Integrated seaweed cultivation on an abalone farm in South Africa. J Appl Phycol 20:579–595

ARTICLE *in* JOURNAL OF APPLIED PHYCOLOGY · OCTOBER 2008

Impact Factor: 2.56 · DOI: 10.1007/s10811-007-9239-7

8 AUTHORS, INCLUDING:

Deborah Vivienne Robertson-Andersson
University of KwaZulu-Natal
19 PUBLICATIONS **307** CITATIONS
SEE PROFILE

J. P. Hansen
Stockholm University
9 PUBLICATIONS **113** CITATIONS
SEE PROFILE

Max Troell
Kungliga Vetenskapsakademien
90 PUBLICATIONS **4,976** CITATIONS
SEE PROFILE

Christina Halling
Stockholm University
13 PUBLICATIONS **2,034** CITATIONS
SEE PROFILE

J Appl Phycol
DOI 10.1007/s10811-007-9239-7

Integrated seaweed cultivation on an abalone farm in South Africa

Deborah V. Robertson-Andersson · Michelle Potgieter · Joakim Hansen · John J. Bolton · Max Troell · Robert J. Anderson · Christina Halling · Trevor Probyn

Received: 22 April 2007 / Revised and Accepted: 19 July 2007

Abstract Land-based abalone aquaculture in South Africa, based on the local species *Haliotis midae*, started in the early 1990s and has grown rapidly in the last decade, with 13 commercial farms now producing over 850 t per annum. Over 6,000 t per annum of kelp *Ecklonia maxima* are now harvested for this purpose, and some kelp beds are reaching maximum sustainable limits. Research into seaweed aquaculture as feed (*Ulva* and some *Gracilaria*) for abalone started in the late 1990s on the southeast coast (where there are no kelp beds) using abalone waste water. A growing body of evidence suggests that a mixed diet of kelp plus other seaweeds can give growth rates at least as good as compound feed, and can improve abalone quality and reduce parasite loads. A pilot scale *Ulva lactuca* and abalone integrated recirculation unit using 25% recirculation was designed and built on the south west coast of South Africa using one 12,000-L abalone tank containing 13,200 15± 2.5 g abalone, connected to two 3,000-L seaweed tanks containing an initial starting biomass of 10 kg of seaweed, replicated 3 times. In an 18-month period, there were no significant differences in abalone health or growth rates, sediment build up and composition, mobile macro fauna densities and species between the recirculation or the flow-through units. Transfer of oxygen generated by the seaweeds to the abalone tanks was poor, resulting in the recirculated abalone tanks having lower (33%) dissolved oxygen concentrations than a comparable flow-through abalone unit. Seaweed nutrient content and specific growth rates in the units were comparable to seaweeds cultivated in fertilized effluent (SGR=3.2±3.4%.day^{-1}; Yield=0.2±0.19 kg.m^{2}.day^{-1}). Indications were that at this low recirculation ratio the seaweeds in the units were nutrient limited and that there were no negative effects to the abalone being cultivated in such a recirculation unit at this recirculation ratio.

Keywords Integrated · Abalone · Seaweed · Aquaculture · *Ulva* · Recirculation

Abbreviations

25% Recirc.	25% Recirculation abalone units
BOD	Biological oxygen demand

D. V. Robertson-Andersson · M. Potgieter · J. J. Bolton
Botany Department, University of Cape Town,
Rondebosch 7701, South Africa

J. Hansen · C. Halling
Department of Systems Ecology, Stockholm University,
SE 106 91 Stockholm, Sweden

M. Troell
Department of Systems Ecology, Stockholm Resilience Centre,
Stockholm University,
SE-106 91 Stockholm, Sweden

M. Troell
The Beijer International Institute of Ecological Economics,
The Royal Swedish Academy of Sciences,
Box 50005, S-104 05 Stockholm, Sweden

R. J. Anderson
Seaweed Unit, Marine and Coastal Management,
Pvt Bag X2 Roggebaai, South Africa

T. Probyn
Aquaculture Unit, Marine and Coastal Management,
Pvt Bag X2 Roggebaai, South Africa

D. V. Robertson-Andersson (✉)
Biodiversity and Conservation Biology,
University of the Western Cape,
Bellville 7535, South Africa
e-mail: drobertson-andersson@uwc.ac.za

DIP	Dissolved inorganic P
FAN	Free (unionised) ammonia nitrogen
FTU	Flow-through abalone units
SGR	Specific growth rate
SST	Sea surface temperature
TAN	Total ammonia nitrogen

Introduction

The South African abalone (*Haliotis midae* L) cultivation industry started developing in the 1990s and developed rapidly and is now the largest producer outside Asia (FAO 2004). Wild harvested kelp (*Ecklonia maxima* (Osbeck) Papenfuss) constitutes the major feed for farmed abalone in South Africa, and 5,447 t was harvested during 2003 (Anderson 2003). This resource is now approaching limits of sustainable harvesting and the annual maximum sustainable yield (6–10% of total standing crop) has been reached in kelp concession areas with high abalone farm concentrations (Troell et al. 2006). The use of kelp for abalone feed has decreased from 5,800 t in 2005 to 3,800 t in 2006 as farms are utilizing more compound feeds and some farms now cultivate *Ulva spp.* as feed. Abalone cultivators saw the need for alternative feed sources for the abalone and this has seen research driven mainly in two main areas: compound feeds (see review by Sales and Britz 2001), and seaweed feeds. Initial research had shown good potential for on-farm integrated seaweed cultivation in South Africa (Fourie 1994; Smit 1997; Hampson 1998; Morgan 2000; Steyn 2000; Miller 2001; Robertson-Anderson 2003; Njobeni 2006). All of the research into land-based seaweed cultivation prior to this was by placing the seaweeds in the effluent flow with no recirculation of the seaweed outflow water. A large body of literature has shown that integration of seaweeds with the primary culture organism (see Brzeski and Newkirk 1997; Troell et al. 1999a, b; Buschmann et al. 2001) and in particular abalone, can bring many benefits to overall farm performance (Neori et al. 1991, 1996, 1998, 2004).

The main aim of this study was to test a fully integrated recirculating seaweed/abalone unit. Such a unit would have hypothesized advantages and disadvantages for the primary cultured organism. Recirculation could increase the temperature of the water and positively affect the primary organism's growth rates. Recirculation may increase sediments, parasites and pest species in the system, adversely affecting the primary organism's health and growth rates. Water quality in an integrated system could also be poorer than a flow though system.

Flow rates, stocking densities and other parameters relevant to *Ulva lactuca* L cultivation in abalone effluent in the available seaweed tanks had been determined by Robertson-Andersson (2003). The data from this study were used in the design and set-up of the integrated system in conjunction with abalone cultivation parameters as determined by the existing abalone cultivation conditions. The integrated units were set up to a ratio 20 kg of abalone to 1 kg of seaweed based on the limitations of the abalone cultivation and optimization of seaweed growth and biofiltering efficiency as determined by Robertson-Andersson (2003).

Materials and methods

Experimental set up

Research took place at an abalone farm (34°37′S, 19°28′E), at Danger Point, Gansbaai, approximately 140 km east of Cape Town. The farm I & J Cape Abalone Mariculture Pty Ltd is a land-based intensive mariculture operation and cultivates primarily abalone (*H. midae*) (~ 240 t per annum), which range from 1- to 6-year-old animals. The abalone were cultivated in concrete flow-through tanks (6.6 × 2.08 m × 0.88 m deep;±12,000-L). The experimental units were designed and built in August 2003, and consisted of three separate integrated units and three separate flow-through units. In September 2003, the units were stocked with abalone 15±2.5 g in weight, from the same brood stock. The abalone culture tanks contained 24 Ivey Blue up™ baskets with 550 abalone per basket. In September 2004, the entire experiment was graded and the stocking density reduced to 450 animals per basket.

The 90 kg of fresh kelp per week, was fed to the animals, for the duration of the experiment (60 kg on Mondays, 30 kg on Fridays). The average protein content of the kelp was 7.8 % (Simmons 1990; Simpson 1994). The abalone tanks were drained and cleaned once a week as per farm cleaning procedures.

The six experimental seaweed tanks were 5×1 m surface area and 0.6 m deep with an outlet 17 cm from the top. They were made of white PVC lining supported on a frame. The PVC lining was rounded on the bottom. The tanks were aerated by a 30-mm PVC pipe that ran along the bottom centre of the tank. Holes (3 mm) were spaced evenly every 250 mm along the pipe and the air was supplied by a blower. The seaweed tanks were stocked with a starting biomass of 10 kg (2 kg m^{-2} stocking density) of *U. lactuca* per tank and were harvested every 14 days to measure growth rates. The tanks were shaded with 50% shade cloth from September to February. Four additional seaweed tanks that were being fed fertilized abalone waste water at 12 volume exchanges per day without recirculation (approximately double the water volume that each integrated seaweed tanks received), were used to compare seaweed growth rates

and seaweed tissue properties. The fertilizer consisted of a 100 g mixture of Maxiphos® and ammonium sulphate in a ratio of 1:6.

Three abalone tanks were on a flow-through system receiving 6,000 L h^{-1} (Fig. 1). Three additional abalone tanks had their waste water gravity-fed to two seaweed tanks each. After the water passed through the two seaweed tanks, 25% (1,500 L h^{-1}) was pumped by a 2-kW pump back to the abalone tank from which it originated. Then, 4,500 L h^{-1} (75 %) of seawater was supplied from the same source as the flow-through units (Fig. 1). The overflow water exited the units from the seaweed tanks. The recirculation ratio of 25% was chosen for the long term monitoring as a small scale study, carried out over 72 h investigating physico-chemical variables at 50% recirculation, showed that the dissolved oxygen concentration was very low and this may have detrimental effects on the abalone in a long term study (see Harris et al. 1999).

Abalone sub-samples

Samples of abalone were taken from tanks from January 2004 to May 2005. At each sampling, 33 animals were randomly removed from each tank, blotted dry to remove excess water and weighed to the nearest 0.01 g. Shell length was measured along the longest axis to the nearest 0.01 mm.

Grading was done in September 2004 as per normal farm grading procedures. Animals were harvested from a tank and the basket number and age group recorded. Animals were then mechanically graded into different size classes and the weights of these size classes were recorded for a total biomass value.

