinant of food preference in abalone[4]. Abalone lack hardened teeth on the radula[5], and are morphologically constrained to consume seaweeds that are soft rather than leathery[6].

Macrocystis pyrifera, a seaweed important in the diet of paua and other species of abalone, is a soft textured seaweed compared with tougher fucoid seaweeds such as *Carpophyllum* spp. *Macrocystis* is the main food source for abalone culture in the U.S.A. and has been identified as a prospective food source for paua culture operations in New Zealand[7]. Other seaweeds suitable for use in paua culture include the red seaweeds *Pterocladia* spp. and *Gracilaria* spp.[8]

Abalone, like other gastropod molluscs, are inefficient feeders[9]: more than half the food ingested can be lost as faeces[10]. In culture, abalone are usually fed seaweed at a daily rate equivalent to 5% or more of the total wet weight of abalone[11].

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[2] A number of studies of different species of abalone have shown a correspondence between the composition of diets and the species composition of seaweeds in the habitat of abalone, e.g. Cox (1962) (ref. 2), Leighton & Boolootian (1963) (ref 3), Shepherd (1973) (ref. 4), Barkai & Griffiths 1999 (ref. 5). Poore (1972) (ref 1) demonstrated similar opportunistic selection of food by paua.

[3] Steinberg (1989) (ref. 6) and Shepherd & Steinberg (1992) (ref. 7) presented arguments for chemical defence of brown seaweeds against abalone.

[4] McShane et al. (1994a) (ref 8) showed that feeding rates of *H. rubra* varied inversely with the toughness of natural and artificial diets.

[5] The radula functions like a toothed tongue in masticating seaweed.

[6] A general discussion of the mechanical aspects of feeding in herbivorous molluscs is provided by Steneck & Watling (1982) (ref. 9).

[7] *Macrocystis pyrifera* is among the fastest growing plants in the world. It is favoured by abalone culturalists because it is easily cropped from the surface and is readily consumed by abalone (Ebert & Houk (1984) (ref. 10)).

[8] Cultured paua grow particularly well on *Gracilaria* spp. (Tong et al. (1992) (ref. 11)).

[9] The general feeding biology and metabolism of marine gastropod molluscs is reviewed by Bayne & Newell (1983) (ref 12).

[10] McShane et al. (1994 (ref 8) and Barkai & Griffiths (1988) (ref. 5) provided information on assimilation of seaweed diets by abalone.

[11] Ebert & Houk (ref. 10) described a general protocol for feeding *H. rufescens* in culture. The daily requirement of food appears consistent among species of abalone. Information on the feeding requirements of paua was provided by Tong et al. (1992) (ref 11) who suggested that juvenile paua can eat up to 30% of their whole body weight per day.

Recent research has developed artificial diets for abalone. This research has been prompted by the often poor growth of cultured abalone on natural diets and the restrictions on the harvest of seaweeds from natural habitats. Artificial diets are expensive and can cause adverse bacterial growth[12]. Nonetheless, recent trials have shown favourable growth rates for abalone grown on artificial diets. Food conversion rates (food consumed in relation to wet weight gained) can be high for artificial diets (1.5:1) in relation to natural diets (2-4:1 for seaweed dry weight)[13] and it is likely that the use of artificial diets in abalone culture will increase[14].

3.2 KINA

Kina *(Evechinus chloroticus)* are sea urchins and they consume mainly drift seaweed, but they also graze intact plants[15]. Some species of sea urchin, including kina, maintain large areas of reef free of large seaweeds by grazing[16]. Kina prefer the laminarian seaweed *Ecklonia radiata* when fed a mixed diet. However kina, like paua, are opportunistic feeders and will consume other species of seaweed in relation to their abundance[17].The daily feeding rate for kina is similar to that of paua[18].

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[12] Prices for artificial foods currently range between $5 and $10 per kg (Promak Technology's brochure for "Makara" artificial food). The Japanese have been using artificial diets in abalone culture for many years, but only in the winter months because high temperatures in summer are associated with adverse bacterial growth (S. Kikuchi, Tohoku Regional Research Laboratory, Tohoku, Japan, personal communication).

[13] Food conversion efficiencies for *H. rubra* were reported for natural diets (Gorfine & King (1991) (ref. 13)) and natural diets (McShane et al. (1994a) (ref 8)). [14] Results of trials of various artificial diets on the growth of abalone were reported by Hahn (1989) (ref. 14), Morrison & Whittington (1991) (ref. 15), and Gorfine & King (1991) (ref. 13).There are a number of research programmes currently in progress developing abalone diets for abalone e.g. Maguire et al. (1993) (ref. 16).

