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Offshore abalone farming development in Port Phillip Bay: A pilot study

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Offshore abalone farming development in Port Phillip Bay: A pilot study

Will Mulvaney, Samad Jahangard, Giovanni Turchini, Anton Krsinich, Peter Lillie, Pia Winberg and Brett A. Ingram

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Executive Summary

Abalone aquaculture is a growing industry in Victoria with production and value generally increasing each year since farming commenced.

Opportunities to further expand the industry onshore in flow-through tanks or raceways are limited, whereas increased development in offshore abalone culture systems in Victorian aquaculture zones, and associated production of diets (seaweed and artificial foods), has the potential to increase overall production of the industry.

A pilot scale project was undertaken primarily to generate baseline information through feeding trials, to determine the feasibility of offshore abalone farming using different food sources. The primary objectives were to:

(a) Evaluate the production performance (growth and health) of abalone fed different diets in offshore aquaculture cages

(b) Identify local (endemic) seaweed species suitable for culture and as a feed for abalone grow-out in Victoria

Abalone culture trials were undertaken over one year in three different systems, offshore cages suspended off a long line in Port Phillip Bay, onshore cages suspended in an earthen effluent pond at an abalone farm, and a conventional (commercial) abalone farm raceway. Hybrid abalone, *Haliotis laevigata* × *H. rubra* (initial size 62 mm), were fed different diets of seaweed (red, green and brown seaweeds) and formulated feeds.

Water quality parameters at the offshore site remained relatively constant throughout the trial period, whereas the onshore site experienced higher and more variable temperature and ammonia concentration and low dissolved oxygen concentration. These parameters may have contributed to the lower survival in onshore cages (43.8%) compared to offshore cages (84.4%). Survival was unaffected by diet.

Abalone in offshore cages initially had comparable growth rates to those onshore, however these slowed over the winter months.

In onshore cages abalone fed formulated feeds or a combination of formulated feed and *Ulva* sp. grew faster than those fed *Ulva* sp. only. In offshore cages abalone fed a combination of formulated feed and *Ulva* sp. grew significantly faster than those fed other diets. Abalone fed brown seaweed had the slowest growth rate and lowest muscle to shell weight ratio, which indicated that they were growing in shell size but not gaining muscle weight.

Cost benefit analyses indicated that for every tonne of abalone produced annually in offshore cages, either 7.2 tonne of seaweed (wt) or 6.8 tonne of seaweed and formulated food (50:50 wt seaweed:dry wt formulated feed) or 2.4 tonne of formulated feed (dry wt) would be needed. This was based on the production costs of estimated each feed type.

Seaweed cultivation trials were conducted in an attempt to produce sufficient abalone biomass for culture trials. Cultivation trials were conducted in tanks mainly on green seaweed (*Ulva* sp.) and red seaweed (*Gracilaria* sp.). The long term trials experienced some challenges however nutrient loads, temperature and light regimes played a significant role in the positive growth of seaweeds.

This study identified a number of key challenges to be met for further development of offshore abalone farming, and proposed recommendations to address these, which included:

- **Feeds and feeding.** Develop feeds and feeding systems that can be delivered remotely, or that will remain stable and active for extended periods. Use of seaweeds exclusively, or in combination with a formulated feed, should be further explored.

- **Culture system.** Design systems that provide adequate shelter for the abalone while still allowing for water flow. They also need to be easy to access for abalone feeding, cleaning and harvesting.

- **Biofouling.** Develop strategies and systems that reduce biofouling on cages.

- **Labour.** Develop commercial-scale systems that reduce the amount of time needed to service the abalone.

Information and recommendation from this study may be used to guide further research and development into offshore abalone farming and associated production of seaweed as either a direct or indirect food source.
Table of Contents

Executive Summary ............................................................................................................ i

Introduction ..................................................................................................................... 1
Objectives ......................................................................................................................... 1

Project Design and Methods ......................................................................................... 2
Abalone culture .................................................................................................................. 2
Source and health status of stock ...................................................................................... 2
Culture trials ...................................................................................................................... 2
Water quality .................................................................................................................... 3
Proximate analyses ......................................................................................................... 3
Cost benefit analysis ...................................................................................................... 6
Seaweed culture ............................................................................................................... 6
Wild harvesting ............................................................................................................... 6
Cultivation ....................................................................................................................... 6

Results ............................................................................................................................ 8
Abalone culture ................................................................................................................ 8
Source and health status of stock .................................................................................... 8
Culture trials ................................................................................................................... 8
Water quality .................................................................................................................. 14
Proximate Composition ................................................................................................. 15
Cost benefit analysis .................................................................................................... 17
Seaweed Culture .......................................................................................................... 19
Wild harvesting ............................................................................................................ 19
Cultivation .................................................................................................................... 19
Proximate analyses ..................................................................................................... 20

Discussion and Recommendations ............................................................................... 22
Abalone culture .............................................................................................................. 22
Cost benefit analysis .................................................................................................... 24
Seaweed culture .......................................................................................................... 24
Challenges of offshore abalone farming: .................................................................... 25
1. Feeds and feeding ..................................................................................................... 25
2. Culture system design .............................................................................................. 25
3. Biofouling ................................................................................................................ 25
4. Labour ..................................................................................................................... 25
Conclusions and recommendations ............................................................................ 25
Recommendations for abalone farming ........................................................................ 25

Abalone culture
Acknowledgements ................................................................. 27

References .................................................................................. 28

Appendix I - Project poster presented at the International Abalone Symposium (Hobart, May 2012) ................................................................. 31
List of Tables
Table 1. Diet treatments used in offshore and onshore abalone feeding trials ........................................ 5
Table 2. Proximate composition of formulated feeds used in the trial........................................................ 5
Table 3. Feed sources and targeted species for offshore and onshore abalone culture trials .................... 6
Table 4. Water quality parameters measured at each of the study sites between November 2011 and December 2012. Values represent range with mean in brackets .................................................. 14
Table 5. Proximate composition of abalone fed several seaweed and/or formulated feeds in offshore and onshore trial systems after 12 months. (Values = mean ± standard error) .................................................. 16
Table 6. Significance values for differences in the proximate analyses of abalone fed different diets ...... 16
Table 7. Cost benefit scenarios for a 5t, 10t and 20t farm with using seaweed feed at costs per kilogram of a) $0.50 b) $1.00 and c) current price of $1.70. Shows the number of people that could be employed for the cost of operation to remain at $25/kg. ........................................................................................................ 18
Table 8. Cost benefit scenarios for a 5t, 10t and 20t farm with using seaweed (S) and formulated (FF) feeds at costs per kilogram of a) $0.50 (S) $1.50 (FF), b) $1.00 (S) $2.00 (FF), and c) current price of $1.70 (S) $2.75 (FF). Shows the number of people that could be employed for the cost of operation to remain at $25/kg. ........................................................................................................ 18
Table 9. Cost benefit scenarios for a 5t, 10t and 20t farm with using formulated feeds at costs per kilogram of a) $1.50, b) $2.00 and c) current price of $2.75. Shows the number of people that could be employed for the cost of operation to remain at $25/kg. ........................................................................................................ 19
Table 10. Seasonal variation in proximate analysis of seaweeds (mean values presented) ................... 21