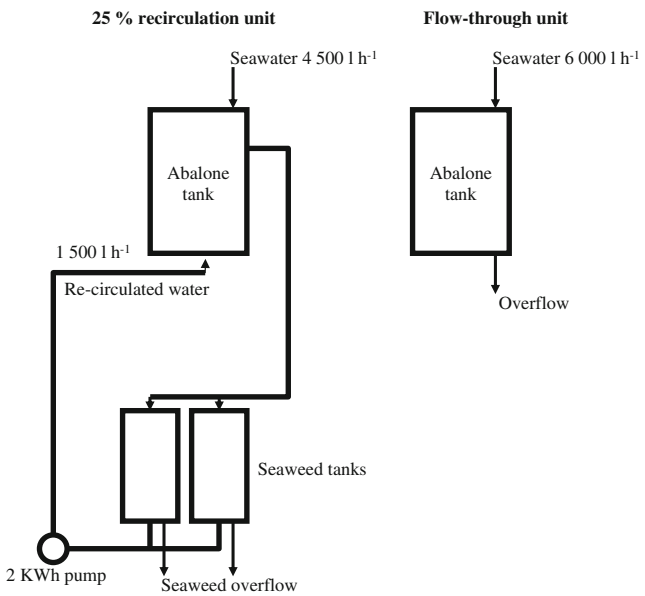

Fig. 1 Schematic diagram of 25% recirculation unit and flow-through unit

Physiochemical variables and water quality

Temperature, pH and dissolved oxygen were recorded daily at 0800, 1200 and 1600 hours for long term monitoring (16 months) in the flow-through abalone tanks, the seaweed tanks, incoming seawater and the integrated seaweed/abalone tanks. Additional intensive short term monitoring was done during three 36-h periods in September 2003 - spring, January 2004 - summer and June 2004 - winter. During this period, water samples for ammonium, phosphate, nitrate and nitrite were taken every 4th hour and analyzed according to the methods below.

Ammonium concentration was determined according to Grasshoff et al. (1976), scaled down to a sample volume of 5 mL and reagent additions of 0.2 mL. Dissolved Inorganic Phosphate (DIP - PO_4^{3-}) concentration was determined using the method described by Grasshoff et al. (1976), with a slight modification in that samples and reagent amounts were reduced by a factor of 10. Nitrate (NO_3^-) and Nitrite (NO_2^-) concentrations were determined using the method described by Nydahl (1976). Ammonium and phosphate samples were taken in triplicate. Nitrate and nitrite were analyzed from a single sample. Testing was done for Total Ammonia Nitrogen (TAN) and then free (unionised) ammonia nitrogen (FAN) was calculated using the TAN concentrations, pH, temperature and salinity values following Bower and Bidwell (1978).

Abalone health

Five sub-samples of abalone were removed from every experimental tank every 3 months by Dr A. Mouton (Abalone Farmers Association of Southern African veterinarian). The health of these animals were analyzed using the standard South African veterinarian procedures and data reported in commercial health reports (Mouton 2004). Veterinary aspects investigated included counting the number of sabellid *Terebrasabella heterouncinata* Fitzhugh, Rouse tunnels on the growing edge of the shell, investigating the gonad histology to determine gonad maturity, a histological examination of all organs to determine parasite status (expressed as the percentage of sample infected) and whether or not the animals were experiencing some form of environmental stress (expressed as either being present or absent), a histological examination of the digestive gland to determine the general condition of the abalone. In addition, animals from both the flow-through units and the 25% recirculation units were compared with animals from the farm's own health reports.

Seaweed growth

Seaweed Specific Growth Rate (in % wet wt day^{-1}) and yield (Y = g wet wt m^{-2} day^{-1}) was determined according to Evans (1972) and calculated as:

$$SGR\% = 100x[ln(W_t/W_0)]/(t_t - t_0)$$
$$Y = [(W_t - W_0)/t]/SA$$

where W_0 and W_t are initial and final wet weights (wt) in grams and t_0, t_t are initial and final times in days, respectively, and SA is the surface area.

Because a brown algal epiphyte *Myrionema strangulans* Greville was found detrimental to seaweed SGR if present in high numbers by Robertson-Andersson (2003), a modification of the Braun-Blanquet (B-B) percentage cover-abundance scale was developed to measure percentage cover of *M. strangulans* on individual thalli. An *Ulva* thallus was placed on a white board and then the percentage coverage of *M. strangulans* was estimated. Five thalli were taken from each seaweed tank. The range of the B-B values given as percentage cover is as follows: 0% cover=1; 1–10% cover=2; 11–25% cover=3; 26–50% cover=4; > 50% cover=5.

Seaweed tissue nitrogen and phosphorus

Seaweed samples were taken from the 25% seaweed recirculation tanks and from fertilized tanks to record dry to wet weight ratios and for biochemical analysis. After each weighing, the seaweed samples collected were washed in distilled water, and visible epiphytes and epifauna were removed. After washing, the samples were spun in a salad spinner for 1 min, weighed on an electronic balance to 2 decimal places, oven dried (70°C, 72 h) and then re-weighed. The dried seaweed was ground using a mechanical grinder with a maximum mesh size of 1 mm. The powder was stored in sealed glass jars in a dessicator at room temperature.

Total nitrogen was determined using the micro-Kjeldahl technique (Solorzano 1969). The protein content was determined by multiplying the N concentration obtained from the micro-Kjeldahl technique by a factor of 6.25, based on the protein N content of 0.16 $g.g^{-1}$ from methods described by Fleurence et al. (1995). This conversion factor, although commonly accepted, includes N not only in the form of protein but includes intracellular reserve pools of N (Fleurence et al. 1995) and therefore the micro-Kjeldahl method would tend to overestimate the actual protein content.

Phosphate (PO_4^{3-}) concentration was determined using the tri acid digestion method described by Murphy and Riley (1962).

Environmental events

Long term temperature monitoring showed that the units were vulnerable to external environmental events that were explained using a series of satellite images, data and tools obtained from http://www.rsmarinesa.org.za of Sea Surface Temperatures (SST).

Sediments

Size distribution of suspended particulate matter as well as the total sediment concentration (wet weight) were measured over a 4 day period. Samples were taken from three locations in the tank; incoming water, water column (30 cm from the surface) and bottom sediment samples. Samples for suspended particulate fractions and total suspended particulate matter were sub-sampled from a 10 L volume siphoned from the tanks. Whatman G/F Filter papers (25 mm) of 1.0 μm were used for syringe filtering and the larger (110 mm) filter papers were used when filtering the particulate fraction samples. Filters were pre-ashed for 2 h at 400°C and weighed. A volume of 5 L was filtered through a series of mesh filters, 50, 40, 30, 20 μm. The filtrate was then transferred to pre-weighed filters paper using de-ionized water. It was assumed that the use of distilled water did not decrease the filtrate and that is was necessary for removing salt. Three sub-samples of 100 mL were taken from the 10 L sample and then syringe-filtered through 25 mm Whatman Glass Fiber filter for analysis of total particle concentration. Sediment accumulation was measured during the cleaning of the abalone tanks. Water from the tank was drained leaving an accumulated layer of sediment at the bottom of the tank. Sediment deposits from baskets and feeder trays were washed down with water, side walls were scrubbed. The sediment rich bottom water was then transferred to 500 L tanks and from this three 20 mL sub-samples and a 5 L sample were collected after vigorous mixing and handled as described for the water column samples. In addition, sediment build-up in the water column of the abalone tanks over the 7-day cleaning cycle was also measured by siphoning 10 l of water and measuring total particle concentration.

Mobile macro-fauna

Samples of mobile macro-invertebrate fauna were taken on one occasion in September 2004 during tank cleaning. Water was drained through a draining hole at the bottom of the tanks and a plankton net (<100 μm mesh) was held in the water flow to collect fauna. After being almost emptied, the drain hole was blocked and the tank walls were brushed and washed. The remaining water and sediment was then sucked out via a pump filling up a 400 L container. From

this container a 50 L sample was taken after rigorous mixing. In addition to the tank sampling intake, seawater to the farm was sampled at three occasions from September to October 2004 during low, mid and high tide (n=9). The pumped seawater was flushed through a plankton net for about 1 h, which correlates to about 2.9–4.1 m^3 depending on flow rate (measured at each occasion). The sediment samples and the material collected in the plankton-net were sieved through a 1 mm mesh to separate the macrofauna (>1 mm). A sub-sample was taken when the density of animals and detritus load was very high. The animals were then sorted to higher taxonomic groups alive and then preserved in 95% ethanol for more detailed identification. The sorted and identified animals were dried in an oven at 60°C to constant weight and weighted. Taxa with extremely low biomass were assigned a minimum weight of 0.1 mg. Air-breathing isopods (e.g., *Ligia dilatata* Brandt), which easily escaped during sampling, had to be excluded. Sessile macrofauna that had to be scraped off the tank walls to be sampled were also excluded. These tank-fouling species included hydrozoans, bryozoans, actiniarias, porifera, bivalves as well as gastropods. Because the herbivorous gastropod the Cape keyhole limpet *Fissurella mutabilis* (Sow.) was found to be so devastating to the seaweed in previous studies (see Robertson-Andersson 2003; Hansen et al. 2006; Njobeni 2006), a modification of the Braun-Blanquet percentage cover-abundance scale was developed to compare numbers of key hole limpets, rather than measuring weights and lengths. A 25 cm quadrat was placed on the side walls of the recirculation tanks and kelp fed tanks and numbers of limpets in the quadrats were noted. The range of the BB values given as percentage cover is as follows: 0 limpets present=1; 1–3 limpets=2; 4–7 limpets=3; 8–10 limpets=4; > 10 limpets=5.

Statistical analysis

All data are expressed as means±standard errors. Analyses were done using STATISTICA V6.1. For abalone growth data, an initial analysis of co-variance was first tested with the baseline value of the outcome, i.e. either length or weight used as a covariate. This was done to account for any differences in starting values. To test for actual differences ANOVAs were performed on the data. Other data was analysed ANOVAs after verifying normal distribution and homogeneity of variances. All data was regarded significant at $p<0.05$.

Results

Abalone growth rates

From September to November 2003 there were no differences in growth or length between abalone in the two systems, indicating that the experimental animals had a 2 month acclimatization phase (Figs. 2, 3). Average length increases in the 25% recirculation units (25% recirc.) were 1.42 mm.month^{-1} vs 1.38 mm.month^{-1} for the flow-through units (FTU) for the duration of the experiment. The 25% recirc. units performed best in autumn and winter, with growth rates of over 4 mm a month. Weight increases in the 25% recirc. units were 3.1 g.month^{-1} vs 2.8 g.month^{-1} in the flow-through units. There were no significant differences between the systems in either length or weight from September 2003 to September 2004. In October and November 2004, abalone in the 25% recirc. units had significantly higher growth rates than those in the flow-through units (ANOVA; $p<0.05$; df=197). This was 2 months after the September grading where the stocking density was reduced in the baskets. At the end of the experiment there was no significant difference in weight or length between abalone in the two systems (Figs. 2, 3).

