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Characterisation of water quality in effluents of land-based abalone farms in the Western Cape, South Africa

T. A. Probyn[1,*], M. Pretorius[2], K. Seanego[1], A. Bernatzeder[2]

[1]Aquaculture Research and [2]Sustainable Aquaculture Management, Department of Agriculture, Forestry and Fisheries, Private Bag X2, Vlaeberg 8018, Cape Town, South Africa

ABSTRACT: Effluent water quality was measured at 9 abalone (*Haliotis midae*) farms in 2 regional nodes (west and south) along the South African coastline. For most farms, effluent total suspended solids (TSS) exceeded the background reference level (80th percentile), and 3 did not comply with the 5 mg l^{-1} standard. Total ammonia nitrogen (NH_4^+) concentrations were mostly greater than reference levels but well below the 43 µmol N l^{-1} standard. Inflow-corrected concentrations of nitrate, nitrite and phosphate were low compared to NH_4^+ and would not pose a significant eutrophication risk. Similarly, the biochemical oxygen demand measured at 3 of the farms was low (median 1.31 mg l^{-1}). Abalone production-specific annual loads of TSS (334 kg per metric tonne [mt]), total N (20.3–38.1 kg N mt^{-1}) and total P (3.2–7.5 kg P mt^{-1}) agree with what has been found for different land-based aquaculture operations. These figures translate to N-based human population equivalents of 5.4–10.6 persons mt^{-1} for both regions. At the broader ecosystem level, the annual TSS loads calculated from 2013 production data of 43 mt yr^{-1} (west) and 369 mt yr^{-1} (south) are, respectively, 0.35 and 2.8% of that estimated for kelp erosion. Similarly, the dissolved inorganic N loads of 1.9 mt N yr^{-1} (west) and 9.4 mt yr^{-1} (south) are trivial by comparison with nitrate advected during upwelling. Local abalone farms have a relatively high specific C footprint — conservatively ~44 kg CO_2 kg^{-1} production. Our findings support a relatively low potential impact of farm effluents in this coastal upwelling environment.

KEY WORDS: Abalone farm · Effluents · Suspended solids · Nutrients · *Haliotis*

INTRODUCTION

Aquaculture has often received media criticism for practices that are perceived as unsustainable environmentally, over and above additional concerns related to food safety, animal welfare and social issues. Much of this criticism has been directed at operations that require feed inputs, such as finfish and shrimp farming. Molluscan shellfish, or more correctly bivalve, culture by way of contrast is often regarded as posing low environmental risk and, in fact, can provide certain ecosystem services, particularly in eutrophic waters (Hargreaves 2011). This favourable perception of bivalves is based primarily on the fact that they feed on naturally occurring seston which develops in response to nutrient inputs to coastal ecosystems (Burkholder & Shumway 2011). By virtue of their filter feeding pursuits, bivalves can serve to improve water quality in coastal embayments subject to excessive anthropogenic nutrient loads and concomitant development of phytoplankton blooms.

Land-based abalone *Haliotis* spp. farming differs from bivalve culture in that feed inputs are required, generally as seaweed or formulated diets. South Africa is currently a significant global producer of farmed abalone, behind only China and Korea (Troell et al. 2006, Cook 2014). The local industry is founded on land-based raceway systems, although

*Corresponding author: trevorp@daff.gov.za

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ranching and sea-based cages are currently being explored (DAFF 2014). Initially, the South African abalone farming industry was based largely on fresh seaweed (mainly kelp) feed, but recently artificial feed has assumed prominence. This shift in feeding strategy has implications for dissolved N release from raceways given the higher protein content of artificial feed (Troell et al. 2006, Naylor et al. 2011). Although much research has been undertaken on various aspects of abalone husbandry from broodstock conditioning to post-harvest handling, effluent quality and potential environmental impacts have not been studied in detail. Findings from the few studies that have been undertaken indicate elevated levels of suspended solids and nutrients, particularly ammonium, in effluents (Samsukal 2004, Yearsley 2007, P. J. Britz & B. P. Godfrey unpubl. specialist study). The requirement for high water quality by abalone and the release of effluents within the same water body as intake establishes the potential for site-specific environmental impact. Nevertheless, abalone farm effluents are regarded as relatively innocuous (ASC 2012), containing highly diluted levels of wastes and uneaten feed.

There are many examples of standards/guidelines that have been established for the protection of natural ecosystems that could be applied to pipeline discharges. Nationally, the former Department of Water Affairs and Forestry (DWAF 1995) provided guidelines for the protection of the natural marine environment, both as numerical values and as narrative statements. Australia and New Zealand have developed a comprehensive set of guideline trigger values for a wide range of physical and chemical stressors, as well toxicants in different categories of aquatic ecosystems (ANZECC & ARMCANZ 2000). The preferred approach in setting these guidelines is to use local biological and/or ecological effects data, but where these are not available, local reference data may be used. This approach adopts the 80th percentile of a reference condition as a conservative guideline for stressors that may cause problems at high concentrations. Reference system data are obtained from the same or a similar ecological system, in an undisturbed condition. These guidelines are applied as low-risk trigger levels that will initiate further site-specific investigation should they be exceeded.

There are considerably fewer examples of water quality guidelines specific to land-based aquaculture facilities. Of particular relevance to the present study are the abalone standards adopted by the Aquaculture Stewardship Council (ASC 2012) as the basis for a certification programme. The standards provide principles, criteria, indicators and standards for addressing a number of potentially negative social and environmental aspects of abalone aquaculture. With regard to discharges from land-based abalone farms, the most important indicators of water quality are total suspended solids (TSS) and total ammonium N (NH_4^+). Limits applied to effluents at the point of discharge are an annual median concentration of <5 mg l^{-1} TSS compared to inflow and <600 µg l^{-1} NH_4^+ (43 µmol N l^{-1}) in effluents. The NH_4^+ limit is apparently uncorrected for influent levels, in contrast with TSS. If measured concentrations in effluents comply with these standards, then effluent sampling is all that is required. Otherwise, receiving water concentrations beyond a zone of initial dilution (mixing zone) need to be considered.

This study builds on preliminary studies of effluent quality for local land-based farms (Samsukal 2004, Yearsley 2007) in an attempt to identify potential environmental stressors of concern both at the local scale and the broader coastal ecosystem level. The present results for end-of-pipeline discharges are compared both with reference percentile data, as in the Australian/New Zealand approach (ANZECC & ARMCANZ 2000), and with the abalone dialogue standards (ASC 2012).

MATERIALS AND METHODS

Sampling

Sampling was limited to the Western Cape where the majority of established abalone (*Haliotis midae*) farms are located (Fig. 1). Company names have been excluded from this study to maintain anonymity of the different facilities. All farms employed flow-through raceway systems with the exception of Farm I, which operated on recirculation with a varying proportion of make-up water. This farm has subsequently ceased operations. Farms have been grouped into 2 nodes according to region: the 6 farms from Hermanus/Gansbaai (Farms A–F), are referred to as 'south coast' for convenience; and the 3 farms from the vicinity of St Helena Bay are referred to as 'west coast' (Farms G–I). Each farm was sampled on 5 occasions (6 for Farm A) and at various times of the year between 2009 and 2015, such that all seasons were covered for each regional node.