List of Figures
Figure 1. Location of abalone trials. (a) Cages on a long line at an offshore mussel farm (Mt Martha); (b and c) Pontoon in pond onshore (GSW, Indented Head). (d) Conventional abalone raceway tanks (GSW, Indented Head). .......................................................... 4
Figure 2. Formulated feeds used in abalone culture trials (a) Adam & Amos Biscuit (b) Adam & Amos pellet (c) Skretting Halo (used in control raceway) ......................................................... 4
Figure 3. Targeted seaweed species for cultivation trials and for feeding abalone in culture trials. (a) Gracilaria. (b) Ulva ................................................................. 7
Figure 4. Tanks and aquaria used for cultivation at DPI Queenscliff (a) 2,500 L tank holding Ulva. (b) Indoor tanks. (c) Glass aquaria holding Gracilaria ........................................ 7
Figure 5. Mean survival rate of abalone reared in cages offshore and onshore during culture trials between November 2011 and December 2012 .......................................................... 9
Figure 6. Growth of abalone (mm) over the trial period, from November 2011 to December 2012, abalone at the onshore and offshore sites and in the control raceway system .......................... 9
Figure 7. Specific growth rates (% day⁻¹) in length of abalone over the trial period, from November 2011 to December 2012, abalone at the onshore and offshore sites and in the control raceway system .... 9
Figure 8. Specific growth rates (% day⁻¹) in weight of abalone over the 388 day trial period at the onshore site and control raceway system (Mean ± SE). Content of feed treatments detailed in Table 1. Note: Feeds sharing the same letter NOT significantly different (Tukeys test, P>0.05) .......... 10
Figure 9. Specific growth rates (% day⁻¹) in weight of abalone over the 377 day trial period at the offshore site and control raceway system (Mean ± SE, n=120). Content of feed treatments detailed in Table 1. Note: Feeds sharing the same letter NOT significantly different (Tukeys test, P>0.05) .......... 10
Figure 10. Total biomass gains (g) per cage of abalone over the trial period ............................................. 10

Abalone culture
Abalone culture
Introduction

Abalone aquaculture is a growing industry in Victoria. Production and value has generally increased each year since farming commenced, and in 2009/10 the Victorian abalone aquaculture industry produced 260 t valued at $8.58 mil., most of which was hybrid abalone (*Haliotis laevigata* x *H. rubra*) (O’Sullivan and Savage 2012). Victorian production of farmed abalone represents about 30% of the total farmed Australian production.

Traditionally in Victoria, abalone are farmed onshore in flow-through tanks or raceways, which require large amounts of well-aerated water. Opportunities to expand onshore abalone farming are, however, limited whereas development of offshore abalone farming, and associated seaweed culture for feeding abalone, has the potential to substantially increase abalone production. Currently there are 976 ha of water in the marine aquaculture zones in Port Phillip Bay and Western Port, Victoria, approximately half of which is unallocated. Seaweed culture in Port Phillip Bay will also contribute to offsetting/reducing nutrient loadings and carbon dioxide biosequestration (Winberg et al. 2009).

During 2010, Fisheries Victoria convened several meetings to discuss options for the growth of the industry with key stakeholders. Development of offshore abalone farming and identification of appropriate diets for feeding abalone in offshore cages were identified as priority areas of research.

While the development of artificial feeds for abalone has been extensively researched and manufactured diets are now widely used in land-based abalone farms (Fleming et al. 1996, Sales and Britz 2001, Vandepeer and van Barneveld 2005, FitzGerald 2008), many of the large-scale abalone-producing nations internationally use mainly seaweeds in offshore culture systems (Fermin and Mae Buen 2002, Neori 2008, Zhang et al. 2010). Seaweed products are also being incorporated into formulated diets for abalone (e.g. Austkelp Seabiscuits are 15% kelp, Australian Kelp Products, www.austkelp.com.au).

Previous research indicates that artificial feeds developed for land-based production are not robust enough for offshore culture systems.

A recent review on the use and production of seaweed and manufactured diets as feed for seabased abalone aquaculture in Victoria indicated that there are options for feeding abalone on selected endemic seaweeds (Kirkendale et al. 2010). Endemic seaweeds, especially those species that can be readily cultivated, may provide an alternative food source. In addition, recent research at a Tasmanian land-based farm demonstrated up to a three-fold increase in growth rates of juvenile abalone fed seaweed diets compared to artificial feeds (Mulvaney 2010, Mulvaney et al. 2013). Concurrently, there is on-going development of artificial diets for feeding abalone in offshore cages.

The key beneficiary of this proposal is the Victorian aquaculture industries (abalone and potentially seaweed culture). Adjunct beneficiaries include associated aquaculture and seafood industries, such as feed manufacturers, value chain partners/agribusinesses (processors, retailers, service industry), new investors and consumers.

Objectives

This pilot project will focus predominantly on generating key baseline information through feeding trials, to determine the feasibility of offshore abalone farming using different food sources. The primary objectives were to:

(c) Evaluate the production performance (growth and health) of abalone fed different diets in offshore aquaculture cages

(d) Trial identified (Kirkendale et al. 2010) local (endemic) seaweed species suitable for culture and as a feed for abalone grow-out in Victoria

This project supports the sustainable development and management of fisheries and aquaculture by increasing productivity and growing the value of aquatic resources. The project was aligned with and linked to the Aquaculture Futures Initiative (AFI), which aimed to transform Victoria’s aquaculture industry into globally competitive sectors.
Project Design and Methods

Abalone culture

Source and health status of stock
Hybrid abalone (*Haliotis laevigata* x *H. rubra*) used in the trials were obtained from Great Southern Waters Pty Ltd. (GSW) (Indented Head). All animals used in trials, which were from the same cohort of stock, were tagged with glue-on shellfish tags (Hallprint Pty Ltd, Hindmarsh Valley, S.A.) for identification purposes.

Movement of abalone as part of this project was undertaken in accordance with the Victorian Abalone Aquaculture Translocation Protocol (Fisheries Victoria 2007), following approval through the Translocation Evaluation Panel (TEP) process. Since Abalone Viral Ganglioneuritis (AVG) is an important disease that has affected abalone stocks in Victoria (Hooper *et al.* 2007, Gavine *et al.* 2009), prior to commencing trials a sub-sample of 21 abalone were submitted to Biosecurity Victoria (Attwood) to be tested for AVG using polymerase chain reaction (PCR) technology.

Culture trials
This study measured the production performance (growth, food conversion efficiency and health) of abalone fed different diets in both offshore and onshore culture systems. The trial was undertaken over 12.5 months, from November 2011 to December 2012.

The trial was conducted in three different systems:

(a) **Offshore cages.** Cages suspended 2 m below the water surface on a long line at sea (Figure 1a). The long line was located on a commercial mussel farm at Mt Martha.

(b) **Onshore cages.** Cages suspended 1 m below the water surface off a pontoon, which was located in an earthen effluent pond at GSW (Figure 1b and c).

(c) **Control.** Conventional (commercial) raceway (slab tank) at GSW (Figure 1d).

Twenty tagged abalone (initial mean size 62 mm, 38g) were placed into each cage (Aquapurse, Tooltech Pty Ltd, Brisbane) in the offshore and onshore systems. There were six replicate cages for each diet treatment (Table 1). A total of 120 tagged abalone were stocked into one control raceway slab tank, amongst other abalone.