The farm-graded biomass increased from September 2003 to September 2004 by 275% (144 kg) in the 25% recirc. and 256% (134 kg) in the flow-through units, respectively. A frequency distribution of weights from the grading done in September 2004 and the final weight

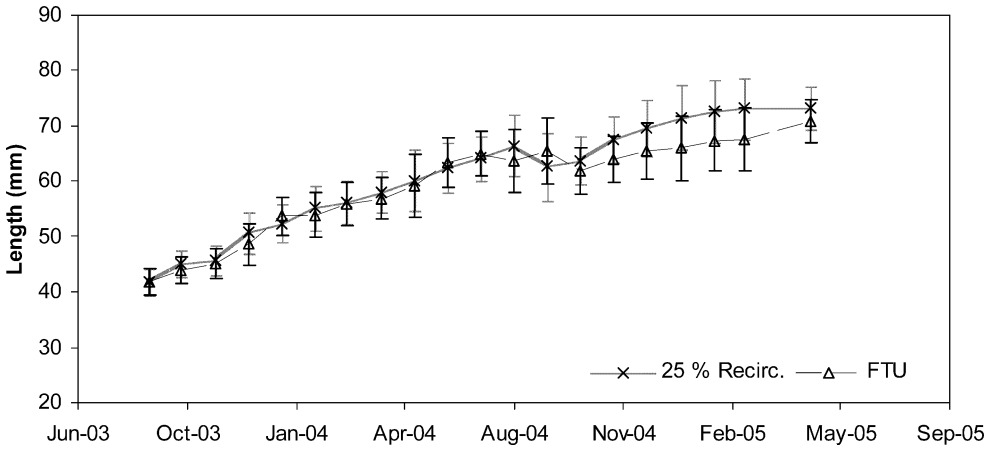

Fig. 2 Length (mm) of abalone in 25% recirc. units vs flow-through units on a kelp-only diet from September 2003 to May 2005 (n=4,000)

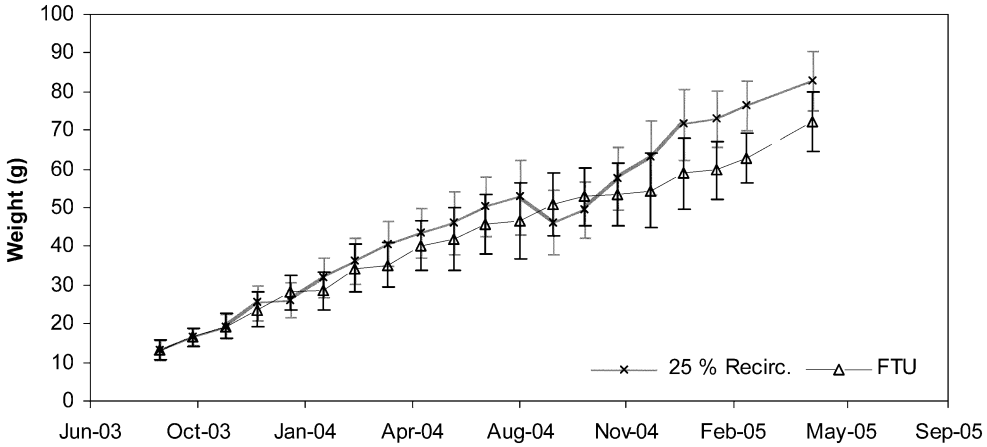

Fig. 3 Weight (g) of abalone in 25% recirc. units vs flow-through units on a kelp-only diet from September 2003 to May 2005 (n=4,000)

measurements showed that there was no significant difference in the mean greatest size of the abalone.

Abalone health

There were no significant differences in the counts of the sabellids between the two treatments over the experimental period. There was also no evidence of shell-boring polychaetes. The animals in both systems were in a good condition for the duration of the experiment. In December 2003, animals in the 25% recirc. units showed signs of environmental stress in their digestive gland histology this corresponded to high temperatures (20.5°C) and high pH (8.00) in the 25% recirc. system.

Gonad condition is a measure of the sexual maturity of the animals and is of critical importance for management. Compared with animals on the rest of the farm whose gonads showed a mixture of developmental stages of sex cells, the gonad development was lower for recirculation units with only immature sex cells present, while the animals in the flow though units remained immature. Histological examinations of the animals showed no differences between units, with both having gut protozoa present (10–50% infected—due to the kelp diet) and the presence of a *Rickettsia*-like intracellular prokaryote (10–30% infected). Histologically, the animals in both treatments were in a better condition than the rest of the farm animals (50–100% infected with *Coccidia, Rickettsia*, gut protozoa and gill inflammation).

Water quality and physiochemical variables

Temperature

In January 2003 (summer), the seaweeds and 25% recirc. units showed a clear diurnal temperature rhythm with the highest temperatures in the units being recorded at 1600 hours and lowest temperatures being recorded at 0000 hours (Table 1). There was a very close correlation between temperatures in the 25% recirc. abalone units and the seaweed tanks, with the 25% recirc. abalone tanks being affected by the temperature in the seaweed tanks (df=42; r=0.85; p<0.0001). The range of temperature was 5°C for both units.

In June 2004 (winter), during the day, the seaweed tanks helped to increase the temperature of the 25% recirc. abalone units above that of the incoming seawater and the flow-through units. At night, the seaweed tanks lost a lot of heat, and this helped to significantly decrease the temperature in the 25% recirc abalone units (ANOVA; df=42; p<0.05) compared to the flow-through units. The maximum daily temperature range was greater in the 25% recirc. units (3°C) compared to the flow-through units (1.9°C) (Table 1).

September 2003 (spring) temperatures were similar to winter and showed that the recirculation lost heat through the seaweed tanks at night, while during the day they imparted heat to the recirculation units (Table 1).

Dissolved oxygen

In January, the dissolved oxygen in the 25% recirc. abalone units (6.7 mg L^{-1} average) were significantly lower than the flow-through units (7.7 mg L^{-1} average) or the seaweed units (8.9 mg L^{-1} average) (ANOVA, df=42; p<0.05). Although the dissolved oxygen in the seaweed tanks was high (8.9 mg L^{-1}) this oxygen was not being transferred to the 25% recirc. abalone units. In addition, during periods of darkness and particularly around 0400 hours in the 25% recirc. abalone units the dissolved oxygen concentration decreased to below 5.4 mg L^{-1}.

In June the dissolved oxygen in the 25% recirc. abalone units was significantly lower compared to the flow-through units (ANOVA; df 28; p<0.05). The oxygen in the seaweed tanks had a significantly higher concentration than both abalone containing units and the ambient seawater (ANOVA;

Table 1 Temperature, pH and dissolved oxygen from three 36-h intensive sampling periods in September 2003, January 2004 and June 2004, in the 25% recirc. abalone units, flow-through units, seaweed tanks and ambient seawater

	September 2003	January 2004	June 2004
	(min) Mean (max)	(min) Mean (max)	(min) Mean (max)
Temperature (°C)			
Flow-through units	(13.6) 15.9 (18.4)	(14.5) 16.6 (19.5)	(14.8) 15.4 (16.7)
25% recirc. units	(13.3) 16.4[a] (19.1)	(15.6) 18.1[a] (20.6)	(13.4) 14.6[a] (16.4)
Seaweed tanks	(12.7) 16.9[a] (19.3)	(16.0) 18.8[a] (24.0)	(13.3) 14.5[a] (16.8)
Ambient seawater	(14.2) 15.6 (16.7)	(14.6) 16.3 (19.5)	(15.0) 15.4 (16.3)
pH			
Flow-through units	(7.4) 8.1 (8.4)	(7.6) 7.9 (8.1)	(7.7) 7.9 (8.2)
25% Recirc. units	(7.8) 8.0 (8.3)	(7.4) 7.6 (7.9)	(7.8) 8.0 (8.2)
Seaweed tanks	(7.8) 8.1 (8.5)	(7.6) 8.0 (9.3)	(7.8) 8.0 (8.4)
Ambient seawater	(8.1) 8.2 (8.3)	(7.9) 8.1 (8.3)	(8.1) 8.2 (8.4)
Dissolved oxygen (mg L^{-1})			
Flow-through units	(6.8) 7.7[b] (8.5)	(6.7) 7.7[b] (8.6)	(6.8) 7.6[b] (8.3)
25% recirc. units	(5.1) 6.9 (8.5)	(5.3) 6.7 (7.9)	(6.3) 6.9 (7.5)
Seaweed tanks	(7.2) 8.4[a] (10.4)	(7.0) 9.0[a] (13.0)	(7.0) 8.3[a] (10.1)
Ambient seawater	(8.0) 8.4[a] (8.9)	(8.0) 9.1[a] (10.3)	(8.0) 8.5[a] (9.0)

Letters indicated values significantly different between treatments (ANOVA, $p<0.05$)

df=28; $p<0.05$). The dissolved oxygen values were higher than those found in summer and the range for all treatments was smaller when compared to the summer values. Spring dissolved oxygen concentrations were similar to winter and the seaweeds showed a diurnal rhythm in oxygen production. Between 2000 and 0400 hours the 25% recirc. units had significantly lower dissolved oxygen values compared to the flow-through units (ANOVA; *df*=28; $p<0.05$) (Table 1).

pH

The pH in the seaweeds tanks in January and June showed a clear diurnal rhythm due to photosynthesis. In both abalone treatments pH showed a diurnal rhythm but this was exacerbated in the 25% recirc. abalone units. There were no significant differences in pH between the flow-through units and the 25% recirc. abalone units in any of the seasons (Table 1).

Long term physiochemical variables

Long term measurements of dissolved oxygen at 25% recirculation was on average 4±0.5 % lower than the flow-through abalone units. Temperature was 1±0.2 % higher and pH was 1±0.1 % lower in the 25% recirc. abalone units compared to the flow-through units over the whole experimental period. There was an inverse linear relationship between temperature and oxygen in the 25% recirc. and flow-through units with less oxygen being available in the water at higher temperatures ($y=-0.3985\times+1.3383$; *df*= 24834; $r=0.2$; $p<0.05$). The dissolved oxygen in the 25% recirc abalone units was 33±6 % lower than in the seaweed tanks with the pH being 2±0.6 % lower. There was a positive linear correlation between temperature and dissolved oxygen ($y=0.1244\times+0.6401$; *df*=24834; $r=0.25$; $p<0.05$), due to the production of oxygen by seaweed photosynthesis.