Water samples were collected at each farm from effluent streams, inflow to the grow-out tanks and, in most cases, intake to the farm itself. Multiple effluent streams (Farms A and C) and inflows (Farm H) were

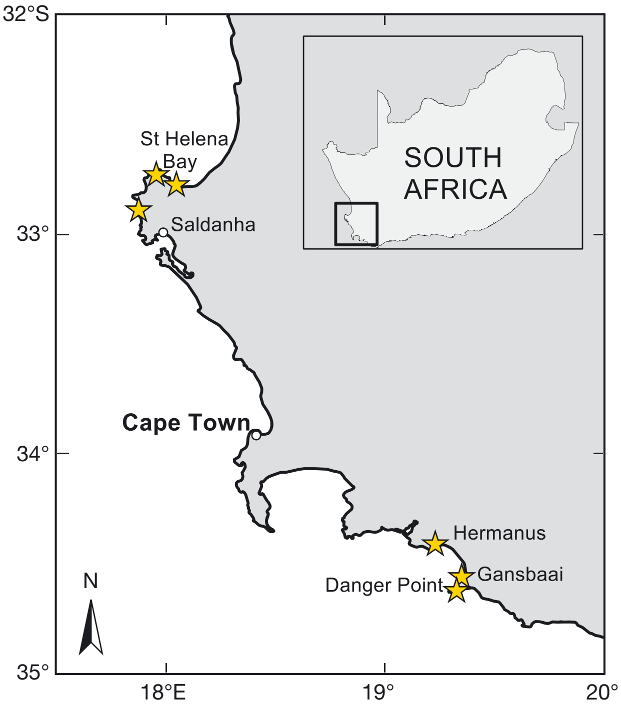

Fig. 1. Location of 'west coast' abalone farms near St Helena Bay and 'south coast' farms in the Hermanus/Gansbaai area, South Africa. Stars indicate locations of individual farms or clusters of farms

sampled individually. Tank inflow and farm intake samples were taken separately, as a number of farms employed some form of particle reduction in intake water prior to release to the tanks. This included drum filtration (Farms A, D, E and F) and settlement, either in ponds (Farms A, F, G and H) or, to a limited degree, in header tanks. The effects of such treatment was, as expected, most obvious for the particulate fractions and less so for dissolved components. Farm intake samples, i.e. prior to any filtration or settlement, are regarded as approximating 'ambient' conditions and are employed as an indicator of background concentrations. For those farms with no filtration treatment and minimal settling in header tanks (Farms B, C and I), intake and inflow samples may be treated as approximately equal. Effluent signals for Farm F included the effect of seaweed culture integrated into the reticulation system.

Samples were collected twice during the day, during working hours and after hours, to account for routine farm activities. In calculating activity-based concentrations, measured concentrations were initially weighted for an 8:16 h working:non-working day to provide an average daily value for a working day. Non-working days corresponded to 24 h of the measured after-hours signal. These were then weighted annually using 250 d as the typical number of working days in a year and 115 d as non-working.

Effluent flow rates were either provided by the respective farm management staff for the day of sampling or calculated directly from measurements of surface velocity and channel dimensions (Farms A, G and I). Measured surface flow velocities were corrected for flow variation with depth by a factor of 0.85 (Meals & Dressing 2008). Multiple effluent streams were combined as a single outflow for each farm, and water quality parameters ultimately presented as a single concentration weighted by flow rate for each channel. Similarly, the 2 different inflows for Farm H were combined to give a single concentration weighted according to respective pump capacity.

Abalone biomass and production

Standing stock data on the day of sampling, as whole wet weight, as provided by the farms, were correlated with volume flow rates to provide a specific discharge rate. Standing stock data included only grow-out sections of a farm; hatchery data (animals <10–15 mm) were not included. Standing stock data were used to provide estimates of average annual production assuming a production:biomass (P:B) ratio of 1.2 (M. Naylor, HIK Abalone Farm, pers. comm.) for the south coast farms that are fed predominantly an artificial diet, and 0.83 for the mainly kelp-fed west coast farms (D. Whyte, West Coast Abalone, pers. comm.). This is equivalent to average specific growth rates ($\ln[1.83]/365 \times 100$ and $\ln[2.2]/365 \times 100$) of 0.17 and 0.22% d^{-1}, for west and south coast farms, respectively, which is in agreement with that measured for market-sized abalone on formulated feed and kelp diets (Francis et al. 2008).

Suspended solids

TSS were measured gravimetrically on 47 mm Whatman GF/F filters (nominal pore size 0.7 µm) that had been thoroughly rinsed with Milli-Q under vacuum to remove friable material and combusted at 450°C overnight in a muffle furnace. Following combustion, filters were cooled in a vacuum desiccator over silica gel and weighed to the nearest 0.1 mg using a Radwag semi-micro, analytical balance. Generally, 1 to 4 l of sample were filtered, depending on particle load, rinsed thoroughly with Milli-Q water (approximately 200 ml), and stored at −20°C for later processing. Some samples taken initially (n = 36) were screened through a 63 µm plankton mesh prior to filtration and subsequent weighing to provide an estimate of the proportion of silt-sized particles.

Both thorough mixing and rinsing (400–450 ml) to remove sea salt held in the filter matrix are crucial to accurate TSS measurements in seawater (Neukermans et al. 2012). Because a rinse volume of 200 ml as used here is insufficient to remove all salt from the filter matrix (Neukermans et al. 2012), we applied corrections for salt and water of hydration (Stavn et al. 2009) where necessary as determined by measurements on filter blanks conducted in our laboratory. Organic material may be lost by rupture of intact cells during the Milli-Q rinse. However, such material losses are considered to be of less significance on glass fibre filters than other filter matrices (van der Linde 1998, cited by Neukermans et al. 2012). In addition, the organic particulate matter in abalone effluents consists mainly of faeces and uneaten feed (predominantly a formulated diet) which is likely to have a low proportion of intact cells. The presence of living cells in inflow water is partially compensated by subtraction from effluent TSS. The salt correction proved to be insignificant (0.046 mg filter^{-1}) given the heavy particle loads on the filters. As the intention was to load the filter with as much particulate matter as practically possible to improve the signal to blank ratio, some filtrations took over 1 h to complete. Given time constraints in the field and long filtration times, TSS measurements were not routinely replicated. However, agreement between replicates can be expected to be better than 5% (replicates CV = 2.54%, n = 15). Heavy loading on filters would obviously result in clogging and hence reduction in effective pore size for such samples, although this effect is considered minor given the mass of material on the filters.

On return to the laboratory, filters were dried at 60°C, cooled under vacuum, and re-weighed. Inorganic matter was determined on a subset of samples after ignition at 450°C overnight. Ashed values were corrected for water of hydration (0.656 mg filter^{-1}) following Stavn et al. (2009). All TSS concentrations are presented as mg dry weight l^{-1}.

Particulate N and P

Particulate N was measured on a separate subset of samples according to the persulfate oxidation method based on Raimbault & Slawyk (1991). Following digestion in an oven at 120°C for 2.5 h, an aliquot of the assay mixture was diluted 5 times with Milli-Q water and adjusted to pH 8 with Tris-HCl buffer to a final concentration of 0.01 M. Nitrate reduction was carried out on a cadmium column following the manual method of Nydahl (1976). Analyses of particulate P followed Suzumura (2008), with persulfate oxidation in an oven at 120°C for 2 h followed by manual PO_4^{3-} analyses (Grasshoff et al. 1983). The present modification of employing oven digestion at 120°C for longer time periods than recommended in the original methods gave slightly better recoveries for N ($p = 0.017$), and similar recoveries for P, compared to autoclave digestion (Mann-Whitney rank sum tests).

Biochemical oxygen demand

Biochemical oxygen demand (5 d) measurements were conducted at 3 farms: 2 from the west coast (including Farm I, which operated on recirculation) and 1 from the south coast. Samples were taken twice a day from each farm, during and after working hours, and analysed in triplicate. Each sample comprised 6 replicate 120 ml Winkler bottles of which 3 were immediately fixed for analysis of dissolved oxygen concentration according the Winkler method of Carpenter (1965). The remaining 3 were incubated at 20°C for 5 d in the dark prior to final oxygen determinations.