There were seven diet treatments in the offshore system (Table 1). Six diets comprised different mixes of seaweeds, and one diet (Diet AU) was a mix of green seaweed (*Ulva*) and formulated biscuit feed (Adam & Amos, Mount Barker, S.A.) (Figure 2, Table 2). Abalone in offshore cages were fed every two weeks. In the diet AU abalone were fed alternately, green seaweed (*Ulva*) for two weeks then formulated biscuit feed for two weeks and so on.

The majority of the seaweed being fed to the abalone in offshore cages was fresh beach cast red, green and brown seaweed, supplemented with cultured green seaweed (*Ulva*) (Table 3) (see Seaweed culture section). Seaweed was collected from beaches in the Queenscliff area. Red seaweeds (Rhodophyta) comprised mainly *Gracilaria*, brown seaweeds included *Ecklonia radiata* and *Macrocystis* *augustifolia*, while green seaweeds (Chlorophyta) were exclusively *Ulva*.

Four diet treatments were used in the onshore system (Table 1). These included two of the treatments that were used in the offshore system, green seaweed (*Ulva*) (Diet U) and Diet AU, and two types of formulated feed supplied by Adam & Amos (Mount Barker, S.A.) (Figure 2a and b, Table 2). These diets were specially designed for offshore culture. Due to biosecurity reasons, only *Ulva* collected on-site at GSW was used. Abalone onshore cages were fed either weekly with green seaweed (*Ulva*) cultured on-site or twice a week with formulated feeds (see Table 1 for treatments). In the latter treatments, degraded uneaten food was removed from cages to reduce fouling. Feed was available to abalone at all times.

Abalone in the control raceway were fed daily with a formulated abalone feed (Skretting) (Figure 2c, Table 2) and cleaned as part of normal farm management practices.

Length measurements were performed at the beginning and end of the trial and every two months during the trial. Abalone were weighed at the beginning and end of the trial only.

Specific growth rates (SGR) were determined as the percentage of growth per day, for both length and weight, using the following formula:
Specific Growth Rate \((SGR) = \frac{\ln L_{t_2} - \ln L_{t_1}}{t_2 - t_1} \times 100\%\)

where:

- \(t\) = time in days.
- \(\ln L_{t_2}\) = natural logarithm of the average length/weight at time \(t_2\).
- \(\ln L_{t_1}\) = natural logarithm of the average length at time \(t_1\).

Survival was monitored across the entire trial period. Biomass gains were determined as the total weight gain per cage/20 abalone for control raceway system (accounting for survival). At the completion of the trial, three abalone from each cage were shucked and the muscle and shell weight were measured. The health of the abalone was determined as the muscle to shell ratio (wet weight) and condition index (length (mm)/weight (g)).

Feed conversion ratio (FCR) was calculated as:

\[
FCR = \frac{\sum \text{Food added (g wet weight)}}{\sum \text{Weight gain (g wet weight)}}
\]

Note that uneaten food was not subtracted from the food added as excess food was given to the abalone to ensure that feed was always available.

**Water quality**

A number of water quality parameters were monitored at each of the sites for the duration of the experiment. These included, temperature, pH, dissolved oxygen (DO) (as % saturation - %sat.) and salinity that were logged hourly, and ammonia that was measured once every month.

**Proximate analyses**

In order to determine the effects of diet on the nutrient composition of abalone muscle, samples of muscle tissue were collected at the beginning of the trial and from each diet treatment at the end of the trial for proximate and lipid (including Omega-3) analyses. Samples of each of the seaweed diets and formulated feeds were also collected for analyses. Seaweed diets were collected every 3 months to examine seasonal changes in nutrient composition.

All samples were sent to the Deakin University Fish Nutrition Laboratories (Warrnambool) for proximate and lipid analysis.

The proximate chemical composition of samples were determined via proximate composition analysis according to standard procedures, routinely implemented at Deakin University Fish Nutrition Laboratories (see Francis et al. 2007, Palmeri et al. 2007, Turchini et al. 2007). Briefly the:

- Moisture content was determined by drying samples in an oven at 80°C to constant weight
- Protein content was determined (Kjeldahl nitrogen; N×6.25) in an automated Kjeltech (Model 2300, Tectar, Höganas, Sweden)
- Total lipid content was determined gravimetrically after total lipid extraction by chloroform/methanol (2/1 v/v) according to Folch et al. (1957).
- Ash content was determined by the incineration of the sample in a muffle furnace (Model WIT, C & L. Tetlow, Blackburn, Victoria, Australia) at 550 °C for 18 h.

The fatty acid content of samples was determined using the following steps:

- The acid catalysed methylation method (Christie 2003) was used to esterify an aliquot of extracted lipids (~30mg) into methyl esters
- A Shimadzu GC 17A (Shimadzu, Chiyodaku, Tokyo, Japan) equipped with an Omegawax 250 capillary column (Supelco, Bellefonte, PA, USA) was then used to determine the content of fatty acid methyl esters (see Francis et al. 2007, Palmeri et al. 2007, Turchini et al. 2007).
- A sub-sample (~30mg) of each lipid extract was further fractionated by thin layer chromatography (TLC) to separate the four major lipid classes, namely triacylglycerol (TAG), phospholipids (PL), cholesterol esters (CE) and free fatty acids (FFA).
- The resultant classes where then analysed for their fatty acid composition, as described above.

To test for a significant difference between treatments (where P<0.05), analysis was undertaken using the SAS General Linear Models Procedure with Bonferroni correction (SAS Institute Inc.).
Figure 1. Location of abalone trials. (a) Cages on a long line at an offshore mussel farm (Mt Martha); (b and c) Pontoon in pond onshore (GSW, Indented Head). (d) Conventional abalone raceway tanks (GSW, Indented Head).

Figure 2. Formulated feeds used in abalone culture trials (a) Adam & Amos Biscuit (b) Adam & Amos pellet (c) Skretting Halo (used in control raceway)
Table 1. Diet treatments used in offshore and onshore abalone feeding trials

<table>
<thead>
<tr>
<th>Treatment (Abbrev.)</th>
<th>Offshore (Mt Martha)</th>
<th>Onshore (GSW)</th>
<th>Control (GSW raceway)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (U)</td>
<td>Green seaweed (<strong>Ulva</strong> - cultured &amp; harvested)</td>
<td>Green seaweed (<strong>Ulva</strong> - cultured on-site)</td>
<td></td>
</tr>
<tr>
<td>2 (R)</td>
<td>Red seaweed (harvested, supplemented with <strong>Gracilaria</strong>)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 (P)</td>
<td>Brown seaweed (harvested)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 (RU)</td>
<td>Mixed seaweed (red and green - equal parts wet wt biomass)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 (PR)</td>
<td>Mixed seaweed (red and brown - equal parts wet wt biomass)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 (PU)</td>
<td>Mixed seaweed (brown and green - equal parts wet wt biomass)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 (AU)</td>
<td>Formulated feed (AA feed1) (biscuit) and Green seaweed (<strong>Ulva</strong>) only. Fed alternately.</td>
<td>Formulated feed (AA feed1) (biscuit) and Green seaweed (<strong>Ulva</strong>) only. Fed alternately.</td>
<td></td>
</tr>
<tr>
<td>8 (A)</td>
<td>Formulated feed (AA feed1) (biscuit)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 (B)</td>
<td>Formulated feed (AA feed2) (pellet)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Seaweed only cages (to monitor seaweed growth and feed stability)</td>
<td>Seaweed only cages (to monitor seaweed growth and feed stability)</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Regular farm feeding practices, feeding with Skretting Halo diet</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Proximate composition of formulated feeds used in the trial.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Adam &amp; Amos¹</th>
<th>Skretting²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Biscuit (Feed 1)</td>
<td>Pellet (Feed 2)</td>
</tr>
<tr>
<td>Size (mm)</td>
<td>250-325 long 50-85 wide</td>
<td>25-50 long 18-22 wide</td>
</tr>
<tr>
<td>Protein (%)</td>
<td>&gt;29</td>
<td>&gt;29</td>
</tr>
<tr>
<td>Lipid (%)</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Fibre (%)</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Ash (%)</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Phosphorus (%)</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