[15] Schiel (1992) (ref 17) described the feeding biology of kina.

[16] A general overview of the effects of grazing by sea urchins on subtidal ecosystems was provided by Lawrence (1975) (ref 18). Schiel & Foster (1986) (ref 19) and Andrew (1988) (ref. 20) described the effects of grazing by kina.

[17] *Ecklonia radiata* is absent in some localities where kina are abundant e.g. the Chatham Islands.

[18] Schid (1992) (ref 18) recorded rates of consumption of seven common seaweeds by kina in aquaria. Consumption rates varied among species of seaweed but ranged from 0 to 17% of the wet weight of kina.

4. Sea-based farming and environmental impacts

The intense cultivation of animals in near-shore habitats can have unfavourable impacts on marine environments. Impacts include loss of aesthetic amenity by the presence of floating sea cages or other growing structures such as mussel lines; increased sedimentation accompanying current attenuation by submerged cages or other structures; and deposition of organic wastes from uneaten food and faecal production[19].

Aesthetic amenity is difficult to define objectively. In this review, aesthetic amenity and the potential negative effects of sea-farming will not be evaluated as an impact. Enhanced sedimentation caused by the attenuation of water currents by submerged structures will vary according to the sediment concentration near sea farms and the current velocity. The main direct impact caused by sea farms is deposition of organic matter. In this review, I will assess the relative deposition of organic matter by intensive rearing of mussels, salmon, paua, and kina. The impacts of intense cultivation of mussels and salmon have been well described and are summarised briefly below.

4.1 MUSSELS

Mussels feed on suspended organic material (mainly phytoplankton) in the water column[20]. Long lines suspended vertically from the sea surface are an efficient way of promoting the growth of mussels. No extra food is required for mussels and most waste comes from particulate matter rejected by the mussel. These wastes or "pseudofaeces" can accumulate on the sea floor and increase the biological oxygen demand in sediments[21]. The alteration of the redox potential of sediments accompanying reduced oxygen levels in the surface layer of the sea bottom profoundly alters the sediment chemistry and can reduce the diversity of benthic fauna. However, the negative effects of mussel farms are generally localised and are usually minimal more than 50 m away. Accumulation of waste material is reduced with increasing current velocity.

In filter-feeding, mussels can remove substantial amounts of particulate matter from the water column. The filtration rate of mussels depends on various factors such as temperature or the amount of suspended particles in the wa-

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[19] Kautsky & Folke (1989) (ref 21) summarised the environmental and ecological limitations of seabased aquaculture.

[20] Mussels feed mostly on phytoplankton but also derive nutrients from detritus and small zooplankton (Carlson et al. (1984) (ref. 22)).

[21] A number of studies both in New Zealand (Kaspar et al. (1985) (ref. 23)) and elsewhere (Asmus & Asmus 1991 (ref 24); Selina (1993) (ref. 25) have shown altered sediment chemistry as a result of mussel farming.

ter[22]. Under intense cultivation, mussels can reduce the concentration of phytoplankton in the water column[23]. However, mussels can also promote the growth of phytoplankton by releasing nutrients such as ammonium into the water column[24].

Rates of sedimentation under mussel farms are enhanced because of the attenuation of nearshore currents by the mussel longlines[25]. Estimated rates of deposition of organic carbon as a result of intense cultivation of mussels range from 1 to 27 $g.m^{-2}. d^{-1}$ [26].

4.2 SALMON

The environmental impacts of sea-based farming of salmon are similar to those for mussels[27]. However, unlike mussels, salmon require feeding and high protein diets introduce an additional source of organic enrichment to marine ecosystems[28]. The major impact is the deposition of organic material directly beneath the fish farm. Such deposition increases biological oxygen demand and decreases species diversity[29]. Deposition of organic wastes beneath a fish farm might be as high as 10 kg. $m^{-2}. y^{-1}$.

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[22] Bayne (1976) (ref. 26) reviewed the feeding biology of mussels.

[23] Asmus & Asmus (1991) (ref. 24) showed that phytoplankton biomass over an intertidal mussel bed was reduced by 37%.They showed that the higher the phytoplankton concentration, the higher was the uptake by the mussel bed.

[24] The release of nitrogen by mussels was examined by Dame & Dankers (1988) (ref. 27) and Asmus & Asmus (1991) (ref. 24). The results suggest that the potential primary production induced by the nutrient release of mussel farms is higher than the uptake of phytoplankton by the mussels.