Environmental events

Six high temperature environmental events occurred (Fig. 4). These events can be divided into two types: advection events and warm water intrusion events. Both are caused by a decrease in wind-forcing. The more common event (4 out of 6) is a decrease in upwelling and increase in solar advection resulting in increased temperatures and high nutrient availability of coastal waters. The other type of event is a warm water intrusion over the Western Agulhas Bank and Agulhas eddies. A warm water intrusion over the Western Agulhas Bank, such as Event C, is seen as a rise in temperature of 3.7°C (Fig. 4), decrease in dissolved oxygen by 1 mg L^{-1}, a 0.3 increase in pH, and a 7-kg decrease in seaweed production per seaweed tank (Fig. 8). In Event D, the farm experienced ambient seawater temperature increasing 4.8°C above the average to 23.4°C (the highest recorded temperature for 2005) (Fig. 4). Coupled with this, the pH and the dissolved oxygen in the water decreased by 1.06 units and 1.8 mg l^{-1} respectively at the height of the event. Seaweed production decreased by 4.5 kg per tank (Fig. 8). In Event F, the local SST increased to a high of 19°C (Fig. 4). This was more due to advection of surface waters and northwards displacement of surface waters from the front back to the inshore region. There was no intrusion of water over the Western Agulhas Bank and the warm water still remained nutrient rich. Seaweed production during this event increased by 2.5 kg per tank.

Upwelling events can be seen by sharp decreases in temperatures over a short time scale (Fig. 4). The lowest temperature recorded at Danger Point (during this study)

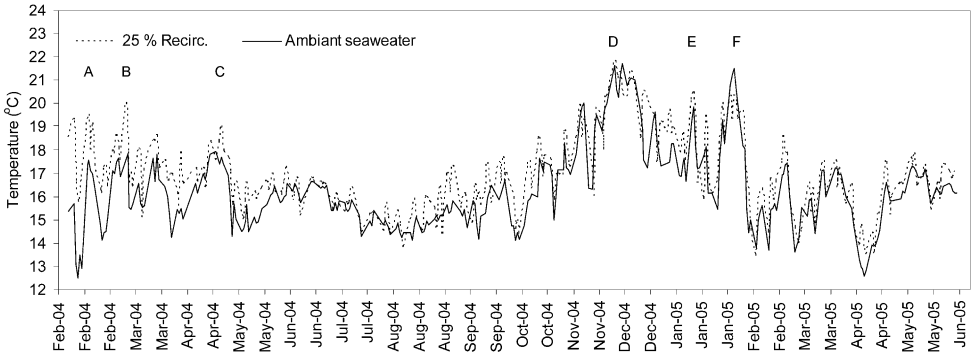

Fig. 4 Daily average long term temperature measurements from February 2004 to May 2005 of the incoming seawater and 25% recirc. abalone units for comparison. *Letters* denote large scale environmental events: Event *A*: from 26 February until 10 March 2004 - advection; Event *B*: 18 March to 26 April 2004 - advection; Event *C*: 21 April to 4 May 2004 - warm water intrusion; Event *D*: 24 January to 7 February 2005 - warm water intrusion; Event *E*: 22 February to 3 March 2005 - advection; Event *F*: 17 March until 1 April 2005 - advection. Sharp decreases in ambient seawater temperatures are indicative of upwelling events

occurred in an upwelling event on 1 August 2003 with an ambient sea temperature of 11.5°C.

Water nutrients

Mean total ammonia nitrogen (TAN) did not accumulate in the recirculation units. The flow-through units had significantly higher TAN (3.3±1.3 μmol) than the 25% recirc. units (2.0±1.1 μmol) (ANOVA; df=12; p<0.05). The seaweed tanks had significantly lower TAN (4.7±1.3 μmol) than the 25% recirc. (ANOVA; df=12; p<0.01). Two peaks in TAN production occurred in both the 25% recirc. and the control abalone treatments between 2000 and 0400 hours. Ambient seawater TAN averaged 3.9±0.8 μmol. There was no seasonal pattern in any of the data.

Table 2 lists ammonia concentrations for summer and winter. In summer the pH and temperatures were high (Table 1) resulting in greater ammonia conversion, compared to winter which had lower temperatures and lower ammonia concentrations.

There was no accumulation of DIP under recirculation. Mean DIP for the flow-through units were 0.88±0.39 μmol, for the 25% recirc units 1.17±0.24 μmol, for the seaweed tanks 1.28±0.36 μmol and for the incoming seawater 0.64±0.41 μmol. The seaweed tanks had significantly lower DIP compared to the flow-through units (ANOVA; df=12; p<0.05). Results were similar in the three seasons tested.

Table 2 Ammonia concentrations in summer and winter of in a 25% recirc. units and flow-through units fed a kelp only diet

	Mean (μmol)	Max (μmol)	Min (μmol)
January 2004 – Summer			
Flow-through units	0.10±0.07	0.29	0.03
25% recirc.	0.08±0.05	0.18	0.02
June 2004 – Winter			
Flow-through units	0.16±0.009	0.34	0.08
25% recirc.	0.06±0.03	0.12	0.04

There was no accumulation of nitrate under recirculation. Mean nitrate concentrations for the flow-through units were 3.47±0.89 μmol, for the 25% recirc. units 1.17±0.22 μmol, for the seaweed tanks 0.25±0.27 μmol and for the incoming seawater 3.07±0.92 μmol. Mean nitrate in the flow-through units was significantly higher (ANOVA; df=12; p<0.05) than 25% recirc. units, which in turn was significantly higher than the seaweed tanks (ANOVA; df=12; p<0.05).

Mean nitrite concentrations for the flow-through units were 0.63±0.46 μmol, for the 25% recirc. units 0.22±0.05 μmol, for the seaweeds 0.08±0.08 μmol and for the incoming seawater 0.84±0.50 μmol. There was more fluctuation in the flow-through units with small peaks in concentrations at 0000 and 0400 hours. The flow-through units had significantly (ANOVA; df=6; p<0.05) higher average concentrations than the seaweeds and the 25% recirc. abalone units. The seaweeds tanks had significantly lower average concentration than the 25% recirc. abalone units (ANOVA; df = 6; p<0.05). There was no accumulation of nitrite under recirculation.

The nutrient uptake efficiency was measured as the average percentage decrease in nutrients (Table 3) (defined by Buschmann et al. 2001; Chopin et al. 2001) it can be seen that phosphate was not removed by the seaweeds. Nitrogen in the seaweed tanks running at 25% recirculation was almost completely removed in nitrate and nitrite forms. There was also a large difference in the uptake efficiency between the abalone units on flow-through vs recirculation, showing that the amount of nutrients removed by the seaweeds decreased nutrients in the whole system compared to a flow-through system.

Table 3 Percentage of dissolved nutrients removed between the flow-through units compared to the 25% recirc. units and between the seaweeds tanks compared to the waste water existing the 25% recirc. units

	NH_4	NO_3	NO_2
25% recirc. abalone	38.06 ±18	64.8±11.1	48.8±25.2
vs flow-through abalone units	32.5–85.4	33.1–77.9	5.1–89.4
Seaweed tanks vs 25% recirc.	80.8±22.6	77.7±24.5	75.7±13.7
abalone units	24.3–99.5	30–100	53.4–100

Seaweed biomass in this study was 2 kg m^{-2}. Mean±SD and range values are shown

Suspended particle loads

There was no significant difference in the suspended solids in the water column between the two systems either in the total load (105.3 mg L^{-1} flow-through units vs 90.6 mg L^{-1} 25% recirc. units) or in the particle size fractionation (Fig. 5). There was no significant difference in the particle fractions between the two systems with the larger size class (> 50 μm) having the highest percentage of the total load. Over a 7-day period there was no significant difference in the suspended solid loads between the two systems (0.085–0.11 g L^{-1} flow-through units and 0.082–0.11 g L^{-1} 25% recirc. units). Regression analysis showed that the concentration of particles in the flow-through units and the 25% recirc. units remained constant over the 7 day period (p=0.75, r=0.149). Particle fractionation over the 7-day period in the two systems showed no significant differences. The greatest load in both systems was in the largest particle size class (> 50 μm). In a 7 day period between 55–72 kg of sediments would be released through the overflow water form both systems.

Sediment accumulation

The amounts of accumulated bottom sediments were significantly more than the suspended particle load (ANOVA, df=12; p<0.05). There was a significant difference between the bottom sediment loads of the two systems (ANOVA; df=72; p<0.001). The particle fractionation showed that the flow-through units had significantly more of the larger particles (> 50 μm and 40–50 μm and 20–30 μm) (p<0.05), while the 25% recirc. abalone units had significantly more particles in the 20–30 μm range) (Fig. 6). The flow-through units would produce 45.45 kg of sediment a year vs the 41.64 kg produced by the 25% recirc. units in bottom sediments alone.

Mobile macro-fauna

The mean dry weights and numbers of mobile macro fauna were respectively, 2.19±0.67 g.DW or 8,232 individuals per abalone tank in the 25% recirc. units and 2.17±1.75 g. DW or 11,648±10,960 individuals per abalone tank in the flow-through units, with no significant difference in either dry weight or numbers. In total, 28 faunal taxa were identified in all the samples. The diversity (including unidentified taxa) was no significantly different between the 25% recirc. and the flow-through units. Thirty-four taxa of mobile and sessile fauna were found in the seaweed tanks alone. The combined system supports approximately 48 taxa.

The total faunal density and diversity was significantly higher in the abalone tanks compared to an equal volume of intake seawater (ANOVA; df=9; p<0.001). The most abundant taxa in the abalone tanks were the amphipod *Paramoera capensis* (Dana) and tanaids (Tanaidacea spp.) together with polychaetes, especially Nereid species. Other abundant taxa were the amphipod *Hyale* sp. and the isopod *Janiopsis palpalis* Barnard, as well as other (unidentified) amphipods. These taxa contributed 81–99 % of the total mobile macrofauna biomass in the abalone tanks.