1. Approximate values only, provide by Adam and Amos

Abalone culture
Table 3. Feed sources and targeted species for offshore and onshore abalone culture trials

<table>
<thead>
<tr>
<th>Seaweed type</th>
<th>Targeted Species</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhodophyta (red) Seaweed</td>
<td><em>Gracilaria</em> and others</td>
<td>Beach cast (offshore only)</td>
</tr>
<tr>
<td>Chlorophyta (green) Seaweed</td>
<td><em>Ulva</em></td>
<td>Beach cast, cultured (offshore only); GSW farm effluent channels (onshore only).</td>
</tr>
<tr>
<td>Phaeophyceae (brown) Seaweed</td>
<td><em>Ecklonia radiata</em></td>
<td>Beach cast (offshore only)</td>
</tr>
</tbody>
</table>

**Cost benefit analysis**
A simple cost benefit analysis was performed. The infrastructure costs of operating the offshore trial system was established based on the value of the existing mussel farm which was used. The cost of formulated feeds was provided by the feed company. The cost of the seaweed was based on the average time taken to collect the beach cast seaweeds at $20 per hour, including travel time. The cost of feed per gram of weight gain in abalone was then established to compare across the treatments. Operating costs were determined as the time spent each week in feeding and cleaning the cages at $35 per hour per person. Fuel costs were also included for the use of the boat, however travel time and costs between the experimental sites were not included because transport of feed is not included in the costings. Superficial operating costs were attained for a current local land-based abalone farm and were compared to the cost benefits of the offshore seaweed based feed systems (industry comments). Previous reports (eg, Weston et al. 2001 and EconSearch Pty Ltd 2011) were also included in this comparison.

**Seaweed culture**
In order to undertake the abalone culture trial, a sufficient biomass of seaweed (red, green and brown) needed to be secured. Two approaches were taken to source seaweed, harvesting from the wild and cultivation.

**Wild harvesting**
Options for collecting seaweed by wild harvest were examined. These included harvest of growing seaweed and collecting cast seaweed, seaweed that has detached from the substrate and washed ashore.

**Cultivation**
Culture trials were conducted on a number of potential culture species, particularly red seaweed (*Gracilaria* spp.) and green seaweed (*Ulva* spp.), which were collected locally from the wild (Figure 3).

Culture trials were conducted in a range of seawater tanks and aquaria located at DPI, Queenscliff (Figure 4). Some trials were also conducted in tanks located in the nursery greenhouse at GSW with the view to cultivate enough *Ulva* on-site to supply feed for abalone reared in cages at the site. This approach aimed to eliminate biosecurity issues associated with bringing seaweeds onto the farm.

Seaweeds were added to tanks and aquaria at a rate of approximately 1 kg/m² after its initial weight was recorded. Water was replaced 3 times a week with ambient flow through water, or 3-4 times daily if there was no addition of nutrients. All tanks and aquaria were well aerated. Temperature, pH, and salinity were monitored throughout the trials. The seaweed was spun dry and weighed weekly to measure growth.

Additional nutrients: ‘Aquasol’ fertilizer was added to provide a maximum TAN of 0.25mg/L for *Ulva* spp., or 0.125mg/L for *Gracilaria* spp.. For a 1g/L solution of ‘Aquasol’, this equated to 0.51 mL or 0.26 mL per litre per day. ‘Green Marine’ nutrient supplement was also added to the *Gracilaria* once a week at a rate of 1mL per 24L, as per directions. In some trials, the growth of the seaweed with and without the addition of nutrients was compared.

Seaweed produced in cultivation trials, particularly *Ulva*, was used in abalone culture trials (see Abalone culture section).
Figure 3. Targeted seaweed species for cultivation trials and for feeding abalone in culture trials. (a) *Gracilaria*. (b) *Ulva*

Figure 4. Tanks and aquaria used for cultivation at DPI Queenscliff (a) 2,500 L tank holding *Ulva*. (b) Indoor tanks. (c) Glass aquaria holding *Gracilaria*
Results

Abalone culture

Source and health status of stock
A total of 21 healthy abalone were tested for AVG by molecular testing (PCR). Given that these abalone did not show clinical signs of disease and were sourced from GSW at Indented Heads (a place where the disease has not occurred) there was an extremely low pre-test probability of abalone being infected with AVG.

Culture trials

Survival
Overall, survival in offshore cages (80-92.5%, mean 84.4%) was slightly greater than for the control raceway system (76.6%) and substantially higher than for onshore cages (37.5-48.7%, mean 43.8%).

There was no significant difference in survival between diet treatments at either the offshore site or the onshore site (P>0.05).

Mortality was high across all of the dietary treatments in the onshore system especially during summer months, which corresponded with high and fluctuating water temperature (peak of 25°C), high ammonia concentrations (up to 0.16mg/L) and low dissolved oxygen (down to 61.7%sat.). This is shown in Figure 5, with a sharp decline in survival over the first third of the trial before a levelling off. The survival of abalone in the offshore system, however, was high over the entire trial period (Figure 5).

Growth
The abalone in each of the systems grew faster in the summer months than in winter (Figure 6, Figure 7). The abalone grew consistently from an average of 62 mm to an average of 84 mm in the onshore system, corresponding closely to the growth of abalone in the control raceway system (Figure 6). Abalone in the offshore system initially had comparable growth rates, however these slowed over the winter months (Figure 7). The abalone in the offshore system grew an average of 6mm over the first 2 months and then another 6mm over the following 10 months (Figure 6).

By weight, the growth of the abalone in the onshore system was comparable to the abalone growth in the control raceway system (Figure 8). Abalone fed formulated feeds or a combination of formulated feed and Ulva (Diet AU) grew significantly faster than the abalone fed Ulva (Diet U) only (P<0.0001) (Figure 8). The slowest growing abalone, those fed Ulva (U), in this system grew at 0.19 %day⁻¹ compared to 0.22 %day⁻¹ for abalone grown in the control raceway system.

By weight, abalone at the offshore site grew significantly slower than those in the control raceway system (Figure 9). There were significant differences in the specific growth rates of the abalone across the dietary treatments offshore. Abalone fed a combination of formulated feed and Ulva (Diet AU) grew significant faster (mean 0.09%day⁻¹) than for other treatments (P<0.0001). However, all of the treatments containing red seaweed (R) also performed well. The treatments that contained brown seaweed (P) had the slowest growth rates for the abalone (Figure 9).