[25] The increased drag of mussel longlines can radically slow ocean currents just as seaweeds attenuate nearshore water movement (Jackson & Winant (1983) (ref. 28)). The slowing of water flows causes increased rates of deposition of fine sediments which are usually maintained in suspension by near shore currents (Eckman et al. (1989) (ref 29)).

[26] Dahlback & Gunnarson (1981) (ref 30) examined the effects of sedimentation associated with mussel farms.

[27] As summarised by Kautsky & Folke (1989) (ref. 21).

[28] Beveridge (1987) (ref 31) reviewed the cage farming of a range of species including salmon.

[29] The negative effects of salmon cage farming are now well established (Brown et al. (1987) (ref 32), Gower & Bradbury (1987) (ref 33), Parsons et. al. (1990) (ref 34), O'Connor et al. (1993) (ref 35)). These studies have shown decreased oxygen levels and increased hydrogen sulphide levels in the sediments beneath salmon farms. Typically, the benthos below fish farms is azooic and the sediments in the immediate vicinity (within a few metres) are dominated by a few species of opportunistic polychates characteristic of polluted sediments. These general effects also occur in salmon farms in New Zealand (Kaspar et al. (1988) (ref 36)).

The rate of accumulation of organic material beneath fish farms depends on water currents and fish farms are usually sited in relatively sheltered waters. The effects of intense fish farming have been compared with the effects of domestic sewage effluent i.e. the impact can be intense but localised[30].

Some of the adverse effects of fish farming can be reversed by harrowing or raking the sediments under sea cages[31].

5. Potential effects of sea-based farming of paua and kina

I could find no published literature on the environmental impact of abalone or sea urchin farming. Many of the existing culture facilities are land-based farms. In Japan, sea farming involves the seeding of natural reefs with abalone which have been reared in land-based farms[32]. Pen culture of sea urchins has begun in some countries[33], but the greater commercial worth of abalone and the high costs of land-based farming have stimulated interest in the sea-farming of abalone.

Because of the similar nutritional biology of paua and kina, the similar grow-out technology (sea cages or barrels), and the similar siting requirements (relatively sheltered coastal waters), the potential impact of intense cultivation of kina may be expected to mimic that of paua.

5.1 SEA-BASED FARMING METHODS

Sea-based abalone farms and prospective and existing sea farms for paua employ barrels suspended from rafts or cages from the sea surface[34]. Generally, juveniles produced by shore-based hatcheries are introduced to the barrels for on-growing to harvestable size (70 to 100 mm shell length). Barrels devel-

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[30] Brown et al. (1987) (ref. 32) cite deposition rates from salmon farms. More general effects of organic enrichment were reviewed by Pearson & Rosenberg (1978) (ref. 37).

[31] O'Connor et al. (1993) (ref 35) showed that regular raking of sediments under a salmon farm released gases from the sediment and dispersed organic material resulting in a sediment with a normal redox potential.

[32] Saito (1984) (ref 38) described the "ocean ranching" of abalone in Japanese waters.

[33] Community-based sea urchin pen culture was described by Juinio-Menez (1995) (ref 39). This involves the establishment of family/village based reserves in the form of sea pens where juvenile sea urchins can be grown and selectively harvested. Such sea farming offers low capital and maintenance costs. Shaw (1987) (ref. 40) summarised the rearing of larval and juvenile sea urchins.

[34] Ebert (1992) (ref. 41) and Walker (1991) (ref. 42).

oped for paua farming have an available surface area of about 7 m^{-2} [35]. Optimal stocking densities depend on the size of paua: 2500 per m^2 for individuals less than 15 mm long and about 250 per m^2 for individuals of harvestable size[36]. Similar grow-out systems and stocking densities would be used for the sea-farming of kina.

Below, I have evaluated the deposition rate of organic material for a paua farm of 100 000 individuals. I have expressed the deposition as rates per surface areas of farm. The deposition rates to the sea floor will depend on the configuration of the growing surfaces or barrels in the sea farm. A farm of 100 000 individuals would have a maximum annual production of about 7t (whole wet weight). In evaluating potential deposition rates, I made the following assumptions:

1. Growth rate determined by von Bertalanffy growth parameters, K = 0.2, L_∞ = 135. The growth rate is consistent with that reported for both cultured and natural populations of paua[37].

   The relationship between shell length in mm (*SL*) and weight (W) in g is $W = 0.00215 * SL^{2.418}$ [38].

2. Daily feeding rates for natural and artificial diets are 5% and 2% of the wet weight of the paua respectively[39].

3. All food provided is eaten[40].

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[35] Barrel culture of paua in New Zealand waters is outlined in promotional literature by Sea-Right Technology (P.O. Box 1790. Christchurch).