Samples were not treated with a bacterial seed, as the natural populations of micro-organisms present were regarded as adequate to facilitate the decomposition process. Dilution of samples to maintain oxygen depletion within bounds was also not deemed necessary, as 5 d biochemical oxygen demand (BOD_5) values <7 mg l^{-1} were expected (limit given by Delzer & McKenzie 2003). The median BOD_5 was 1.51 to 3.31 mg l^{-1} for all 3 farms, with values very slightly in excess of 7 mg l^{-1} occurring only occasionally. Another criterion for acceptable BOD values is that the final oxygen concentration should be >1 mg l^{-1} (Delzer & McKenzie, 2003). Median final oxygen concentrations were 4.48 to 6.65 mg l^{-1} for the 3 farms with concentrations <1 mg l^{-1} occurring on only 1 occasion.

Dissolved nutrients

Inorganic nutrients were determined on Whatman GF/F filtered samples generally within 2 h of collection. Total ammonium nitrogen (NH_4^+), soluble reactive phosphate (PO_4^{3-}) and nitrite (NO_2^-) were measured in triplicate according to the manual methods described by Grasshoff et al. (1983), and nitrate

(NO_3^-) following the cadmium reduction method of Nydahl (1976). All methods were scaled to 5 ml sample volume. The mean SDs, in µmol l^{-1}, for replicates in this study were 0.10 for NH_4^+, 0.18 for NO_3^-, 0.03 for NO_2^- and 0.02 for PO_4^{3-}.

Nutrient budget

Although not the primary aim of the present study, partial N and P budgets were formulated for those farms where feed and harvest data were available. Data from 2015 were used as example case studies. This exercise provides an indicator of the magnitude of losses not accounted for in the sampling programme. Annual farm inputs, as artificial feed and seaweed provisions, and outputs, as harvested and discharged particulate and dissolved inorganic fractions, were formulated from farm data on monthly feed usage and standing stock. Inputs were converted to a production basis using P:B ratios of 0.83 and 1.2 for the west and south coast farms, respectively. Farm output data were calculated for harvested soft tissue/shell, and dissolved/particulate components in the effluent. Effluent data, corrected for inflow, were based on the generic, industry-wide relationships formulated in this study.

Statistics

Normality of data was established with the Shapiro-Wilk test. Differences between variables with a normal distribution were tested using a *t*-test. Comparisons between non-normal distributions used the Mann-Whitney rank sum test for independent samples and the Wilcoxon signed-rank test for matched samples. The significance level was set at $p < 0.05$ for all comparisons. All regression analyses and statistical tests, with the exception of analysis of covariance (ANCOVA), were performed in SigmaPlot 12.0. Comparison of regressions by ANCOVA followed the procedures given by Zar (1974). The median absolute deviation was calculated as half the interquartile range.

RESULTS

Flow rates

We found a significant relationship between standing stock and volume flow rates at the farm level (Fig. 2). The specific discharge rate for all farms collectively was 17.9 m^3 h^{-1} metric tonne $(mt)^{-1}$ (or l h^{-1} kg^{-1}). The west coast farms tended towards slower rates, i.e. 8.0 m^3 h^{-1} mt^{-1} (inclusive of Farm I that functioned on variable recirculation) as opposed to south coast farms only (18.6 m^3 h^{-1} mt^{-1}; Fig. 2). Excluding the recirculation farm had a negligible effect on these rates. The different rates are statistically significant (ANCOVA, $p < 0.001$), suggesting considerably lower pumping costs for west coast farms.

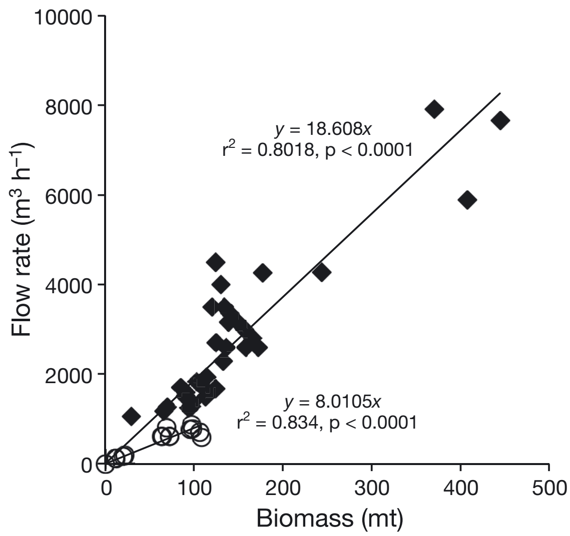

Fig. 2. Relationship between flow rate and standing stock for south coast (filled diamonds) and west coast (circles) abalone (*Haliotis midae*) farms. Regressions were formulated in SigmaPlot 12.0 and compared using ANCOVA

Particulate matter composition

Particles <63 µm comprised 87 and 79% of the total dry mass, respectively, for the inflow and effluent streams (Table 1). The difference between inflow and effluent values was not statistically significant (median = 83%). Concentrations were significantly larger in effluent streams for organic matter and particulate N and P. This was most noticeable for N where effluent streams were almost double that of the inflow for both regions. A significant difference between regions was found only for particulate N, where values for south coast farms exceeded those of the west coast.

Water quality

Median TSS concentrations in farm effluent waters measured during working hours (10.07 mg l^{-1}) exceeded those measured after hours (0.56 mg l^{-1}) for

Table 1. Composition of particulate matter in seawater inflow and effluents for abalone (*Haliotis midae*) farms either combined, where no significant difference between regions (S: south, W: west) was evident (Mann-Whitney rank sum test, $p > 0.05$), or separated into the 2 regions ($p < 0.05$). Data were not normally distributed and are presented as a median. The median absolute deviation is given in parentheses. *Denotes a significant difference between inflow and effluent values

Variable	Region	Inflow n	Inflow Median (SD)	Effluent n	Effluent Median (SD)	p
<63 µm fraction (% total)	S & W	19	87.14 (12.83)	19	78.77 (20.30)	0.260
Organic matter (% dry weight)	S & W	43	57.52 (14.35)	50	63.82 (14.12)	0.017*
Particulate P (% dry weight)	S & W	45	0.24 (0.07)	49	0.33 (0.13)	0.017*
Particulate N (% dry weight)	S	27	1.08 (0.44)	31	2.02 (0.63)	<0.001*
	W	53	0.76 (0.24)	23	1.43 (0.41)	<0.001*

inflow-corrected effluent signals (Wilcoxon signed rank test, $p < 0.001$, $n = 44$). In fact, in some cases there was a reduction in TSS concentrations in the effluent relative to the inflow for the non-working period, indicating settling out in the grow-out units overnight.

For most farms, weighted median TSS concentrations exceeded the 80th percentile TSS limit calculated for the reference condition at the point of discharge (Fig. 3a). In addition, 3 farms exceeded the 5 mg l^{-1} guideline limit for inflow-corrected TSS (Fig. 3b). However, regional median values, i.e. 4.52 mg l^{-1} for the south coast farms and 3.74 mg l^{-1} for the west coast farms, were within the guideline. The datasets were characterised by considerable variability with respective median absolute deviations of 4.10 mg l^{-1} and 7.03 mg l^{-1}. Differences between net effluent concentrations were not significantly different (*t*-test, $p = 0.600$), yielding a combined value of 4.18 mg l^{-1} for all data.