Biomass gain
The total biomass gains were determined by combining survival and weight gain data (Figure 10). Results showed that just one treatment in the offshore system and two treatments in the onshore systems had a biomass gain of greater than 100 g/cage. These treatments were a combination of formulated feed and Ulva (Diet AU) in both onshore and offshore systems and the formulated biscuit feed (Diet A) in the onshore system. Abalone fed a mix of red and brown seaweed (Diet RP) and just red seaweed (Diet R) in the offshore system also showed slight gains, whereas all other diets treatments across the two culture systems resulted in a loss of biomass (Figure 10). There is a significant difference between the total biomass gains in the experimental systems and in the control raceway system. The biomass gain in the latter was 550 g (which is based on an industry standard survival of 95% rather than 76% observed in the current study)
Figure 5. Mean survival rate of abalone reared in cages offshore and onshore during culture trials between November 2011 and December 2012.

Figure 6. Growth of abalone (mm) over the trial period, from November 2011 to December 2012, abalone at the onshore and offshore sites and in the control raceway system.

Figure 7. Specific growth rates (% day⁻¹) in length of abalone over the trial period, from November 2011 to December 2012, abalone at the onshore and offshore sites and in the control raceway system.
Figure 8. Specific growth rates (%day⁻¹) in weight of abalone over the 388 day trial period at the onshore site and control raceway system (Mean ± SE). Content of feed treatments detailed in Table 1. Note: Feeds sharing the same letter NOT significantly different (Tukeys test, P>0.05).

Figure 9. Specific growth rates (%day⁻¹) in weight of abalone over the 377 day trial period at the offshore site and control raceway system (Mean ± SE, n=120). Content of feed treatments detailed in Table 1. Note: Feeds sharing the same letter NOT significantly different (Tukeys test, P>0.05).

Figure 10. Total biomass gains (g) per cage of abalone over the trial period.

Abalone culture
Health
Condition index and muscle to shell weight ratios were used as an indication of the health of the abalone in the trial systems. The condition indices of the abalone in the onshore system were comparable across the treatments (Figure 11). However, the abalone fed Ulva (Diet U) had a significantly higher condition index than the other treatments (P<0.0001). This difference did not translate into the muscle to shell weight ratio in which there was no significant difference between the treatments (P=0.14).

There were significant differences in both condition indices (P<0.0001) and muscle to shell weight ratios (P= 0.026) between the treatments in the offshore trial system (Figure 12, Figure 13). The high condition index and low muscle to shell ratio of the abalone fed brown seaweed only (Diet P) indicated that they were growing in shell size but not gaining muscle weight. In comparison, the abalone fed Ulva only (Diet U) had a healthy growth of both the shell and the muscle tissue.

FCRs and feed costs
The feed conversion ratios (FCR) in the onshore system were significantly different across the feed treatments (P<0.0001) (Figure 14). The abalone fed formulated feeds (Diets A and B) had significantly higher FCRs compared with those that contained Ulva (Diets AU and U). The abalone fed Ulva (Diet U) had a FCR similar to that for abalone reared under the normal farm conditions of the control raceway system.

The slow growth rates of the abalone in the offshore system contributed to the inflated FCRs (>10) that were produced in this system. FCRs were significantly different across the dietary treatments (P=0.032). The feed treatments containing brown seaweed produced the highest FCRs while those containing red seaweed produced the lowest (Figure 15). None of the treatments in the experimental offshore system had FCRs that compare to the current farm FCRs seen in the control raceway system.

When the costs of producing the different feed types are taken into account a cost conversion ratio can be calculated. For abalone grown in onshore cages, all dietary treatments had a similar or lower cost conversion ratio to that for control raceway system (Figure 16). Abalone that were fed a combination of formulated feed and Ulva (Diet AU) had the lowest feed costs per kg of growth.

For abalone grown in offshore cages, all diet treatments had feed costs per kg of growth that were substantially greater than for abalone reared in cages in the onshore system and the control raceway system (Figure 17). Of the treatments in offshore systems, red seaweed (Diet R) and the combination of formulated feed and Ulva (Diet AU) had the lowest costs of production.

![Figure 11. Condition indices of abalone over the 388 day trial period at the onshore site and control raceway system (Mean ± SE). Content of feed treatments detailed in Table 1. Note: Feeds sharing the same letter NOT significantly different (Tukeys test, P>0.05).](image-url)
Figure 12. Condition indices of abalone over the 377 day trial period at the offshore site and control raceway system (Mean ± SE). Content of feed treatments detailed in Table 1. Note: Feeds sharing the same letter NOT significantly different (Tukeys test, P>0.05).

Figure 13. Muscle: shell weight ratios of abalone over the 377 day trial period at the offshore site and control raceway system (Mean ± SE). Content of feed treatments detailed in Table 1. Note: Feeds sharing the same letter NOT significantly different (Tukeys test, P>0.05).

Figure 14. Feed conversion ratios (FCR) of abalone over the 388 day trial period at the onshore site and control raceway system (Mean ± SE). Content of feed treatments detailed in Table 1. Note: Feeds sharing the same letter NOT significantly different (Tukeys test, P>0.05).

Abalone culture
Figure 15. Feed conversion ratios (FCR) of abalone over the 377 day trial period at the offshore site and control raceway system (Mean ± SE). Content of feed treatments detailed in Table 1. Note: Feeds sharing the same letter NOT significantly different (Tukeys test, P>0.05).

Figure 16. Cost conversion ratio ($/kg) of abalone over the 388 day trial period at the onshore site and control raceway system (Mean ± SE). Content of feed treatments detailed in Table 1.

Figure 17. Cost conversion ratio ($/kg) of abalone over the 377 day trial period at the offshore site and control raceway system (Mean ± SE). Content of feed treatments detailed in Table 1.
Water quality
A summary of water quality data measured at each of the study sites during the trial are provided in Table 4. The onshore trial site was within an effluent settlement pond. As a result of this the water quality was lower and temperatures variable compared to the other sites. The average ammonia content over the trial period was 0.07±0.02 mg/L, with higher levels in summer compared to winter, peaking at 0.16mg/L in February. Dissolved oxygen was also quite low, averaging 86.11 ± 0.58%sat., with a minimum of 61.7%sat. in January. This corresponded with seasonal fluctuations in water temperature (Figure 18). The pH remained stable at 7.97 ± 0.04 throughout the trial.

Water quality parameters at the offshore site remained relatively constant throughout the trial period. Ammonia levels remained low, at 0.005 ± 0.0002 mg/L. Dissolved oxygen and pH were 98 ± 0.04%sat. and 8.01 ± 0.01, respectively. Water temperature was similar to the onshore site however fluctuations were not as variable as for the onshore site (Figure 18).