[36] Studies of the culture of Asian abalone show negative effects on growth and mortality if the stocking density is too high (Chen (1984) (ref 43)). Stocking densities of 8 mm individuals at 2000 per barrel were described for North American abalone (Ebert (1992) (ref 41)).

[37] Growth data were provided by McShane et al. (1994b) (ref. 44). Growth rates of paua in culture are about 25 mm/y over the first two years (G. Moss, Mahanga Bay, Wellington pers. comm.).

[38] McShane et al. (1994c) (ref 45) provided a general relationship for shell length and weight of paua.

[39] Feeding rates were provided for paua by Tong et al. (1994) (ref 11). They suggested much higher daily feeding rates but consumption rates for other species of abalone are about 5% of their total body weight per day (Ebert & Houk (1984), ref. 10) and McShane et al. (1994a) (ref. 8).

[40] In fact, there is likely to be uneaten food. However, in the scenario presented, a conservative daily feeding rate is used. If a higher feeding rate is used, as suggested by Tong et al. (1992) (ref. 11) (about 20% per day), there may be considerable wastage of uneaten food and increased faecal deposition rates over those shown in Table 1.

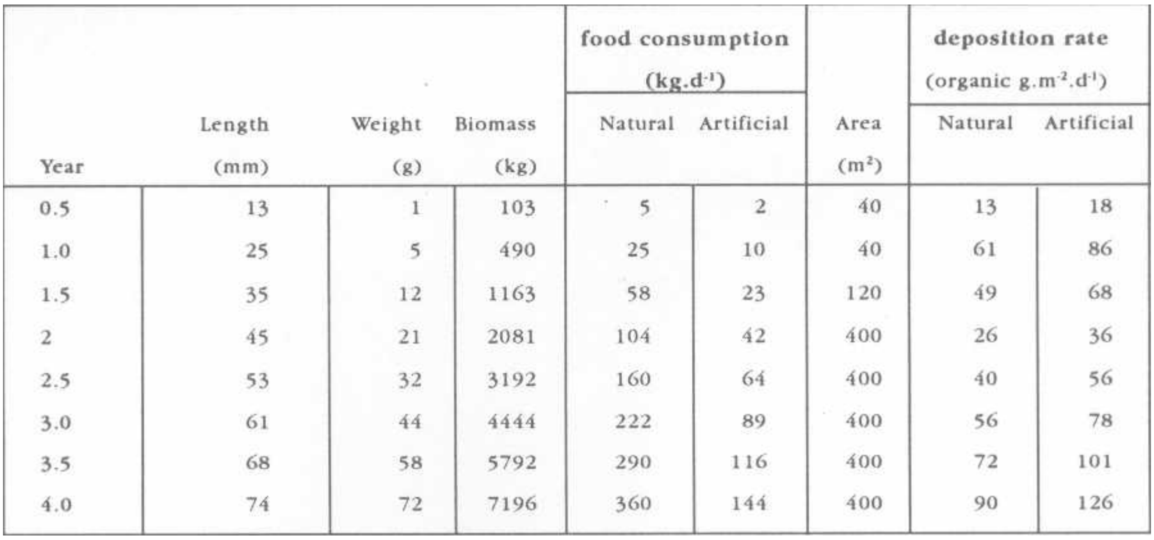
4. Organic content of natural diets is 20% of the wet weight of the diet[41]. Organic content of artificial diets is 70% of the dry weight of the diet (artificial diets are already dried to a low moisture content)[42].

5. Of food eaten, 50% is egested as faeces[43].

6. Stocking densities are 2500 per m^2 for individuals below 15 mm length and 250 per m^2 for individuals over 40 mm[44]. For barrel culture, this is equivalent to about 15 000 per barrel and 1700 per barrel respectively[45].

These assumptions may be used to examine the deposition rates from a paua farm over a 4 year period (Table 1). The estimated deposition rates will apply to a farm of any size with the nominated stocking densities.

Table 1. Deposition rates of organic material from the provision of natural and artificial diets to 100 000 paua cultivated over a four year period.



				food consumption ($kg.d^{-1}$)			deposition rate (organic $g.m^{-2}.d^{-1}$)	
Year	Length (mm)	Weight (g)	Biomass (kg)	Natural	Artificial	Area (m^2)	Natural	Artificial
0.5	13	1	103	5	2	40	13	18
1.0	25	5	490	25	10	40	61	86
1.5	35	12	1163	58	23	120	49	68
2	45	21	2081	104	42	400	26	36
2.5	53	32	3192	160	64	400	40	56
3.0	61	44	4444	222	89	400	56	78
3.5	68	58	5792	290	116	400	72	101
4.0	74	72	7196	360	144	400	90	126

The table shows that deposition rates of organic material are high and similar to those reported for intensive salmon farming. However, the estimated deposition rates are conservative because they are expressed in relation to surface area of the farm (estimated surface area of barrels) rather than rates per area of the sea floor.