The dissolved components of abalone farm discharges show very little difference between working and non-working hours signals for both raw effluent and inflow-corrected effluent. For example, mean inflow-corrected NH_4^+ concentrations for working (3.44 µmol N l^{-1}) and non-working (3.39 µmol N l^{-1}) hours were not significantly different (paired *t*-test, $p = 0.821$, $n = 45$). Although of less importance than for the particulate fraction, dissolved components were weighted in a similar manner as for TSS. Uncorrected effluent NH_4^+ exceeded the 80th percentile reference level for all farms except Farm I (Fig. 4). However, effluent NH_4^+ levels, uncorrected for inflow concentration (Fig. 4, median = 6.94 µmol N l^{-1}), were all well within the 43 µmol N l^{-1} limit.

The other macronutrients were only slightly elevated above inflow values by comparison with NH_4^+ (Table 2). The inflow-corrected BOD ranged between −0.17 and 3.67 mg O_2 l^{-1}, with a median value of 1.31 mg l^{-1} for the 3 farms at which BOD was measured.

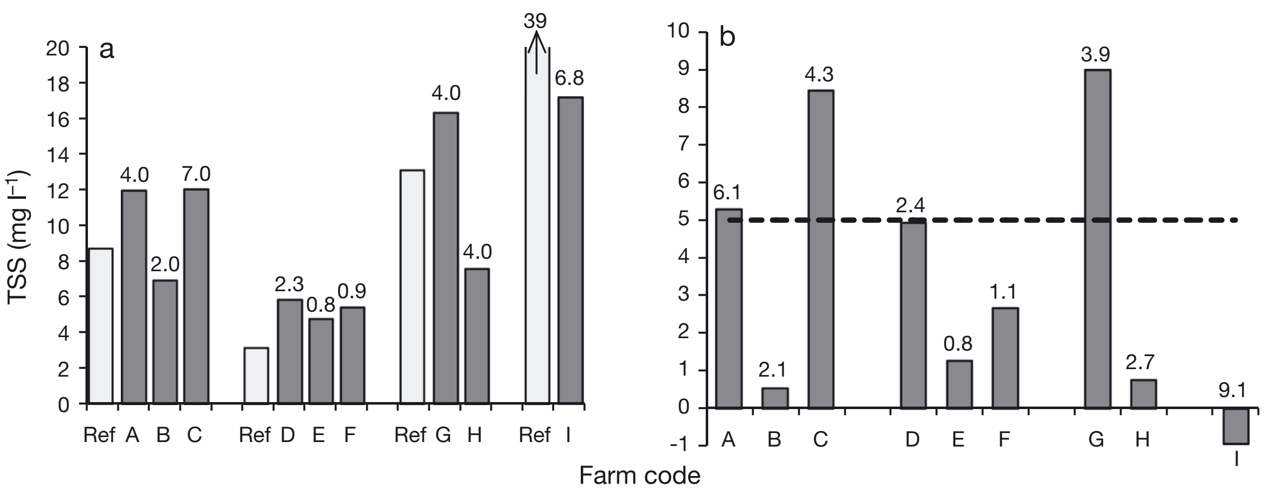

Fig. 3. Median total suspended solid (TSS) concentrations for effluents of south coast (A–F) and west coast abalone farms (G–I). South coast farms are presented separately for Hermanus (A–C) and Gansbaai (D–F). Farm I was operating on partial recirculation. (a) Gross TSS concentrations compared to the 80th percentile (Ref); (b) concentrations in excess of inflow relative to the 5 mg l^{-1} standard. The numbers above the dark grey bars are the median absolute deviation. The arrow indicates off-scale reading equal to number above it

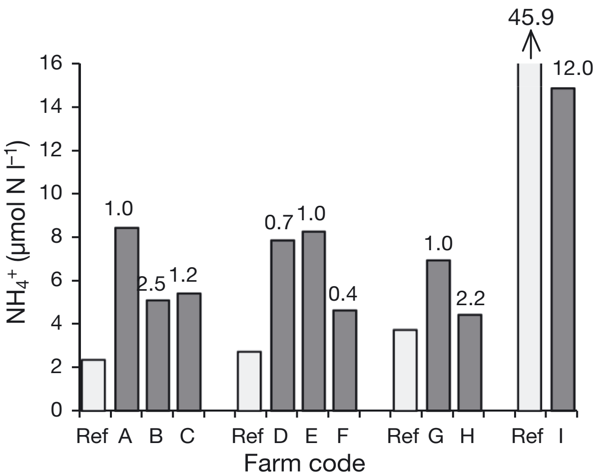

Fig. 4. Median total ammonium (NH_4^+) concentrations for effluents of south coast (A–F) and west coast abalone (*Haliotis midae*) farms (G–I) compared with the 80th percentile (Ref). South coast farms are presented separately for Hermanus (A–C) and Gansbaai (D–F). Farm I was operating on partial recirculation. The numbers above the dark grey bars are the median absolute deviation. The arrow indicates off-scale reading equal to number above it

Annual loads

Average effluent concentrations, both uncorrected and inflow-corrected, together with effluent flow rates have been used to calculate mean annual loadings of the various water quality parameters. These have been plotted against abalone production for each farm as estimated from standing stock values (Fig. 5). A mean of each variable (e.g. TSS, NH_4^+), and estimated production for all sample dates, scaled to an annual production cycle for each farm, was used in these correlations. Calculated absolute TSS loads, corrected for inflow values, range between 17 and 149 mt yr^{-1} and, with the exclusion of 2 outliers from the south coast, are well correlated with estimated annual abalone production. This relationship gives a specific TSS release of 0.33 mt TSS mt^{-1} production for the majority of farms. The TSS loads from the 2 outlier farms amount to about 1.4 mt TSS mt^{-1} production. The 2 outlier farms (Fig. 5) included those exceeding the 5 mg l^{-1} limit (Fig. 3b).

As with TSS, nutrient release appeared to be related to abalone biomass/production (Fig. 5). Ammonium dominated in terms of dissolved inorganic N with a specific NH_4^+ release rate in excess of inflow of 13.2 kg N mt^{-1} of abalone production. Nitrate discharge was 1.2 kg N mt^{-1} and nitrite 0.2 kg N mt^{-1}. Although not shown in Fig. 5, production specific NH_4^+ release in excess of inflow appears to be lower for farms using mainly kelp, i.e. all west coast farms (3.8 kg mt^{-1}, r^2 = 0.731, p = 0.347) as opposed to artificial feed, i.e. most south coast farms (18.6 kg mt^{-1}, r^2 = 0.652, p = 0.098). However, the relationships were not statistically significant and thus a single value of 13.2 kg NH_4^+-N mt^{-1} is applied here for all farms. The outlier in the NH_4^+ regression (Fig. 5) corresponds to Farm F with seaweed culture integrated into the system. Phosphate loads made up 2.1 kg P mt^{-1} abalone production in the effluents, yielding a dissolved inorganic N:P ratio of 6.95 by weight.

Table 2. Median concentrations of nutrients (µmol N or P l^{-1}) in excess of inflow values for south (n = 62) and west (n = 28) coast abalone farm effluents. The median absolute deviation is given in parentheses

	NH_4^+	NO_3^-	NO_2^-	PO_4^{3-}
South coast	3.99 (1.71)	0.55 (0.53)	0.25 (0.09)	0.51 (0.21)
West coast	2.03 (1.59)	1.21 (0.80)	0.41 (0.18)	0.86 (0.34)

Partial nitrogen budget

For all the farms considered, a substantial proportion of estimated annual inputs as artificial feed/seaweed (Table 3) remained unaccounted for by outputs as abalone harvest and effluent dissolved and particulate components (Table 4). The mean deficits for all farms were −17.8 kg N mt^{-1} (SD = 7.0) and −4.3 kg P mt^{-1} (SD = 3.9). The same exercise using farm-specific effluent outputs as opposed to the generic relationships given in Fig. 5 resulted in similar mean deficits of −18.7 kg N mt^{-1} (SD = 14.0) and −4.4 kg P mt^{-1} (SD = 2.5). Harvested abalone (Table 4) accounted for 33.0% (SD = 4.5%) of N and 12.1% (SD = 2.3%) of P input as feed. Predominantly kelp fed farms showed significantly greater recoveries of N (37.9%) and P (15.1%) than those using mainly formulated feed, i.e. 30.1% as N and 11.8% as P (*t*-test, p = 0.002 for N and p = 0.039 for P).