The water quality in the control raceway system was better than for the onshore site. The ammonia level remained low, averaging 0.017 ± 0.003 mg/L. Dissolved oxygen was high over the trial period at an average 99.4 ± 0.004%sat. and pH remained stable at 8.16 ± 0.04.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Offshore (Mt Martha)</th>
<th>Onshore effluent pond</th>
<th>Control Raceway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>11.1-22.9 (16.4)</td>
<td>10.1-24.7 (16.1)</td>
<td>10.1-24.3 (16.1)</td>
</tr>
<tr>
<td>pH</td>
<td>7.91-8.12 (7.97)</td>
<td>7.8-8.3 (8.0)</td>
<td>8.1-8.5 (8.2)</td>
</tr>
<tr>
<td>DO (% saturation)</td>
<td>95-102 (98)</td>
<td>62-103 (86)</td>
<td>96-101 (99)</td>
</tr>
<tr>
<td>Salinity S/cm</td>
<td>28.0-40.15 (33.82)</td>
<td>14.6-37.2 (29.7) ppt</td>
<td>No data</td>
</tr>
<tr>
<td>Ammonia (mg/L)</td>
<td>0.003-0.01 (0.005)</td>
<td>0.01-0.16 (0.07)</td>
<td>0.01-0.04 (0.017)</td>
</tr>
<tr>
<td>Phosphorus (mg/L)</td>
<td>0.07-0.10 (0.08)</td>
<td>0.04-0.07 (0.05)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Water quality parameters measured at each of the study sites between November 2011 and December 2012. Values represent range with mean in brackets.

Figure 18. Water temperatures recorded at onshore and offshore sites between November 2011 and December 2012.

Abalone culture
Proximate Composition

Proximate composition of abalone fed different diets is presented in Table 5. The proximate composition of abalone reared in a raceway (Control) did not change significantly over the trial.

In onshore treatments, the proximate composition of abalone fed different diets in cages were not significantly different to each other, but all were significantly different to abalone reared in a raceway (Control). The only exception to this was for total P content, which was not significantly different (Table 6). When the Control was excluded from the analysis, there were significant differences in ash and lipid composition for the different diet treatments.

In offshore cages, the moisture content of abalone fed different diets were all significantly different to that of the control abalone. When the Control was excluded from the analysis, the lipid content of abalone feed a diet of Ulva (U) only was significantly greater than other diet treatments except red seaweed (R) (Table 6).

Two diet treatments, Ulva only (U) and Ulva + biscuit (AU) were used both onshore and offshore. For Ulva only, there were significant differences in most proximate variables, especially protein and lipid content (Table 6). there were also significant differences in proximate composition of abalone fed Ulva and biscuit (Table 6).

A total of 48 lipid fractions (as mg/g/lipid) were extracted and analysed. Two fractions (18:1n-7 and 20:1n-11) were significantly different between control abalone samples collected at the beginning and end of the trial. A total of 39 lipid fractions were significantly different (P<0.05) (15 with P<0.0001) for abalone fed different diets in onshore cages (analysis includes Control). In offshore cages, 22 lipid fractions were significantly different (P<0.05) (9 with P<0.0001) for abalone fed different diets (analysis includes Control).

For the two diets that were used in both onshore and offshore cages, there were 25 and 10 lipid fractions significantly different for the Ulva(U) diet and the Ulva + biscuit (AU), respectively.
Table 5. Proximate composition of abalone fed several seaweed and/or formulated feeds in offshore and onshore trial systems after 12 months. (Values = mean ± standard error)

<table>
<thead>
<tr>
<th>Diet</th>
<th>Moisture (% wet wt)</th>
<th>Ash (% dry wt)</th>
<th>Protein (% dry wt)</th>
<th>Lipid (% dry wt)</th>
<th>NFE* (% dry wt)</th>
<th>Total P.** (% dry wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>72.3 ± 0.65</td>
<td>6.05 ± 0.26</td>
<td>72.9 ± 1.25</td>
<td>3.86 ± 0.05</td>
<td>17.14 ± 1.49</td>
<td>0.68 ± 0.01</td>
</tr>
<tr>
<td>Final</td>
<td>70.9 ± 0.1</td>
<td>5.69 ± 0.01</td>
<td>65 ± 2.05</td>
<td>3.4 ± 0.2</td>
<td>25.93 ± 2.32</td>
<td>0.63 ± 0.02</td>
</tr>
<tr>
<td>Offshore</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biscuit (A)</td>
<td>73.6 ± 0.35</td>
<td>6.88 ± 0.16</td>
<td>80.1 ± 1.73</td>
<td>4.62 ± 0.12</td>
<td>8.46 ± 1.96</td>
<td>0.66 ± 0.02</td>
</tr>
<tr>
<td>Pellet (B)</td>
<td>73.6 ± 0.23</td>
<td>7.16 ± 0.12</td>
<td>80.2 ± 1.82</td>
<td>4.21 ± 0.1</td>
<td>8.48 ± 1.99</td>
<td>0.64 ± 0.01</td>
</tr>
<tr>
<td>Ulva (U)</td>
<td>74.1 ± 0.21</td>
<td>7.37 ± 0.17</td>
<td>82.6 ± 0.77</td>
<td>4.74 ± 0.08</td>
<td>5.43 ± 0.7</td>
<td>0.66 ± 0.02</td>
</tr>
<tr>
<td>Ulva + Biscuit (AU)</td>
<td>72.9 ± 0.29</td>
<td>6.34 ± 0.19</td>
<td>79.4 ± 2.21</td>
<td>4.18 ± 0.18</td>
<td>10.01 ± 2.5</td>
<td>0.6 ± 0.01</td>
</tr>
<tr>
<td>Brown (P)</td>
<td>75.2 ± 0.17</td>
<td>7.99 ± 0.53</td>
<td>67.6 ± 4.43</td>
<td>4.3 ± 0.06</td>
<td>20.06 ± 4.51</td>
<td>0.5 ± 0.03</td>
</tr>
<tr>
<td>Red (R)</td>
<td>75.9 ± 0.38</td>
<td>8.67 ± 0.13</td>
<td>70.6 ± 4.06</td>
<td>4.63 ± 0.17</td>
<td>16.21 ± 4.1</td>
<td>0.63 ± 0.01</td>
</tr>
<tr>
<td>Red &amp; Brown (PR)</td>
<td>75 ± 0.43</td>
<td>7.65 ± 0.47</td>
<td>85.5 ± 1.15</td>
<td>4.28 ± 0.15</td>
<td>2.64 ± 1.38</td>
<td>0.6 ± 0.01</td>
</tr>
<tr>
<td>Ulva (U)</td>
<td>74.1 ± 0.72</td>
<td>8.7 ± 0.38</td>
<td>66 ± 1</td>
<td>4.9 ± 0.26</td>
<td>20.4 ± 1.32</td>
<td>0.59 ± 0.03</td>
</tr>
<tr>
<td>Ulva + Biscuit (AU)</td>
<td>73.7 ± 0.25</td>
<td>7.86 ± 0.82</td>
<td>65.3 ± 6.83</td>
<td>3.71 ± 0.03</td>
<td>23.27 ± 6.37</td>
<td>0.61 ± 0.03</td>
</tr>
<tr>
<td>Ulva + Brown (PU)</td>
<td>74 ± 0.66</td>
<td>7.27 ± 0.31</td>
<td>81.6 ± 1.59</td>
<td>3.74 ± 0.13</td>
<td>7.29 ± 1.87</td>
<td>0.54 ± 0.03</td>
</tr>
<tr>
<td>Ulva &amp; Red (RU)</td>
<td>75.1 ± 0.21</td>
<td>8.22 ± 0.64</td>
<td>82.9 ± 2.4</td>
<td>4.1 ± 0.11</td>
<td>4.74 ± 1.98</td>
<td>0.57 ± 0.02</td>
</tr>
</tbody>
</table>

* NFE = Nitrogen Free Extract, consisting of carbohydrates, sugars and starches.
** P = Phosphorous.