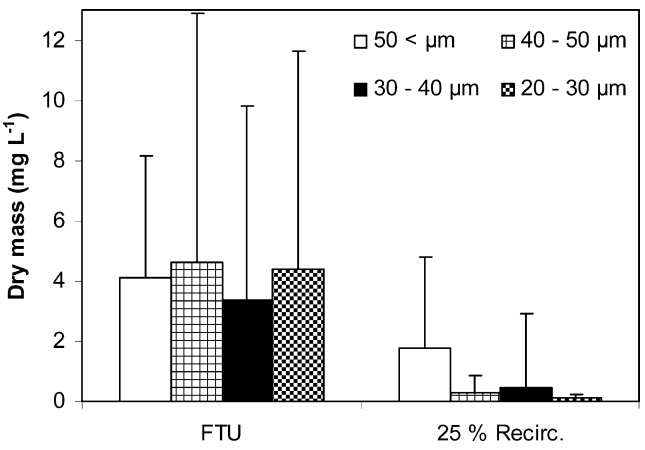

Fig. 5 Particle fraction of water column suspended particles between the flow-through units and the 25% recirc. units

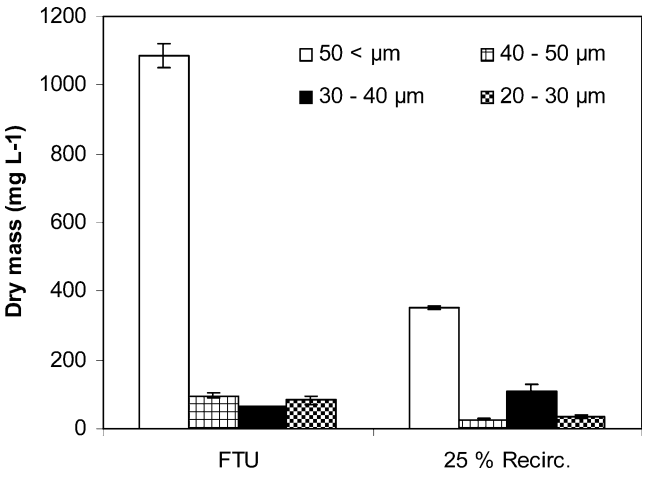

Fig. 6 Particle fraction of bottom sediments between the flow-through units and the 25% recirc. units

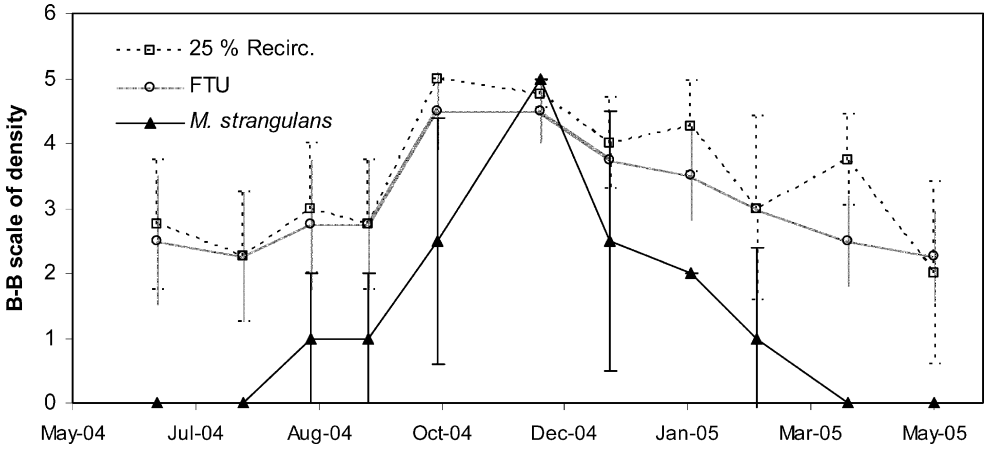

Fig. 7 Density of keyhole limpets in the 25% recirc. seaweed tanks (n=6) and the flow-through seaweed tanks (n=4) and percentage cover of *Ulva* thalli by *M. strangulans* from the seaweed tanks

Keyhole limpet numbers showed a seasonal trend in number with an increase around September (Fig. 7). Although there were slightly higher numbers in the 25% recirc. units in the winter months, this was not significantly different from the flow-through units.

Seaweed production, nutrient and water content

There was a seasonal trend in SGR of the seaweeds with highest SGR (6.25±3.4 day^{-1}) and yields (0.12–2 kg m^{-2} day^{-1}) occurring in September through to February in the 25% recirc. seaweed tanks. The high standard error was due to low growth rates in some tanks which experienced a *M. strangulans* infestation (Fig. 7). SGR in June and July was lower (1.59±1.1% day^{-1}) with an average of 3.2% day^{-1} with yields of 0.0–0.03 kg m^{-2} day^{-1} over the experimental period. *Ulva* production per tank (Fig. 8) shows that during the winter months the algae did not increase in biomass but rather declined as the amount harvested per tank was lower than the initial 10 kg stocking density. There was no significant difference in algal production between fertilized flow-though seaweed tanks and the 25% recirc. seaweed tanks.

Table 4 lists the proportions of N and P in the seaweeds at different seasons in the spring and summer months. The N content in the seaweeds was low and this corresponded with periods of high SGR. In addition, the water content in the seaweeds was higher from October 2001 to February 2002 (late spring to late summer) and decreased in March 2002 to August 2003 (autumn to winter). Phosphate content in the seaweeds increased in the autumn and winter months. Average tissue protein values obtained for this study were 36.6%, from the 25% recirc. seaweed tanks and 33.4% from the fertilized seaweed tanks.

Discussion

Abalone growth rates

This study did not find a significant difference in abalone growth rates at the conclusion of the experiment. Thus, abalone growth rates were not affected by being cultivated in a recirculation system and were similar to those obtained on the farm under normal culture conditions. Fleming et al.

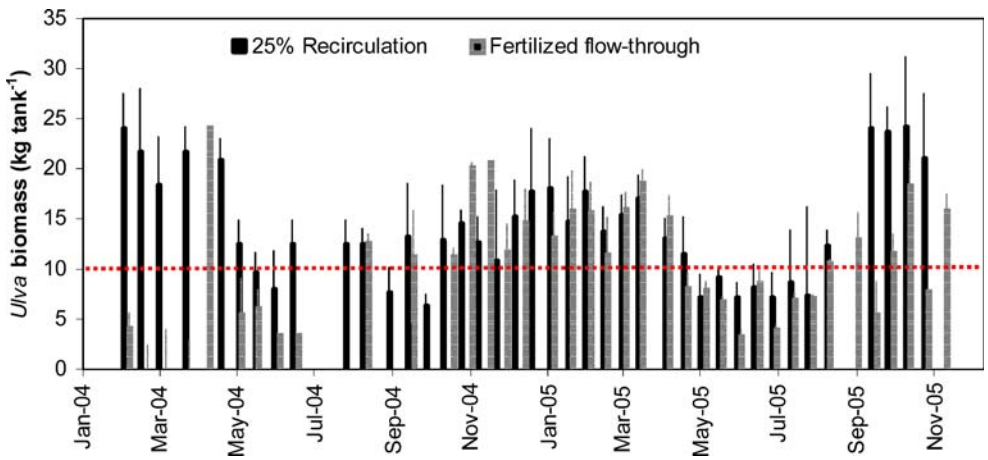

Fig. 8 *Ulva* biomass harvested per tank (n = 6) from January 2004 to May 2005 in the 25% recirc. seaweed tanks (n=6) and the flow-through seaweed tanks (n=4). The fertilized flow-through tanks are for comparison and received 12 volume exchanges per day while the 25% recirc. seaweed tanks received 7.2 volume exchanges per day

Table 4 Tissue N and P concentrations in seaweed samples from 25% recirc. abalone units and fertilized flow-through seaweed tanks

		September 2003	December 2003	April 2004	July 2004
P ($mg.g^{-1}$)	25% recirc.	0.65± 0.40	0.80*±0.01	2.27^{b}±0.20	3.78^{a}±0.66
	Fertilized flow-through units	1.05^{c}±0.13	0.66±0.03	2.33^{b}±0.08	3.15^{a}±0.49
N ($mg.g^{-1}$)	25% recirc.	11.51±1.91	13.98±2.44	45.02^{a}*±6.06	43.80^{a}±5.13
	Fertilized flow-through units	22.54^{c}*±2.48	14.96±6.6	36.04^{b}±0.43	51.64^{a}*±2.27
N:P ratio	25% recirc.	17.71±2.66	17.53±2.75	20.05*±4.42	11.67±0.64
	Fertilized flow-through units	21.46±1.4	22.48±8.84	15.48±0.36	11.59±7.76
SGR ($\%.d^{-1}$)	25% recirc.	2.33±3.79	3.53±0.73	1.62±0.88	− 0.85±1.71
	Fertilized flow-through units	-0.89^{1}±2.96	3.28±0	2.14±3.69	− 5.73±2.15
% water	25% recirc.	88.06±0.45	88.31±0.12	85.93±0.38	85.89±1.15
	Fertilized flow-through units	87.99±0.65	89.25±0.92	85.62±0.17	85.79±0.85

* Values significantly higher between treatments (ANOVA, $p<0.05$)
Letters indicated values significantly different within treatments
(n=6 for 25% recirc. seaweed tanks and n=4 for fertilized flow-through seaweed tanks. (Mean±s std SD)
[1] Low growth rates reported due to a loss of seaweed biomass due to a *M. strangulans* infestation

(1996) and Mai et al. (2001) state that most abalone farmers would be satisfied with a growth of 2–3 mm per month. This however relates to tropical abalone which grow much faster than the temperate species *H. midae*. There was some indication that growth rates were significantly different at certain times of the year in the different units, but this did not affect the outcome of the experiment. It is possible that the 1 and 2% increase in temperature in the recirculation units was too low to positively affect growth rates. The low recirculation ratio could also account for the lack of negative effects on abalone growth rates.

Gonad index

This is a measure of the sexual maturity of the animals and is of critical importance for management, as a mature gonad may make up 15–20% of an abalone's body weight in a fully mature individual (Hahn 1989). One of the hypotheses was that a recirculation system would cause an increase in the gonad index due to increased temperatures, meaning that animal energy was going to reproductive growth and not somatic growth. The increase in gonad index in the recirculation units also corresponded with a natural increase due to wild abalone spawning seasons (Hahn 1989) and thus was not an effect of the animals being under recirculation.

Seaweed nutrient content

The protein content of the *Ulva* grown in the recirculation units is less than the 44% reported by Goldburg and Triplett (1997) in their recirculation system. Our results fall within the protein range found to be most beneficial to *H. midae* (36–44% protein) (Shipton 1999; Britz 1996; Sales and Britz 2001). Average tissue protein values obtained for this study were much higher than wild harvested *Ulva* (3.7–24%) (Smith and Young 1954; Nisizawa et al. 1987; Simpson 1994; Castro-Gonzales et al. 1996; Simpson and Cook 1998; Wilkinson 2001; Wong and Cheung 2001) and has positive effects on abalone growth when used as a food source (Naidoo et al. 2006). During summer, the seaweeds experienced higher SGR but lower tissue N. This finding agrees with previous reports (Duke et al. 1986, 1987, 1989a, b), of an inverse relationship between SGR and tissue nitrogen, but is in contrast with studies by Neori et al. (1991). This result may have been confounded as a result of the *M. strangulans* infestation.

Work done by Björnsäter and Wheeler (1990) showed that there is a relationship which exists between tissue N and P for *Ulva* in the North-east Pacific with a ratio of 16:24 indicating that the seaweeds were nutrient sufficient and our cultivated seaweeds ratios fall within the low end of this range. This relationship however, needs to be tested to see if it holds true for the *Ulva* cultivated in this experiment.