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[41] Composition data for a range of seaweeds including *Macrocystis pyrifera* is given by McShane et al. (1994x) (ref. 8).

[42] Composition data for "Makara" artificial diets provided in promotional brochure by Promak Technology P/L (P.O. Box 444, Hawera, New Zealand). Moisture content of artificial foods is about 10% (from Nosan p/l, Yokohama, Japan promotional brochure).

[43] McShane et al. (1994x) (ref 8).

[44] Stocking densities suggested for abalone by Chen (1984) (ref. 43) and Ebert & Houk (1984) (ref 10).

[45] From the stated surface area of a Sea Right barrel. Promotional literature supplied by Sea-Right Technology (P.O. Box 1790, Christchurch).

At peak production, about 50 barrels are required for 100 000 individuals. In longline culture of two barrels per square metre, the surface area of sediment receiving the deposition is only about 25 square metres[46]. The uneaten food has not been included in the estimated deposition rates.

Thus, expressed as rates deposited to the seafloor, natural diets can produce 720 $g.m^{-2}.d^{-1}$ and artificial diets can produce 1008 $g.m^{-2}.d^{-1}$. These estimated deposition rates are much higher than those produced from intensive fish fanning (4 to 200 $g.m^{-2}.d^{-1}$)[47]. The table shows that deposition rates are one-third higher, on average, for artificial foods than those estimated for natural diets. Furthermore, the nitrogen content of artificial diets is much higher than that of natural diets[48]. The potential addition of nitrogen to the sediments beneath a paua farm is greater with the use of artificial foods than with natural diets. The estimated deposition rates with artificial or natural diets show that the potential impacts of sea-based farming of paua are therefore at least those of intensive salmon fanning, and at least five times higher than the estimated deposition rates from mussel farms[49].

The environmental impacts of localised organic deposition have been well documented[50]. The potential successional stages for paua farming are as follows:

1. Enhanced respiration of aerobic bacteria and deposit-feeding benthos accompanying increased levels of organic carbon in the sediment beneath the paua farm.

2. Decreased levels of oxygen in the sediment and a build up of anaerobic bacteria and benthos tolerant to low levels of oxygen.

3. Reduction of sulphate to hydrogen sulphide and nitrate to ammonium caused by decreased redox potential of sediments.

4. Release of hydrogen sulphide and ammonium from the sediments causing mortality of most of the infaunal and epifaunal species below the paua farm.

5. Azooic area beneath the paua farm and low species diversity in the immediate vicinity (within 20 m) of the farm. Biota dominated by opportunistic polychaetes such as *Capitella capitata.*

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[46] Promotional literature supplied by Sea-Right Technology gives information on barrel dimensions and configuration in longline culture.

[47] From deposition rates summarised in a review by Beveridge (1987) (ref 31).

[48] Artificial diets contain about 30 to 40% protein. The nitrogen content of seaweeds is relatively low. McShane et al. (1994a) (ref. 8) reported nitrogen levels of about 2% of the dry weight of *Macrocystis pyrifera*.

[49] Mussel longlines deposit organic carbon at rates up to 27 $g.M^{-2}.d^{-1}$ (Dahlback & Cunnarsson (1981) (ref 30)).

[50] Reviewed by Pearson & Rosenberg (1978) (ref. 37).

The effects may be modified by water movement and water temperature near the paua farm. Mild water movement and warm water temperatures may exaggerate the effects whereas strong water movement and cool water temperatures may ameliorate the effects[51].

6. Limiting the impact of sea-based paua farming

In the scenario assessed above, I assumed that the faecal production would be deposited on the sea floor below the farm. Paua farmers might remove waste products and uneaten food from barrels or other containers on a regular basis thus decreasing the deposition rate to the sediments. Paua farmers could rake or harrow the sediments beneath the farms on a regular basis. This practice has been shown to reduce the negative effects of salmon farming on the bottom sediments[52]. Alternatively, the paua farm might be sited in an area of high tidal flow so that organic wastes are dispersed. Water movement and bathymetry will interact to modify the effects of organic deposition from sea-based farms.

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