Table 6. Significance values for differences in the proximate analyses of abalone fed different diets

<table>
<thead>
<tr>
<th>Diet</th>
<th>Moisture (% wet wt)</th>
<th>Ash (% dry wt)</th>
<th>Protein (% dry wt)</th>
<th>Lipid (% dry wt)</th>
<th>NFE* (% dry wt)</th>
<th>Total P.** (% dry wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Initial V final)</td>
<td>0.1765</td>
<td>0.3126</td>
<td>0.0813</td>
<td>0.1584</td>
<td>0.0859</td>
<td>0.1889</td>
</tr>
<tr>
<td>Onshore diets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Including Control</td>
<td>0.0001</td>
<td>&lt;0.0001</td>
<td>0.0009</td>
<td>0.0001</td>
<td>0.0006</td>
<td>0.01285</td>
</tr>
<tr>
<td>Excluding Control</td>
<td>0.0536</td>
<td>0.0013</td>
<td>0.5931</td>
<td>0.007</td>
<td>0.4079</td>
<td>0.0822</td>
</tr>
<tr>
<td>Offshore diets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Including Control</td>
<td>0.0001</td>
<td>0.0501</td>
<td>0.0126</td>
<td>&lt;0.0001</td>
<td>0.0095</td>
<td>0.0161</td>
</tr>
<tr>
<td>Excluding Control</td>
<td>0.0197</td>
<td>0.4843</td>
<td>0.0161</td>
<td>&lt;0.0001</td>
<td>0.0186</td>
<td>0.0182</td>
</tr>
<tr>
<td>Offshore V Onshore</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ulva (U)</td>
<td>0.5915</td>
<td>0.0117</td>
<td>&lt;0.0001</td>
<td>0.2331</td>
<td>&lt;0.0001</td>
<td>0.0556</td>
</tr>
<tr>
<td>Ulva + Biscuit (AU)</td>
<td>0.1205</td>
<td>0.0399</td>
<td>0.0383</td>
<td>0.1142</td>
<td>0.0481</td>
<td>0.5931</td>
</tr>
</tbody>
</table>

* NFE = Nitrogen Free Extract, consisting of carbohydrates, sugars and starches.
** P = Phosphorous.

Abalone culture

16
Cost benefit analysis

The main operational costs in the cost of production of abalone were the cost of the feed and the amount of time needed to maintain (feed/ clean) the abalone, with regard to boat and labour costs.

Several cost benefit scenarios were performed to compare the feasibility of producing abalone offshore for $25/kg, a figure which is achieved by many land-based operations. The scenarios compared the amount of labour that can be allocated to each of the operations given the budget constraints. This was compared at different scales of operation (5, 10 or 20 tonne), with different feed costs, and with different feed types: seaweeds, seaweed and formulated feed, and formulated feed.

Assumptions:
Scenarios conducted here were based on the following assumptions:

- Cost of production of $25/kg (an average cost of $26.52 was previous used (EconSearch Pty Ltd 2011))
- Values derived from the current study
  - Initial size at stocking – 38 g.
  - Specific growth rates and feed rates from results of the current trial, which were:

<table>
<thead>
<tr>
<th>Feed</th>
<th>SGR (%/day)</th>
<th>Feeding Rate (kg/abalone/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seaweed</td>
<td>0.07</td>
<td>0.405</td>
</tr>
<tr>
<td>Seaweed + Formulated Feed</td>
<td>0.09</td>
<td>0.405</td>
</tr>
<tr>
<td>Formulated Feed</td>
<td>0.24</td>
<td>0.2</td>
</tr>
</tbody>
</table>

- Survival of 85%/year (industry standard for raceway culture is typically >95%/year).
- Operational costs include veterinary checks, of $715/year, insurance and moorings $180/year.
- Labour costs at $35/hour, 35 hour weeks, 48 weeks/year.
- Boat costs at $55.20/hour: purchase of boat ($300 000), depreciating at 8%/annum= $24,000/year converts to $12.50/hour. Fuel costs, diesel= $1.60/L (-$0.38 rebate), at 35L/hour.

Results from the cost benefit analyses for using seaweeds, seaweed and formulated feed, and formulated feed are presented in Table 7, Table 8 and Table 9, respectively.

Cost benefit analyses indicated that for every tonne of abalone produced offshore in cages, either 7.216 tonne of seaweed (wet wt), 6.819 tonne of seaweed and formulated food (50:50 wet wt seaweed, dry wt formulated feed) or 2.385 tonne of formulated feed (dry wt), is needed each year.
Table 7. Cost benefit scenarios for a 5t, 10t and 20t farm with using seaweed feed at costs per kilogram of a) $0.50 b) $1.00 and c) current price of $1.70. Shows the number of people that could be employed for the cost of operation to remain at $25/kg.

<table>
<thead>
<tr>
<th>Production</th>
<th>5 tonne</th>
<th>10 tonne</th>
<th>20 tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of abalone</td>
<td>89 082</td>
<td>178 163</td>
<td>356 327</td>
</tr>
<tr>
<td>Quantity of seaweed required (kg)</td>
<td>36 078</td>
<td>72 156</td>
<td>144 312</td>
</tr>
<tr>
<td>Number of employees required when feed costs:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) $0.50/kg</td>
<td>0.7</td>
<td>1.4</td>
<td>2.8</td>
</tr>
<tr>
<td>b) $1.00/kg</td>
<td>0.6</td>
<td>1.2</td>
<td>2.3</td>
</tr>
<tr>
<td>c) $1.70/kg</td>
<td>0.4</td>
<td>0.8</td>
<td>1.7</td>
</tr>
<tr>
<td>Cost of Production ($/kg)</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Operational Costs ($)</td>
<td>125 000</td>
<td>250 000</td>
<td>500 000</td>
</tr>
<tr>
<td>Average Price ($/kg)</td>
<td>26.52</td>
<td>26.52</td>
<td>26.52</td>
</tr>
<tr>
<td>Income ($)</td>
<td>132 600</td>
<td>265 200</td>
<td>530 400</td>
</tr>
</tbody>
</table>

Table 8. Cost benefit scenarios for a 5t, 10t and 20t farm with using seaweed (S) and formulated (FF) feeds at costs per kilogram of a) $0.50 (S) $1.50 (FF), b) $1.00 (S) $2.00 (FF), and c) current price of $1.70 (S) $2.75 (FF). Shows the number of people that could be employed for the cost of operation to remain at $25/kg.