DISCUSSION

Flow rates

The farm-level specific discharge rates of 8.0 to 18.6 m^3 h^{-1} mt^{-1} for the west and south coast facilities, respectively, compares with experimentally determined recommended minimum specific rates of 9.7 to 14.5 l h^{-1} kg^{-1} for small, 20–30 g, *Haliotis midae* (Yearsley 2007) and 7.2 to 9 l h^{-1} kg^{-1} for larger, 50–60 g, animals (Naylor et al. 2011). The slower

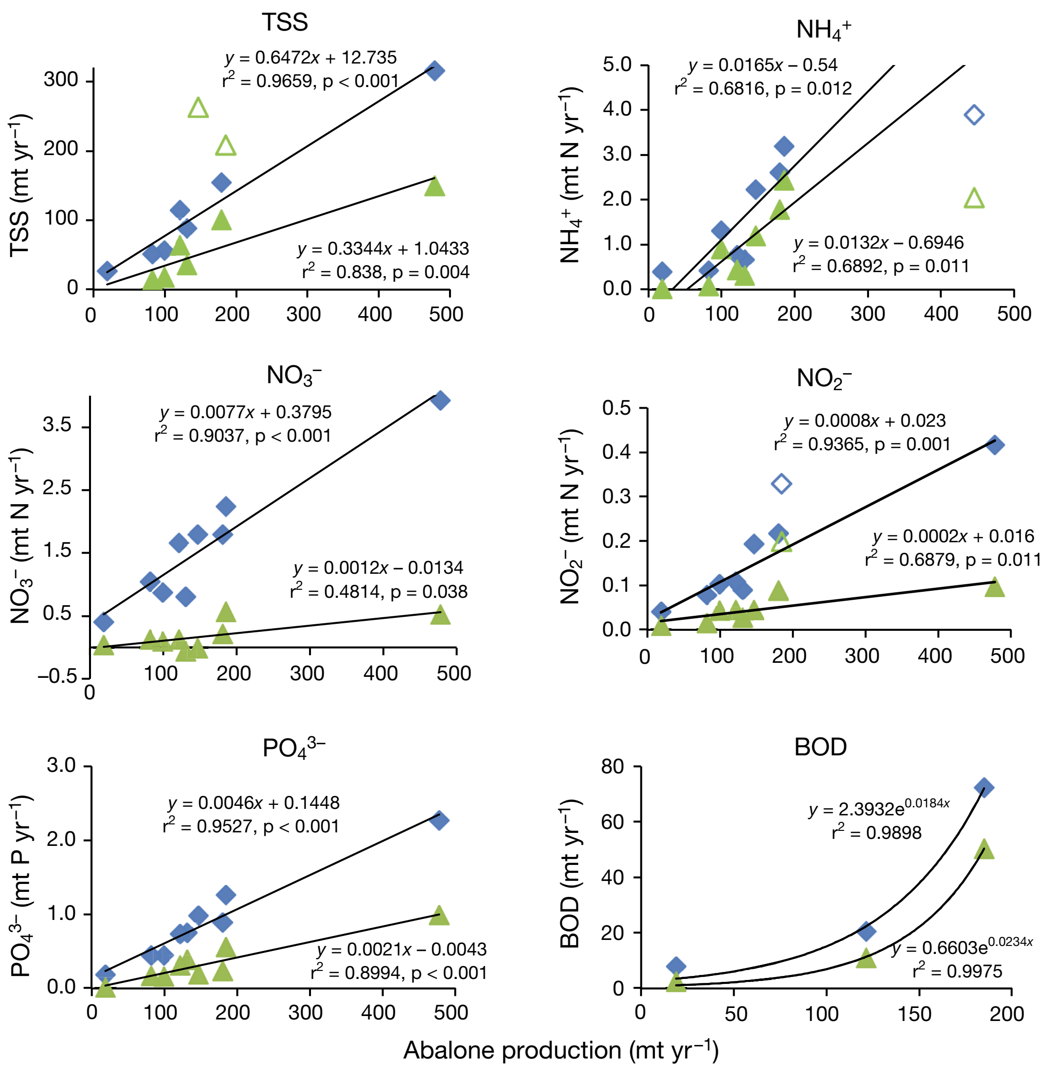

Fig. 5. Mean annual discharge rates of the various water quality variables for each farm, as related to abalone (*Haliotis midae*) production. Data are presented uncorrected (blue diamonds) and corrected (green triangles) for inflow concentrations. Regression analyses were performed using SigmaPlot 12.0. All linear relationships were significant at the 95% level. Un-filled symbols represent data excluded from the correlations. TSS: total suspended solids, BOD: biochemical oxygen demand, mt: metric tonnes

turnover rate for the west coast farms may be related to the fact that they were largely kelp-fed during the period of this study. The lower NH_4^+ release expected of abalone raceways maintained on a relatively low-protein kelp diet would reduce the water turnover required to flush the toxic free ammonia moiety from the growth units (Naylor et al. 2011). The biomass-specific discharge rates measured here translate to an annual production-specific water use of about 85 000 to 136 000 m^3 mt^{-1} based on P:B ratios of 0.83 and 1.2 for the west and south coast farms, respectively. These water-use indices correspond to some of the highest shown by other land-based aquaculture facilities (Boyd et al. 2007). These rates can be used to estimate future farm waste input scenarios with expansion of the industry.

Water quality

The marked difference between TSS measured during working and non-working hours illustrates the need to account for variation in farm maintenance activities, particularly cleaning of tanks, in assessing TSS release by abalone farms. Comparison of effluent signals with reference background concentrations for the respective locations showed most farm discharges were in excess of the 80th percentile

Table 3. Farm N and P inputs as artificial feed, kelp *Ecklonia maxima* and *Ulva* spp. normalised to production (kg N or P mt^{-1} yr^{-1}). For farm inputs, standing stock was converted to production assuming production:biomass ratios of 0.83 and 1.2 for the west and south coast farms, respectively. Commercial artificial feed used by most of the farms was formulated for 34 % protein. The P content of the feed was 0.99 % (T. A. Probyn unpubl. data). Kelp biomass was converted to N and P using a moisture content of 81.95 % and N and P content of 1.7 and 0.27 % of dry weight, respectively (Smith 2007). Similar calculations for farmed *Ulva* spp. were based on a moisture content of 85 %, protein of 18.31 % (Cyrus et al. 2013) and P content of 0.18 % (Robertson-Andersson et al. 2008)

	South coast												West coast			
	Farm A		Farm B		Farm C		Farm D		Farm E		Farm F		Farm G		Farm H	
	N	P	N	P	N	P	N	P	N	P	N	P	N	P	N	P
Feed	64.7	11.1	23.6	4.1	43.0	7.4	67.2	13.1	61.7	10.6	46.5	8.5	17.9	3.3	11.1	2.0
Kelp	–	–	22.0	3.5	12.7	1.4	–	–	–	–	2.6	0.4	33.1	5.3	35.8	4.7
Ulva spp.	–	–	15.8	1.9	–	–	–	–	–	–	0.3	0.02	–	–	–	–
Total input	64.7	11.1	61.4	9.5	55.7	8.8	67.2	13.1	61.7	10.6	49.4	8.9	50.9	8.5	47.0	7.7
Deficit	−24.8	−6.7	−21.4	−5.1	−15.8	−4.4	−27.3	−8.7	−21.8	−6.2	−9.5	−4.4	−13.0	−4.1	−9.0	−3.3

trigger level for TSS at the point of outfall. However, this depiction is misleading in that end-of-pipeline measurements do not account for a mixing zone within which water quality standards may be exceeded. Effluent values were only marginally above the reference condition, implying that such a zone of non-compliance would be very limited in extent. In support, P. J. Britz & B. P. Godfrey (unpubl. specialist study) showed rapid dilution of dissolved nutrients in an open effluent stream of an abalone farm as it flowed across the intertidal. Initially elevated ammonia concentrations were indistinguishable from background environmental concentrations at the spring low tidal level. Similarly, effects on the intertidal biota gradually attenuated towards the lower intertidal zone (approximately 40 m from the outfall), with no visual evidence of community effects in the subtidal directly below the effluent stream.