Seasonal changes in tissue N and P can be explained by coastal oceanographic process. Boyd et al. (1985) showed that there is an increase in nitrogen values in the seawater in the Walker Bay area (close to I & J) in autumn and winter. Phosphate content in the seaweeds increased in the autumn and winter months, as found by Robertson-Andersson (2003) and corresponds with a seasonal increase in phosphate concentrations in the Walker Bay area (Hutchings and Andrews 1980; Chapman and Shannon 1985; Mitchell-Innes and Walker 1991).

Seaweed SGR

This research has shown how seaweed SGR is either positively or negatively affected by large scale (nutrient upwelling and advection or intrusion) environmental events in the adjacent environment. In addition, their SGR was also affected by events on a tank scale. One of the most notable negative effects on seaweed growth rates was the presence of a

M. strangulans infestation which occurred in spring and persisted over the summer months. This algae forms small round epiphytic crusts ('brown spots') on the surface of the *Ulva* and, as the *Myrionema* ages, the centre of the crusts disintegrates, apparently encouraging break-up of the host thallus. The decrease in *Ulva* SGR was accompanied by increasing occurrence of *M. strangulans* on the algae (a relationship previously described in Robertson-Andersson 2002, 2003; Robertson-Andersson and Wilson 2004). The increase in *M. strangulans* presence is known to correlate with a linear decrease in SGR (Robertson-Andersson 2003). Another negative effect on seaweed growth rates in the same period was the increased presence of a grazer, the Cape key-hole limpet (Hansen et al. 2006).

The research in this paper is complicated due to the effects of shading the seaweed treatments with a 50% shadecloth. Robertson-Andersson (2003) studied effects of seasonal shading in the same seaweed tanks over the same seasonal period and compared this to unshaded tanks and found that the tanks that were shaded had a significantly higher SGR than the unshaded tanks, mainly due to an infestation of *M. strangulans* causing the complete loss of the seaweed culture in the unshaded tanks. There were no significant differences in any of the physiochemical variables tested or differences in the water quality, when seaweed cultures were shaded or unshaded. The maximum benefit in terms of SGR and decreased *M. strangulans* presence occurred when the seaweed tanks were shaded from September to February (Robertson-Andersson 2003). Additional experiments looked at the type of shade cloth used. No change in *M. strangulans* percentage cover was obtained using a 20% shadecloth while an 80% shadecloth decreased SGR significantly (Robertson-Andersson 2003). As the primary goal of this research was to maintain the seaweed as biofilters to enable the recirculation system to continue functioning efficiently over the period tested, it was deemed necessary to shade the seaweed tanks.

SGR showed a seasonal trend and was highest in summer. SGRs observed in this study were similar to those found by Robertson-Andersson (2003) in the abalone treatment but lower than those obtained in the literature, although in most cases, smaller tank sizes were used in the latter studies (Lapointe and Tenore 1981; Duke et al. 1989a, 1989b; Björnsäter and Wheeler 1990; Neori et al. 1991). Robertson-Andersson (2003), showed that there is a decrease in SGR when scaling up tank sizes. Growth rates for *U. fenestrata* Postels et Ruprecht under experimental conditions were 16% wet wt.day^{-1} (Björnsäter and Wheeler 1990). This is lower than those obtained for *U. curvata* (Kützing) De Toni, 52% wet wt.day^{-1} in short-term laboratory studies (Duke et al. 1989a, b); *U. lactuca*, 18.6% wet wt.day^{-1} (Neori et al. 1991) and *U. fasciata* Delile, 36% wet wt.day^{-1} (Lapointe and Tenore 1981). The low growth rate for *U. fenestrata* may be attributed to the lower water temperature (13°C) compared to other experiments (Björnsäter and Wheeler 1990). The SGR obtained by Neori et al. (1991) were low and could be due to the scaling up of the tank sizes as the other studies were in experimental, small-scale setups.

Seaweed water content

The tissue water content for both systems falls within the range of 80–90% which is the case for many macro-algae (DeBoer 1981). Our data seem to suggest that at high SGR with correspondingly low tissue protein there is more cellular water in the seaweed, although this relationship has not been tested.

Physiochemical variables

Over the long term, the integrated system raised the water temperature by 1% at 25% recirculation. During the short term studies in September, and in the study by Lindström (2006) using the same experimental set-up during spring 2005, the flow-through units had higher night-time temperatures while the 25% recirc. abalone tanks were losing heat at night, by being connected to the seaweed tanks which were cooler (minimum of 13.3°C). This means that the seaweed tanks were losing more heat or were less able to retain the heat at higher recirculation in the winter periods, due to the seaweed tanks having a lower latent heat capacity and no insulation. They were thus more vulnerable to cooler night time temperatures. During the day, the seaweed tanks heated up very quickly and were able to raise the temperature of the recirculating abalone tanks, while the flow-through units were dependant on incoming seawater temperatures and would remain low in an upwelling event. Schuenhoff et al. (2003) showed that an integrated fish/abalone/seaweed culture system with 50% re-circulation in Israel using *U. lactuca* as the biofilter also experienced heat loss during winter re-circulation. The construction of a greenhouse cover over the biofilter tanks prevented this heat loss. They found maximum heat loss in early mornings and maximum heat-gain around 1600 hours, the same pattern experienced in this study and by Lindström (2006). The temperature ranges experienced in the seaweed and abalone tanks were within the optimum physical range for *H. midae* (Britz et al. 1997).

It is generally thought that connected seaweed tanks should be able to provide higher dissolved oxygen concentrations to the re-circulating culture system (Troell et al. 2003; Neori et al. 2004). Schuenhoff et al. (2003) found that water re-circulated through seaweed tanks raised dissolved oxygen levels and that this could support fish-tanks without additional oxygen "at times of highest oxygen demand". Neori et al. (1996) studied a land-based fish/seaweed re-circulation system and

found that connected seaweed tanks contributed to the oxygen balance in the fish compartment by significantly slowing the rate of oxygen depletion. However, in the current study at 25% recirculation dissolved oxygen was 4% lower compared to flow-through units. This was despite the fact that the seaweed tanks in the re-circulation system had produced oxygen even at high temperatures and had 33% more oxygen than the 25% recirc. abalone units. The data showed that the dissolved oxygen in the seaweed tanks was not being transferred to the abalone tanks. Various theories were proposed and changes were made to the system from August 2003 to December 2003 to try to improved oxygen concentrations. The loss of oxygen was not due to bacterial depletion (unpublished data). Two mixing systems were designed and built (1) to increase the mixing time to allow the oxygen to become more saturated and (2) to increase oxygen through tumbling. Both designs failed in their objectives and it is thought that the seaweeds were supersaturating the oxygen in the tanks and that during the pumping this oxygen was being blown off and did not remain in the recirculated water. A larger system with a longer water retention time might improve these values. At higher recirculation ratios in spring and summer, when the temperature in incoming seawater is higher (intrusion event) and air temperature is also high (the abalone system picks up heat from warm air being blown into the tank for aeration) and at night when there is a large amount of seaweed in system with the oxygen holding capacity being low, this is likely to be a critical failing of the system. Robertson-Andersson (2003) showed that a high stocking density (4.5 kg m^{-2} in the same system), compared to lower densities (0.5–2 kg m^{-2}), exhibited the highest concentrations of dissolved oxygen at day time and the lowest at night time, due to photosynthesis and respiration.

Water nutrients

The low ammonium, nitrate and nitrite concentrations in the seaweed tanks under recirculation indicates that biofiltration by the seaweeds is occurring. The low nitrate and nitrite concentration in the seaweed tanks supports the notion of N-starvation, since seaweeds are known to prefer ammonium before nitrate (Lobban et al. 1985; Loban and Harrison 1994), and a good supply of ammonium would result in less reduction of nitrate and nitrite. Phosphate was the only nutrient analyzed that showed significantly higher concentrations in re-circulating tanks compared to controls, which is an indication of N-limitation in the system (Troell et al. 2003). Schuenhoff et al. (2003) show reduced N/P ratios in an integrated fish/abalone/seaweed culture and suspected N-limitation in the system.

If water quality biofiltration is the main goal of integrated aquaculture using seaweeds, it is often necessary to starve the seaweeds to obtain maximum reduction of the water nutrient concentrations (Troell et al. 2003; Neori et al. 1998, 2003, 2004). In a 1-stage biofilter such as the one in our study, a large biofilter area is required to strip nutrients efficiently, hence the high seaweed to abalone ratio. Our system could have been made more efficient if we had used a multi-stage biofilter with the two seaweed tanks in series rather than in parallel as in the study by Neori et al. (2003). Reasons for having the seaweed tanks in parallel and not in series were to prevent transfer of potential diseases, pathogens and epiphytic algae harming the biofilter. *Myrionema strangulans* can completely decimate the seaweed biofilter and, if the seaweed tanks were in series, transfer of this alga would result in both seaweed tanks having infestations. By having the two tanks in parallel one tank could be infected while the other would remain unaffected, thus maintaining the biofiltration capacity of the system. As Lindström (2006) found and with the results presented by Robertson-Andersson (2003)—in the same system—it is important to optimize seaweed densities to obtain maximum nutrient reduction. Nitrogen-starved seaweeds do not provide a good quality feed (Neori et al. 1998, 2004; Troell et al. 2003). By altering the seaweed stocking density one can change the products of a recirculation system to optimise either seaweed biofiltration efficiency or seaweed quality and growth. Biofiltration efficiency can change over the cultivation period of the seaweeds, this was one of the reasons for the short harvesting period of 14 days, Robertson-Andersson (2003) found optimum nutrient efficiency occurred when the seaweeds were stocked at 3.5 kg m^{-2} and that nutrient efficiency decreased at 4.5 kg m^{-2}. By stocking the tanks with an initial biomass of 2 kg m^{-2} and harvesting them more frequently, we were able to maintain a high nutrient efficiency over the 14-day period regardless of season. Another means of changing biofiltering efficiency is to alter the water flow rates, with low flow rates having high biofiltering efficiencies and low biomass production (Buschmann et al. 2001). The flow rates in the seaweed tanks in our recirculation system were low due to the low recirculation ratio. When flow rates were increased by increasing the recirculation ratio, biofiltration efficiency decreased (Lindström 2006). For normal operating conditions a balance that provides for both a high biofiltation capacity and a high biomass needs to be found (Neori et al. 1998; Troell et al. 2003).

Sediments

Suspended solids management is a key factor in determining the success of re-circulation systems and suspended solids concentration should not exceed 15 mg L^{-1} for re-circulating systems (Chen et al. 1993). In this study, the surface particle concentration was greater than 90 mg L^{-1}, which is six times this limit. The Chen et al. (1993) study was based on a gravel bed drawdown biofilter which is

highly sensitive to clogging by particulates. In our study, the total tank accumulations of sediments in the flow-through units and re-circulation systems were not significantly different from each other. This is an important result because it provides evidence to dismiss the notion that the re-circulation systems accumulate more particles than a flow-through unit.

Our results showed that there no significant differences in particle size fractionation in the water column, total particle load, or the loading of 35 μm or smaller fractions between a flow-through system and a recirculation system. Brandt (2006) showed that this trend remained even when the recirculation ratio was changed to 50 and 75%. Since sabellids prefer organic particles smaller than 35 μm as feed (Chalmers 2002), these results indicate that, at least from a feed perspective, kelp fed re-circulating systems do not favour sabellids by increasing their available feed. This is supported in the sabellid count data, as higher counts of sabellids would indicate a higher food availability in the recirculation systems.

Mobile and sessile macro-fauna

A mobile macro-fauna population can easily become established in an abalone culture system via association with the cultured species, feed input (fauna coming in with the kelp as it is not cleaned before being placed in the tanks), or introduction from the surrounding ecosystems through the seawater intakes as few filters are used. Within re-circulation systems there is, theoretically, a higher potential for build up of mobile macro-fauna densities, since the fauna can circulate with the water and may stay long enough to reproduce. This could have positive and negative impacts on the target aquaculture species. In integrated animal-seaweed cultivation, positive effects may be anticipated from the conversion of particles to dissolved nutrients that can be taken up as a nutrient source for the cultivated algae, or through grazing on epiphytes and microfilms (Shacklock and Doyle 1983; Brawley and Fei 1987; Anderson et al. 1998; Klamermans et al. 2002), increasing seaweed growth and reducing the need for cleaning. No significant differences in densities or taxa of mobile macrofauna between the 25% recirc. and the flow-through units were found. In addition, numbers of *F. mutabilis* were not significantly different between treatments, contrary to what was expected. Thus, recirculation at this low water exchange rate does not influence mobile fauna densities. The cleaning of the abalone tanks in the system every 7th day and the harvesting of the seaweed tanks every 14th day is also likely to prevent the build up of a mobile fauna population in these tanks. None of the taxa found in the tanks are pest species and most are detritivores. However, the amphipod *Hyale* sp. is largely a herbivore and several of the other amphipod species found may graze on both micro and macro algae. The keyhole limpet *F. mutabilis* is known to graze by trapping floating thalli in the cultivated seaweed tanks (Robertson-Andersson 2003). It becomes more problematic in the system in September when large numbers are found (Robertson-Andersson 2003, 2007; Hansen et al. 2006). Fortunately, it can be controlled through the use of fresh water washing of the tanks and seaweeds for longer than 20 min, which is not harmful to the seaweeds (Robertson-Andersson 2003; Smit et al. 2003; Hansen et al. 2006). Other problematic species, such as *Paridotea reticula* Barnard, have been found in *G. gracilis* seaweed tanks on the farm (Smit et al. 2003; Njobeni 2006; Hansen et al. 2006) A 3 h freshwater treatment has been successfully used to control this pest isopod (Smit et al. 2003). This exposure had a minor effect on seaweed growth.

Environmental events

The I & J farm, located on the Western Agulhas Bank, is subject to intermittent wind-driven coastal upwelling, particularly northward of prominent capes (including Danger Point) (Boyd et al. 1985; Probyn et al. 1994). On the Western Agulhas Bank, the upwelling season starts later (i.e., summer) (Jury 1988) and is episodic in nature (Largier et al. 1992). There is an 18°C thermal front moving westwards from Cape Agulhas, which contains colder water and nutrients inshore of it (Largier et al. 1992). This front clearly marks longshore variations in upwelling associated with Cape Agulhas. There is a measured jet in roughly the same position (Bang and Andrews 1974). Upwelling and subsequent containment of water inshore results in higher nutrient levels inshore of the front with lower to negligible levels above the front and offshore of the front (Largier et al. 1992). Although the upwelling is episodic on the Western Agulhas Bank the subsurface thermoclines remain tilted upwards towards the coast throughout the upwelling season (Boyd et al. 1985). When the wind-forcing weakens in this upwelled system, warm surface water moves shorewards at the surface, but the isotherm still remains tilted. The nutrient rich waters are still contained inshore of this front. This results in warm nutrient rich water in the Walker Bay area. If the thermocline deepens, then a warm water intrusion of the Agulhas current water occurs particularly over the outer shelf (Boyd et al. 1985; Probyn et al. 1994). This results in very high temperatures with low nutrient concentrations (Largier et al. 1992). The SGR of seaweed in the recirculation system was either positively or negatively affected by these environmental events. This was surprising as the system was designed on data from a previous study (Robertson-Andersson 2003) and these effects had not been investigated in that study.

Conclusions

All studies performed on 25% recirc. units showed that the dissolved nutrient concentration, particle concentration, abalone SGR, abalone health, bacterial and mesoherbivore abundance are similar in the 25% re-circulating units and the flow-through units (Flodin 2005; Hansen 2005; Potgieter 2005; Brandt 2006; Lindström 2006; Robertson-Andersson 2007). The lack of transfer of oxygen between the seaweed tanks and the abalone tanks in the recirculation system is problematic, especially at night. There were no adverse effects on the abalone with respect to health or growth rate or the seaweeds by running the system at 25% recirculation, with both cultured organisms behaving similarly to ones cultivated in a flow-through system. Possible environmental impacts from accumulated and suspended sediment build up over the 7 day cleaning cycle which would decrease water quality, increase bacteria loading and meso-herbivore feed availability particularly sabellids were all non existent. The relatively low recirculation rate is probably the reason for this. And is an indication that aside from problems with dissolved oxygen this system can be run at a higher recirculation ratio.

Acknowledgements The authors would like to thank SIDA (Swedish International Development Agency), the South African National Research Foundation, the SANCOR student travel grant and the DEAT Frontier programme for providing funding for this research. MC&M and DEAT for providing research facilities. A special thank you to the I & J farm and staff who without their time, effort and facilities, this research would have been impossible.

References

Anderson RJ (2003) Seaweed. In: Research highlights 2001–2002. Department of Environmental Affairs and Tourism and Marine and Coastal Management Cape Town, pp 31–32

Anderson RJ, Smit AJ, Bolton JJ (1998) Differential grazing effects by isopods on *Gracilaria gracilis* and epiphytic *Ceramium diaphanum* in suspended raft culture. Aquaculture 169:99–109

Bang ND, Andrews WRH (1974) Direct current measurements of a shelf edge frontal jet in the southern Benguela system. J Mar Res 32:405–417

Björnsäter BO, Wheeler PA (1990) Effect of nitrogen and phosphorus supply on growth and tissue composition of *Ulva fenestrata* and *Enteromorpha intestinalis* (Ulvales, Chlorophyta). J Phycol 26:603–611

Bower CE, Bidwell JP (1978) Ionization of ammonia in seawater: effects of temperature, pH and salinity. J Fish Res Board Can 35:1012–1016

Boyd AJ; Tromp BBS, Horstman DA (1985) The hydrology off the South African south western coast between Cape Point and Danger Point in 1975. S Afr J Mar Sci 3:145–168

Brandt M (2006) A re-circulating integrated abalone/seaweed culture system in South Africa: effects on particulate and sediment load. MFS Dissertation, Stockholm University, Stockholm

Brawley SH, Fei XG (1987) Studies of meisoherbivory in aquaria and an un-barricaded mariculture farm on the Chinese coast. J Phycol 23:614–623

Britz PJ (1996) Effect of dietary protein level on growth performance of South African abalone, *Haliotis midae*, fed fishmeal-based semi-purified diets. Aquaculture 140:55–61

Britz PJ, Hecht T, Mangold S (1997) Effect of temperature on growth, feed consumption and nutritional indices of *Haliotis midae* fed a formulated diet. Aquaculture 152:191–203

Brzeski V, Newkirk G (1997) Integrated coastal food production systems — a review of current literature. Ocean Coast Manage 34:66–71

Buschmann A, Troell M, Kautsky N (2001) Integrated algal farming: a review. Cah Biol Mar 43:615–655

Castro-Gonzales MI, Perez-Gil Romo F, Perez-Estrella S, Carillo-Dominguez SD (1996) Chemical composition of the green alga *Ulva lactuca*. Ciencas Marinas 22:205–213

Chalmers R (2002) An investigation into the feeding biology and factors influencing the population dynamics of *Terebrasabella heterouncinata* (Polychaeta: Sabellidae), a problematic tube welling polychaete in farmed abalone in South Africa. M.Sc. Dissertation, Rhodes University, Grahamstown

Chapman P, Shannon LV (1985) The Benguela ecosystem part II: Chemistry and related processes. Oceanogr Mar Biol Ann Rev 23:183–251

Chen S, Timmons MB, Aneshansley DJ, Bisogni JJ (1993) Suspended solids characteristics from re-circulating aquacultural systems and design implications. Aquaculture 112:143–155

Chopin T, Buschmann AH, Halling C, Troell M, Kautsky N, Neori A, Kraemer GP, Zertuche-González JA, Yarish C, Neefus C (2001) Integrating seaweeds into marine aquaculture systems: a key towards sustainability. J Phycol 37:975–986

DeBoer JA (1981) Nutrients. In: Lobban CS, Wynne MJ (eds) The biology of seaweeds. Botanical monographs Vol. 17. Blackwell, Oxford, pp 356–392

Duke CS, Lapointe BE, Ramus J (1986) Effects of irradiance on growth, RuBPCase activity and chemical composition of *Ulva* species (Chlorophyta). J Phycol 22:362–370

Duke CS, Litaker W, Ramus J (1987) Seasonal variation in RuBPCase activity and N allocation in the Chlorophyte seaweeds *Ulva curvata* (Kutz.) and *Codium decorticatum* (Woodw) Howe. J Exp Mar Biol Ecol 112:145–164

Duke CS, Litaker W, Ramus J (1989a) Effects of the temperature, nitrogen supply and tissue nitrogen on ammonium uptake rates of the Chlorophyte seaweeds *Ulva curvata* and *Codium decorticatum*. J Phycol 25:113–120

Duke CS, Litaker W, Ramus J (1989b) Effect of temperature on nitrogen limited growth rate and chemical composition of *Ulva curvata* (Ulvales, Chlorophyta). Mar Biol 100:143–150

Evans GC (1972) The quantitative analysis of plant growth. Studies in Ecology. Blackwell, Oxford

FAO (2004) The state of the world fisheries and aquaculture 2004. Rome, FAO.