Table 4. Farm N and P outputs normalised to production (kg N or P mt^{-1}) as calculated for harvested soft tissue/shell and as measured in effluents. Soft tissue moisture (77.9 %) and protein (62.3 %) for *Haliotis midae* is from Britz & Hecht (1997). Shell moisture (16.51 %) and protein (6.31 %) were calculated from Knauer et al. (1994) assuming soft tissue is 75 % of whole weight (M. Naylor pers. comm.). The P soft tissue (0.70 %) and shell (0.022 %) content was as calculated from data in Tan et al. (2001) for *H. discus hannai*

	Coast	Soft tissue		Shell	
		N	P	N	P
Abalone harvest		16.5	1.2	2.1	0.06
Net effluent	South	21.3	3.2		
	West	19.3	3.2		
TOTAL	South	39.9	4.4		
	West	37.9	4.4		

A more appropriate comparison of effluent TSS is with the abalone standard, which is specific for discharges from abalone farms (Fig. 3b). Although the standard is applied as a single value across all ecosystems, effluent concentrations are corrected for inflow levels and thus do account in a certain manner for natural variability in the indicator. Abalone farm net effluent TSS concentrations (median 4.18 mg l^{-1} for all farms) is in agreement with that measured at a single South African abalone farm (Yearsley 2007), i.e. 1.64–4.43 mg l^{-1}, and similar to that emanating from land-based trout raceways, 1.9–9.0 mg l^{-1} (Viadero et al. 2005, Koçer et al. 2013). These values are considerably less than those for shrimp ponds, which range between 19 and 60 mg l^{-1} (Páez-Osuna et al. 1997, Casillas-Hernández et al. 2006).

With regard to dissolved nutrients, all farm effluents were well below the recommended 43 µmol l^{-1} NH_4^+ (ASC 2012). These findings indicate the toxicity risk of unionised NH_3 is negligible, as free ammonia is only 2–5 % of total NH_4^+ at a typical seawater pH. Ammonium concentrations in excess of inflow (Table 2, median 2.0–4.0 µmol l^{-1}) were similar to that measured at an abalone farm (2.67–3.05 µmol l^{-1}; Yearsley 2007) and semi-intensive shrimp pond effluents (<5 µmol l^{-1}; Páez-Osuna et al. 1997, Casillas-Hernández et al. 2006) but generally substantially less than that for intensive shrimp ponds (Briggs & Funge-Smith 1994, Páez-Osuna 2001) and trout raceways (Boaventura et al. 1997, Viadero et al. 2005, Koçer et al. 2013) where concentrations 1–2 orders of magnitude higher are not uncommon. The other nutrients were only marginally elevated above background as has been measured for other flow-through aquaculture operations (e.g. Páez-Osuna et al. 1997, Koçer et al. 2013) and as such pose little risk of

Table 5. Comparison of net discharges per metric tonne of production of total suspended solids (TSS), NH_4^+-N, PO_4^{3-}-P, total N (TN) and total P (TP) for some land-based aquaculture facilities

Species	Effluent loads (kg mt^{-1})					Reference
	TSS	NH_4^+	PO_4^{3-}	TN	TP	
Abalone						
Haliotis midae	334	13.2	2.1	20.3–38.1	3.2–7.5	This study
H. midae[a]	290	7.4				Yearsley (2007)
H. tuberculata[b]		22.6		109.9		Neori et al. (1998)
Shrimp – intensive						
Penaeus monodon[c]				39.1	3.7	Briggs & Funge-Smith (1994)
P. monodon				71.9		Jackson et al. (2003)
Shrimp – semi-intensive						
Litopenaeus vannamei				28.6	4.6	Páez-Osuna et al. (1997)
L. vannamei[d]				18.7	2.5	Teichert-Coddington et al. (2000)
L. vannamei[e]				21.8	11.3	Casillas-Hernández et al. (2006)
Finfish						
Oncorhynchus mykiss[f]	449	57.0	14.8			Boaventura et al. (1997)
O. mykiss	278	14.6[g]	1.8[g]	43.9	8.8	Koçer et al. (2013)
Trout species	148			40.8	8.7	Roque d'Orbcastel et al. (2008)
Dicentrarchus labrax[h]		43.9	5.3	82.9	8.9	Lemarié et al. (1998)
Sparus aurata	9105	36.4	2.6			Tovar et al. (2000)

[a] Calculated assuming similar weightings as used in the present study and a production:biomass ratio of 1.2
[b] Calculated assuming a production:biomass ratio of 1
[c] Mean calculated as overflow plus drainage from Table 5 in Briggs & Funge-Smith (1994)
[d] Calculated for overflow plus drainage from Table 4 and Fig. 3 in Teichert-Coddington et al. (2000)
[e] Calculated means for 2 feeding modes from data on outlet water loads and production values
[f] Mean of 3 farms
[g] Calculated as 33 % of total N and 20 % of total P from Table 4 in Koçer et al. (2013)
[h] Calculated from feed conversion ratio = 1.5 and mean values for different batches given in Table IV of Tovar et al.

eutrophication. As with TSS, the BOD of 1.31 mg l^{-1} for the 3 farms is at the low end of the range reported for trout farms, 0.4–14 mg l^{-1} (Boaventura et al. 1997, Viadero et al. 2005, Koçer et al. 2013) and well below maximum levels in shrimp pond effluents (Páez-Osuna 2001). The Global Aquaculture Alliance Best Aquaculture Practices certification standards for finfish and crustaceans have a target effluent BOD of 30 mg l^{-1} (subsequent to an initial value of 50 mg l^{-1}), further illustrating the benign nature of abalone farm effluents (GAA 2016). Given the limited sample size at present and the sometimes high variability in indicator values (Figs. 3 & 4), additional sampling will better constrain these values, particularly with regard to TSS.

Results obtained in this study indicate that effluents from land-based abalone farms constitute a relatively low-risk threat to coastal receiving waters. However, the use of indicator concentrations as the measure of effluent quality has been subject to some criticism as it is possible to achieve compliance with numerical water quality criteria by increasing the volume of water passing through a farm to facilitate dilution. Using a load-based approach precludes such pseudo-mitigation measures and provides a more meaningful indication of potential impact on the receiving environment. As absolute loads of pollutants from aquaculture are highly dependent on standing stock/production and feeding regimens, a common approach is to normalise to production (Boyd et al. 2007). The abalone production-specific TSS value excluding outliers of 334 kg TSS mt^{-1} measured in this study is in general agreement with what has been measured for some other land-based aquaculture operations, whereas the production-specific loadings of 13.2 kg NH_4^+-N mt^{-1} and 2.1 kg PO_4^{3-}-P mt^{-1} are somewhat lower (Table 5).

Total N and total P

Farm activities significantly enrich discharged particulate matter relative to inflow in organics, N and P, most noticeably particulate N (Table 1). The mean particulate N (PN) concentration in south and west coast abalone farm effluents was 2.02 % and 1.43 % dry weight, respectively (Table 1). Based on the production-specific TSS release rates of 334 kg TSS mt^{-1}, one can estimate a PN release of 6.7 and 4.7 kg N mt^{-1} abalone production. By comparison, the dissolved inorganic N (DIN) loading was 14.6 kg N mt^{-1}, of which NH_4^+ was the most important (Fig. 5). Combining PN and DIN gives estimates of total N (TN) of 21.3 kg N mt^{-1} abalone production for south coast farms and 19.3 kg N mt^{-1} for the west coast (mean 20.3 kg N mt^{-1} for all farms). These values are underestimates in that the contribution of dissolved organic N (DON) was not taken into account. Neori et al. (1998) showed that DON can contribute nearly 50% to the TN in *H. tuberculata* effluents. A high proportion of DON (34%) has similarly been reported for European seabass (Lemarié et al. 1998). Assuming the N deficit identified in Table 3 (mean 17.8 kg N mt^{-1}) resides in the unmeasured dissolved organic fraction, TN increases to 38.1 kg N mt^{-1}. The range in TN calculated for *H. midae* farms is in general agreement with that reported for other land-based aquaculture operations (Table 5).

Open water finfish aquaculture systems tend to impose slightly higher nutrient loads on the environment. Nitrogen loads calculated from mass balance and bioenergetics models for open water finfish systems include 50–54.2 kg N mt^{-1} for Norwegian salmon and rainbow trout farms (Azevedo et al. 2011, Wang et al. 2012), and 66.2–86.9 kg N mt^{-1} for non-salmonids (Gillibrand et al. 2002, Davies & Slaski 2003). As an extreme comparison, model predictions for farmed southern bluefin tuna, characterised by extremely high metabolic rates and fed an un-optimised diet of baitfish, reveal high environmental losses of the order of 260–505 kg N mt^{-1} production (Fernandes et al. 2007).

Similar calculations with P yield 2.1 kg PO_4^{3-}-P mt^{-1} and 1.1 kg particulate P mt^{-1} production based on Fig. 5 and Table 1. Thus, the total P (TP) discharge by abalone is estimated at 3.2–7.5 kg P mt^{-1}, with the upper limit incorporating the P deficit based on budget calculations (Table 3). As with N, TP discharge rates are similar to what have been reported for other land-based aquaculture facilities (Table 5). Open water systems have similar TP release rates, e.g. 9.3 kg P mt^{-1} for Norwegian salmon farms (Wang et al. 2012) and 7.5–15.2 kg P mt^{-1} for freshwater rainbow trout (Bureau et al. 2003, Azevedo et al. 2011).

The ratio in which macronutrients are available has been regarded as important to coastal ecosystems both from the perspective of phytoplankton assemblages/harmful algal blooms and stoichiometric regulation of food webs (Heisler et al. 2008, Glibert et al. 2011). In addition, the form in which a particular nutrient is available, i.e. either dissolved or particulate, organic or inorganic, reduced or oxidised inorganic, can influence phytoplankton community structure. The discharged TN:TP ratio of 5.1–6.3 is somewhat less than the Redfield ratio of 7.2 by weight. This compares with a range for finfish of 5.4–9.3 for rainbow trout (Koçer et al. 2013) and seabass (Lemarié et al. 1998), respectively, and 5.5–7.3 for shrimp (Teichert-Coddington et al. 2000, Casillas-Hernández et al. 2006). The slightly lower TN:TP ratio for abalone than other farmed species suggests greater N retention within these farm systems. This relative excess of P is further illustrated by the poor recovery of dietary P (13%) relative to N (33%) in abalone harvest. The N accretion value is similar to some of the higher values recorded for finfish (Hargreaves 1998, Wang et al. 2012) and semi-intensive shrimp culture, even if fertiliser input is included (Teichert-Coddington et al. 2000, Casillas-Hernández et al. 2006). Nitrogen recovery in intensive shrimp farms may be less (e.g. Briggs & Funge-Smith 1994, Jackson et al. 2003). The proportion of dietary P recovered in abalone harvest is generally lower than for fish (27–31%; Lemarié et al. 1998, Wang et al. 2012) and shrimp (19–25%; Teichert-Coddington et al. 2000, Casillas-Hernández et al. 2006). The poorer accrual of artificial feed P relative to kelp is probably related to the fact that abalone are slow feeders, and P leaching rates from artificial feed may be high (Tan et al. 2001, Sales et al. 2003).

It is now established that non-symbiotic diazotrophy is not limited to open ocean environments but occurs in coastal upwelling environments through the action of heterotrophic bacteria (Fernandez et al. 2015). The slight excess of P calculated for abalone farm effluents could theoretically promote N_2 fixation. However, given the fact that abalone farm input of nutrients is a minor to insignificant fraction of natural fluxes, as will be shown in the following section, it is highly unlikely they will exert major ecosystem effects beyond the near field.

A load-based approach as presented here could provide the most effective means of environmental protection, where marked departures from an industry achievable standard as given by the relationships in Fig. 5 (e.g. TSS) could be used to initiate technological or management interventions at individual farms. Such an approach also allows one to project waste loads that could be imposed on receiving water bodies through expansion of production without resorting to extensive effluent monitoring (Boyd et al. 2007). In addition, as best management practices and improved technologies are increasingly exploited by industry, the requirement for compliance monitoring could be reduced dramatically.

Comparison with other inputs

Aquaculture waste loads are often compared with other more common sources of pollution such as domestic sewage to provide a framework that is more easily understood by the broader stakeholder community. Discharges from aquaculture can thus be converted to human population equivalents to provide a common currency for application to specific indicators. The estimated per capita excretion of N in urine and faeces for South Africa is 3.4 kg N person^{-1} yr^{-1} (Jönsson et al. 2004). Human population equivalents can be calculated from the abalone production values of 1106 mt yr^{-1} for the south coast and 128 mt yr^{-1} for the west coast (Dept of Agriculture Forestry and Fisheries unpubl. data), and TN release values reported in the previous section. After correcting for the fact that only 64% of particulate matter in abalone farm effluent is organic (Table 1), the approximate water pollution load of the south coast abalone farms is equivalent to excretion by 6100–11 900 people. For west coast farms, the population equivalent in terms of N is 660–1300 people. Thus the human population equivalents per mt of abalone is approximately 5.4–10.6 as an average for both west and south coast farms. This range of N-specific pollutant loads, though highly speculative, is comparable to that calculated for closed system shrimp farms and raceway production of trout, i.e. 4.2 and 11.9, respectively (Boyd et al. 2007).

The above approach does allow comparison between different sources of pollution but does not fully consider natural sources of the various indicators. In addition, the use of variables based on concentration, although corrected for background or inflow levels, do not explicitly account for natural supply rates. To place abalone aquaculture discharges in a more ecological perspective, a brief comparison is provided with estimated natural supply rates of TSS and NH_4^+ to the inshore environment. These comparisons are made at the broader ecosystem level and thus address the cumulative impacts from a number of farms.

The farms considered in this study are all located in the productive Benguela upwelling system, characterised by high nutrient input and extensive kelp beds. Kelps typically introduce large quantities of particulate organic matter (POM) to the coastal zone from the erosion of their blades. Newell & Field (1983) have shown that kelp plus understory algae produce 2.81 kg dry matter m^{-2} yr^{-1}, of which 70% is released as POM. The south and west coast farms fall in 2 kelp concession areas; Area 6 and Area 11 of 682 ha and 618 ha in extent, respectively (Anderson et al. 2007). Using the above data, one can calculate the total annual production of POM by kelp beds as 13 429 mt yr^{-1} (south coast, Area 6) and 12 169 mt yr^{-1} (west coast, Area 11). Based on actual annual abalone production data for 2013 of 1106 mt for the south coast farms and 128 mt for the west coast, and using the correlation between production and TSS load (Fig. 5), the estimated annual TSS release from the abalone farms is 369 mt yr^{-1} (south) and 43 mt yr^{-1} (west). Thus, for the majority of farms, TSS discharges amount to about 2.8% (south) and 0.35% (west) of the natural production of POM from kelp beds in the 2 areas. For the outlier farms these proportions are 11 and 1.4%, respectively.