Fleming AE, Van Barneveld RJ, Hone PW (1996) The development of artificial diets for abalone: a review and future directions. Aquaculture 140:5–53

Fleurence J, Le Coeur C, Mabeau S, Maurice M, Landrein A (1995) Comparison of different extractive procedures for proteins from the edible seaweeds *Ulva rigida* and *Ulva rotundata*. J Appl Phycol 7:577–582

Flodin JMT (2005) Bacterial water quality in South African abalone (*Haliotis midae*) tank culture: effects on bacterial levels from seaweed integration and feed choice. MFS Dissertation. Stockholm University, Stockholm

Fourie AM (1994) Tank culturing of *Gracilaria verrucosa* for use as a food source for abalone. MSc Dissertation. University of Port Elizabeth, Port Elizabeth

Goldburg R, Triplett T (1997) Murky Waters: Environmental Effects of Aquaculture in the United States. Environmental Defense Fund, Washington, DC

Grasshoff K, Ehrhardt M, Kremling K (1976) Methods of seawater analysis. Weinheim, Germany

Hahn KO (1989) CRC Handbook of culture of abalone and other marine gastropods. CRC Press, Boca Raton

Hansen J (2005) Densities of mobile macrofauna and control of the herbivorous Keyhole limpet *Fissurella mutabilis* in an integrated abalone-seaweed tank-culture in South Africa. MFS Dissertation, Stockholm University, Stockholm

Hansen J, Robertson-Andersson DV, Troell M (2006) Control of the herbivorous gastropod *Fissurella mutabilis* (Sow.) in a land-based integrated abalone-seaweed culture. Aquaculture 255:384–388

Hampson S (1998) Evaluation of effluent water from an abalone mariculture system as a culture medium for two strains of *Gracilaria gracilis*. M.Sc. Dissertation. University of Port Elizabeth, Port Elizabeth

Harris JO, Maguire GB, Edwards SJ, Johns DR (1999) Low dissolved oxygen reduces growth rate and oxygen consumption rate of juvenile greenlip abalone, *Haliotis lae igata* Donovan. Aquaculture 174:265–278

Hutchings L, Andrews WRH (1980) Upwelling in the southern Benguela Current, South Africa. Prog Oceanog 9:l–81

Jury MR (1988) A climatological mechanism for wind-driven upwelling near Walker Bay and Danger Point, South Africa. S Afr J Mar Sci 6:175–181

Klamermans P, Malta J - E, Verschuure JM, Schrijvers L, Lentz LF, Lien AT (2002) Effects of grazing by isopods & amphipods on growth of *Ulva* spp. (Chlorophyta). Aquat Ecol 36:425–433

Lapointe BE, Tenore KR (1981) Experimental outdoor studies with *U. fasciata* Delile, I: interaction of light and nitrogen on nitrogen uptake, growth and biochemical composition. J Exp Mar Biol Ecol 53:135–152

Largier JL, Chapman P, Peterson WT, Swarts VP (1992) The western Agulhas bank: circulation, stratification and ecology. S Afr J Mar Sci 12:319–339

Lindström A (2006) A re-circulating integrated abalone/seaweed culture system in South Africa: effects on water quality. MFS Dissertation. Stockholm University, Stockholm

Lobban CS, Harrrison PJ (Eds) (1994) Seaweed ecology and physiology. Cambridge University Press, Cambridge

Lobban CS, Harrrison PJ, Duncan MJ (1985) The Physiological Ecology of Seaweeds. Cambridge University Press, Cambridge

Mai K, Wu G, Zhu W (2001) Abalone, *Haliotis discus hannai* Ino, can synthesize Myo-Insitol de novo to meet physiological needs. J Nutrition 131:2898–2903

Miller D (2001) Outdoor cultivation of *Gracilaria* in pond and raceway systems at Jacobsbaai Sea Products (Pty) Ltd., South Africa. Honours Dissertation, University of Cape Town, Cape Town

Mitchell-Innes BA, Walker DR (1991) Short term variability during an anchor station study in the Southern Benguela upwelling system: phytoplankton production and biomass in relation to species changes. Prog Oceanog 28:65–89

Morgan D (2000) The potential for *Gracilaria* polyculture at Jacobs Bay Sea Products Pty. Honours Dissertation. University of Cape Town, Cape Town

Mouton A (2004) Veterinary health reports for Abalone farms details of methods used and results determination. AFASA report afa03074

Murphy J, Riley JP (1962) A modified single-solution method for the determination of phosphate in natural waters. Analytical Chim Acta 27:31–36

Naidoo K, Maneveldt G, Ruck K, Bolton JJ (2006) A comparison of various seaweed-based diets and formulated feed on growth rate of abalone in a land-based aquaculture system. J Appl Phycol 18:437–443

Neori,A, Cohen I, Gordin H (1991) *Ulva lactuca* biofilters for marine fish pond effluents. II. Growth rate, yield and C:N ratio. Bot Mar 34:483–489

Neori A, Krom M, Ellner S, Boyd C, Popper D, Rabinovitch R, Davison P, Dvir O, Zuber D, Ucko M, Angel D, Gordin H (1996) Seaweed biofilters as regulators of water quality in integrated fish-seaweed culture units. Aquaculture 141:183–199

Neori A, Ragg NLC, Shpigel M (1998) The integrated culture of seaweed, abalone, fish and clams in modular intensive land-based systems: II. Performance and nitrogen partitioning within an abalone (*Haliotis tuberculata*) and macroalgae culture system. Aquac Eng 17:215–239

Neori A, Msuya FE, Shauli L, Schuenhoff A, Kopel F, Shpigel M (2003) A novel three stage seaweed (*Ulva lactuca*) biofilter design for integrated mariculture. J Appl Phycol 15:543–553

Neori A, Chopin T, Troell M, Buschmann AH, Kraemer GP, Halling C, Shpigel M, Yarish C (2004) Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern aquaculture. Aquaculture 231:361–391

Nisizawa K, Noda H, Kikuchi R, Watanabe T (1987) The main seaweed foods in Japan. Hydrobiologica 151/152:5–29

Njobeni A (2006) The cultivation of *Gracilaria gracilis* (Rhodophyta) in an integrated aquaculture system, for the production of abalone feed and the bioremediation of aquaculture effluent. MSc Dissertation, University of Cape Town, Cape Town

Nydahl F (1976) On the optimum concentrations for reduction of nitrate to nitrite by cadmium. Talanta 23:349–357

Potgieter M (2005) A comparison of suspended particle size and sediment loading produced by artificial and seaweed diets in integrated flow-trough and re-circulating aquaculture systems on a commercial South African abalone farm. MSc Dissertation, University of Cape Town, Cape Town

Probyn TA, Mitchell-Innes BA, Brown PC, Hutchings L, Carter RA (1994) A review of primary production and related processes on the Agulhas Bank. S A J Sci 90:166–173

Robertson-Andersson DV (2002) The Brown Strangler. 50th Newsletter of the Phycological Society of Southern Africa, Cape Town. 11–12.

Robertson-Andersson DV (2003) The cultivation of *Ulva lactuca* (Chlorophyta) in an integrated aquaculture system, for the production of abalone feed and the bioremediation of aquaculture effluent. MSc Dissertation, University of Cape Town, South Africa

Robertson-Andersson DV (2007) Biological and economical feasibility studies of using seaweeds *Ulva lactuca* (chlorophyta) in recirculation systems in abalone farming. PhD Dissertation, University of Cape Town, South Africa

Robertson-Andersson DV, Wilson D (2004) Nitrogen and thallus colour. 58th Newsletter of the Phycological Society of Southern Africa, Cape Town. 15–17.

Sales J, Britz PJ (2001) Review; Research on abalone (*Haliotis midae* L.) cultivation in South Africa. Aquaculture Res 32:863–874

Schuenhoff A, Shpigel M, Lupatsch I, Ashkenazi A, Msuya FE, Neori A (2003) A semi-recirculating, integrated system for the culture of fish and seaweed. Aquaculture 221:167–181

Shacklock PF, Doyle RW (1983) Control of epiphytes in seaweed cultures using grazers. Aquaculture 31:141–151

Shipton TA (1999) The protein requirements of the South African abalone, *Haliotis midae*. PhD Dissertation, Rhodes University, Grahamstown

Simmons R (1990) Abalone farming: how should the stock be fed? In: Cook P (ed) Proceedings of a workshop convened by The Mariculture Association of Southern Africa. The Mariculture Association of Southern Africa, Cape Town, pp 33–42

Simpson BJA (1994) An investigation of diet management strategies for the culture of the South African abalone, *Haliotis midae*. MSc Dissertation, University of Cape Town, Cape Town

Simpson BJA, Cook PA (1998) Rotation diets: a method of improving growth of cultured abalone using natural algal diets. J Shellfish Res 17:635–640

Smit AJ (1997) Optimising *Gracilaria verrucosa* production in a laboratory based culture system. MSc Dissertation, University of Port Elizabeth

Smit AJ, Fourie AM, Robertson BL, Du Preez DR (2003) Control of the herbivorous isopod *Paridotea reticulata* in *Gracilaria gracilis* tank cultures. Aquaculture 217:385–393

Smith DG, Young EG (1954) Amino acids of marine algae. J Biochem 217:845–853

Solorzano L (1969) Determination of ammonium in natural waters by the phenol-hypochlorite method. Limnol Oceanogr 14: 799–801

Steyn PP (2000) A comparative study of the production and suitability of two *Ulva* species as abalone fodder in a commercial mariculture system. M. Sc. Dissertation. University of Port Elizabeth, South Africa

Troell M, Kautsky N, Folke C (1999a) Applicability of integrated coastal aquaculture systems. Ocean Coast Manag 42:63–69

Troell M, Rönnback P, Halling C, Kautsky N, Buschmann A (1999b) Ecological engineering in aquaculture: use of seaweeds for removing nutrients from intensive mariculture. J Appl Phycol 11:89–97

Troell M, Halling C, Neori A, Chopin T, Buschmann AH, Kautsky N, Yarish C (2003) Integrated mariculture: asking the right questions. Aquaculture 226:69–90

Troell M, Robertson-Andersson DV, Anderson RJ, Bolton JJ, Maneveldt G, Halling C, Probyn T et al (2006). Abalone farming in South Africa: perspectives on kelp resources, abalone feed, potential for on-farm seaweed production and socio-economic benefits. Aquaculture 257:266–281

Wilkinson S (2001) An investigation of protein variation in *Ulva lactuca* and *Ulva rigida* under high nitrogen culture conditions. Honours Dissertation, University of Cape Town, Cape Town

Wong KH, Cheung PCK (2001) Nutritional evaluation of some subtropical red and green seaweeds. Part II. In vitro protein digestibility & amino acid profiles of protein concentrates. Food Chem 72:11–17