Similar calculations can be done for a local scale using a different dataset. Levitt et al. (2002) showed that the kelp beds on the northern and southern parts of Danger Point, Gansbaai, occupy approximately 336 ha of the immediate sub-tidal zone extending along 16 km of coastline. The standing stock of kelp in this area is given as 22 973 mt wet weight, which corresponds to 3192 mt dry weight using a conversion factor of wet to dry of 7.14 for kelp fronds, as calculated from data in Field et al. (1980). Applying a kelp P:B ratio of 3.5 (R. Anderson pers. comm.) and 70% release of POM (Newell & Field 1983), gives 7822 mt POM yr^{-1}. The release of TSS by farms in the Gansbaai area (160 mt yr^{-1}) can thus be estimated as 2.3% of this value; similar to what was calculated for the broader Concession Area 6. If one assumes that the major zone of influence of farm-based TSS is restricted to 1 km of the coastline, the proportional contribution of the Gansbaai farms increases 5-fold to 12.3% of natural release from kelp, for an equivalent length of coastline. Increasing the assumed zone of influence for a farm decreases the calculated relative input. Given the highly exposed nature of both the west and south coast farms, the assumption of a 1 km length scale for a farm is likely to be highly conservative.

Equivalent comparisons can be made with the dissolved components of abalone farm effluents. Upwelling of cold, deep waters in response to equatorward winds introduces high concentrations of NO_3^- (and other nutrients) into the near-shore southern Benguela environment. Model-derived annual mean volume flux for the Cape Peninsula (lowest of the major upwelling cells within the Benguela) is 0.07 Sv (Sv = 10^6 m^3 s^{-1}) for a coastline length of 111 km

(Veitch et al. 2009). Assuming a typical source water concentration of 20 mmol m^{-3} NO_3^-, this volume flux translates to 5569 kg N m^{-1} yr^{-1} (or mt N km^{-1} yr^{-1}). Adopting the nominal 1 km length scale for the zone of farm influence means 5569 mt N $farm^{-1}$ yr^{-1}. By comparison, estimated dissolved N discharges, based on regional production figures, range between 9.4 mt N yr^{-1} for all 6 south coast farms, and 1.9 mt N yr^{-1} for the 3 smaller west coast farms. Clearly, coastal upwelling influences a much wider shelf region than one could expect for farm discharges and as such, the above comparison is somewhat artificial. However, these calculations do serve to illustrate the insignificance of the estimated total annual dissolved N release from all abalone farms, predominantly as NH_4^+ (90% of inorganic), in the context of the larger ecosystem. On an individual farm basis, N input to the coastal zone as inorganic dissolved N from abalone farms can be estimated as 0.01–0.05% of the N introduced as NO_3^- by upwelling over a nominal coastline length, i.e. 1 km. Equivalent calculations with PO_4^{3-} at 2 mmol m^{-3} show a similar farm contribution of 0.01–0.03% of that introduced by upwelling.

Carbon footprint

The overall industry water-use index of 85 000–136 000 m^3 mt^{-1} produced is indicative of a high specific energy cost. The mean installed pump capacity for the South African abalone industry in 2007 was equivalent to 2.8 kW mt^{-1} of production, with a range of 1.4–5.5 kW mt^{-1}, depending on local geomorphology (W. Barnes, Abalone Farmers Association, pers. comm.). An additional 2.2 kW mt^{-1} production was used for aeration. The total direct electricity usage of 5 kW mt^{-1} is equivalent to 43.8 kWh kg^{-1} over an annual production cycle. By comparison, direct energy inputs for semi-intensive shrimp farms are smaller at about 15 kWh kg^{-1} of a total energy input of 44–47 kWh kg^{-1} (Troell et al. 2004, Bunting & Pretty 2007). The energy usage for abalone can be converted to CO_2 equivalents using the national conversion factor of 1.01 kg CO_2 kWh^{-1} for 2014–2015 (see www.eskom.co.za). This conversion factor is one of the highest worldwide, as South Africa derives most of its central grid electricity from coal-fired power stations. Thus the direct energy inputs for water and aeration impose a relatively high production-specific C footprint for abalone of about 44 kg CO_2 kg^{-1}. Prior calculations for a South African abalone farm yield an even higher estimated C emission of 97 kg CO_2 kg^{-1} when operating in monoculture (Nobre et al. 2010). By comparison, C footprints of 11.7 kg CO_2 kg^{-1} (Bunting & Pretty 2007) and 10.9 kg CO_2 kg^{-1} (Troell et al. 2004) have been calculated for shrimp farms.

Although direct electricity usage is likely to be a major energy input in abalone farming, other operational activities such as the production of feed and seed as well as indirect energy inputs associated with fixed infrastructure will need to be taken into account for a more rigorous energy inventory. Nevertheless, the above production-specific CO_2 emission gives an industry C footprint of 65 000 mt CO_2, based on 2013 abalone production of 1470 mt (DAFF 2014). This compares with an average total C footprint for livestock in South Africa of about 30 million mt CO_2 equivalents for 2000–2010 (DEA 2013). Although underestimated to the extent that only direct energy usage by the industry was considered, the abalone farming sector is currently too small to make a significant contribution to the national C footprint. Although there are a number of constraints to the continued development of the industry such as availability of feed and concerns over China flooding the market, projections are optimistic failing any major global economic downturn (Cook 2014). Given current trends in the South African farmed abalone industry (DAFF 2014), farmed production in 2013 could double by 2018 or reach 10 000 mt by 2030.

SUMMARY AND CONCLUSIONS

The 80th percentile background reference level to end-of-pipeline discharges proved unsatisfactory as a guideline. This finding is not surprising given that the appropriate application of this reference level requires consideration of a mixing zone. However, environmental sampling around a discharge is often logistically challenging and, in the case of a highly exposed coastline characteristic of the South African situation, potentially hazardous. The ASC (2012) standards are thus preferred as a regulatory goal.

Concentrations of the various water quality parameters, particularly NH_4^+ and TSS, were generally lower than measured in other land-based farms such as finfish and shrimp. However, abalone farms are characterised by very high water use indices, resulting in production-specific loadings of TSS, TN and TP that were similar to those measured for other operations. This requirement for rapid water turnover also imposes a high specific energy demand on individual farms with implications regarding the industry-specific C footprint.

Our results show that environmental risk posed by farm-derived NH_4^+ and the other dissolved inorganic nutrients was minimal, particularly for a coastal upwelling environment where natural inputs of nutrients are overwhelmingly predominant. The requirement for regulatory monitoring of NH_4^+ at abalone farms in this environment, as a stressor itself or as an indicator for other nutrients, is thus debatable. Similarly, farm-derived TSS for the most part constituted only a small proportion (0.35–2.8%) of that calculated for natural particulate release from the ubiquitous kelp beds occurring along the coastline. Assuming an average TSS concentration of double the limit, i.e. 10 mg l^{-1}, the calculated annual TSS load based on 2013 abalone production amounts to only 1–11% of that generated from kelp beds in the west and south coastal nodes, respectively. This suggests that there may well be scope for relaxing the 5 mg l^{-1} limit where natural POM loads are high. Such an approach would need to address the cumulative impact of changing production scenarios within regional nodes.

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