<table>
<thead>
<tr>
<th>Production</th>
<th>5 tonne</th>
<th>10 tonne</th>
<th>20 tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of abalone</td>
<td>84 187</td>
<td>168 374</td>
<td>336 747</td>
</tr>
<tr>
<td>Quantity of seaweed and formulated feed required (kg)</td>
<td>34 096</td>
<td>68 191</td>
<td>136 383</td>
</tr>
<tr>
<td>Number of employees required when feed costs:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) $1.00/kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b) $1.50/kg</td>
<td>0.5</td>
<td>1.0</td>
<td>1.9</td>
</tr>
<tr>
<td>c) $2.22/kg</td>
<td>0.3</td>
<td>0.6</td>
<td>1.3</td>
</tr>
<tr>
<td>Cost of Production ($/kg)</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Operational Costs ($)</td>
<td>125 000</td>
<td>250 000</td>
<td>500 000</td>
</tr>
<tr>
<td>Average Price ($/kg)</td>
<td>26.52</td>
<td>26.52</td>
<td>26.52</td>
</tr>
<tr>
<td>Income ($)</td>
<td>132 600</td>
<td>265 200</td>
<td>530 400</td>
</tr>
</tbody>
</table>
Table 9. Cost benefit scenarios for a 5t, 10t and 20t farm with using formulated feeds at costs per kilogram of a) $1.50, b) $2.00 and c) current price of $2.75. Shows the number of people that could be employed for the cost of operation to remain at $25/kg.

<table>
<thead>
<tr>
<th>Production</th>
<th>5 tonne</th>
<th>10 tonne</th>
<th>20 tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of abalone</td>
<td>59 617</td>
<td>119 235</td>
<td>238 469</td>
</tr>
<tr>
<td>Quantity of formulated feed required (kg)</td>
<td>11 923</td>
<td>23 847</td>
<td>47 694</td>
</tr>
<tr>
<td>Number of employees required when feed costs:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) $1.50/kg</td>
<td>0.7</td>
<td>1.4</td>
<td>2.8</td>
</tr>
<tr>
<td>b) $2.00/kg</td>
<td>0.7</td>
<td>1.3</td>
<td>2.7</td>
</tr>
<tr>
<td>c) $2.75/kg</td>
<td>0.6</td>
<td>1.2</td>
<td>2.4</td>
</tr>
<tr>
<td>Cost of Production ($/kg)</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Operational Costs ($)</td>
<td>125 000</td>
<td>250 000</td>
<td>500 000</td>
</tr>
<tr>
<td>Average Price ($/kg)</td>
<td>26.52</td>
<td>26.52</td>
<td>26.52</td>
</tr>
<tr>
<td>Income ($)</td>
<td>132 600</td>
<td>265 200</td>
<td>530 400</td>
</tr>
</tbody>
</table>

Seaweed Culture

Wild harvesting

Seaweed culture is not covered under the Fisheries Act. Advice from DSE suggested that a permit would not be required if the activity does not impact on any protected flora/fish, not in any National Parks Act 1975 managed waters, or impacts on wildlife.

Several local beaches were identified as having a consistent supply of beach cast seaweed which could be hand collected with minimal impacts on the environment. Sufficient quantities could be collected for use in the abalone culture trial. To overcome potential supply issues, beach cast seaweed was stockpiled in tanks at DPI Queenscliff.

At GSW, there was sufficient amounts of Ulva present in drains and settlement ponds which could be harvested for feeding abalone in the trial on-site.

A licence is required for commercial seaweed harvesting. Although it was considered possible to harvest large amounts of the exotic brown seaweed (Undaria pinnatifida) as abalone feed, this was not pursued further due to the risks of spreading this invasive species.

Cultivation

Cultivation trials were conducted during the early months of the study, primarily to produce sufficient seaweed biomass for the abalone culture trial.

Finding the most appropriate seaweeds for cultivation was largely unsuccessful with several trials conducted on a range of local species yielding zero growth and even decay. Eventually several target species, and sources for these, were established which enabled work to begin on larger scale growth trials. These trials focused on red seaweeds, particularly Gracilaria chilensis and green seaweed (Ulva), which have previously been shown to produce healthy growth rates in abalone grow-out (O’Bryen and Lee 2003, Robertson-Andersson 2004).

Growth of G. chilensis and Ulva was generally slow within the trial systems, but both species increased biomass through tumble-culture and nutrient feeding in large (2,500 L) outdoor tanks. Culture trials at GSW also experienced limited growth of G. chilensis in greenhouse tanks.

Growth of three species of Gracilaria was monitored in a three week trial. Gracilaria Sp 1 grew by 8.9% in one of the replicates (Sp1b) yet it decreased by 7.5% in the other (Sp1a) (Figure 19). Gracilaria Sp 2 lost weight after the first week but grew by 13.1% over the following 2 weeks, whereas Gracilaria Sp 3 grew consistently over the 3 week period, increasing its weight by 21.4%. Fragmentation and attachment was observed in all of the aquariums and could be representative of further growth of each of the seaweed species. In this trial, temperature pH, salinity and light intensity were at 18.12°C ± 0.34, 8.02 ± 0.01, 36.53ppt ± 0.25 and 20890 LUX ± 405 (mean ± SD), respectively.
Cultivation factors that supported positive growth of seaweeds were included:

**Ulva spp:**
- Tumble culture: moving water through aeration that allowed *Ulva* even access to nutrients and light. This has been shown to work in other systems around the world as well.
- Max depth of 1 m culture units to ensure high light exposure.
- Addition of nutrients to a maximum TAN of 0.25mg/L for growth and protein content of seaweed (which enhances its suitability as an abalone feed)
- Species will spore after a period of desiccation.

**Gracilaria:**
- Tumble culture: not as productive.
- Requires lower light levels at depths of approximately 1m.
- Addition of nutrients to a maximum TAN of 0.125mg/L increases growth.

Some of the key issues experienced during culture trials were the presence of grazers (due to poor water filtration), insufficient lighting system (require higher range blue light).

Cultivation trials were scaled back in latter months of the study as sufficient amounts of beach cast seaweed could be readily obtained.

**Proximate analyses**
Seasonal variations in the proximate composition of seaweeds are presented in Table 10. Ash and moisture content varied little between seaweed type and season. Protein content of red seaweed was more variable across seasons than for other seaweeds. Lipid content was mainly between 1.69% and 5.33%, but was highest in red seaweed in autumn (5.47%). Total phosphorous content was between 0.08% and 0.36%, with the exception of brown seaweed that peaked at 0.43% in Spring.

Figure 19. Proportionate growth (as a percentage of initial weight) of three *Gracilaria* species over a 3 week culture trial
Table 10. Seasonal variation in proximate analysis of seaweeds (mean values presented)

<table>
<thead>
<tr>
<th>Diet</th>
<th>Season</th>
<th>Moisture (% wet wt)</th>
<th>Ash (% dry wt)</th>
<th>Protein (% dry wt)</th>
<th>Lipid (% dry wt)</th>
<th>NFE* (% dry wt)</th>
<th>Total P.** (% dry wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brown</td>
<td>Aut</td>
<td>73.3</td>
<td>25.53</td>
<td>6.5</td>
<td>2.71</td>
<td>65.26</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>Win</td>
<td>69.6</td>
<td>17.78</td>
<td>4.0</td>
<td>1.69</td>
<td>76.55</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>Spr</td>
<td>63</td>
<td>19.87</td>
<td>4.9</td>
<td>2.18</td>
<td>73.04</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>71.5</td>
<td>21.44</td>
<td>5.5</td>
<td>2.05</td>
<td>71.08</td>
<td>0.21</td>
</tr>
<tr>
<td>Red</td>
<td>Aut</td>
<td>72.9</td>
<td>23.38</td>
<td>13.9</td>
<td>5.47</td>
<td>57.46</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Win</td>
<td>72.6</td>
<td>26.69</td>
<td>16.6</td>
<td>2.09</td>
<td>54.49</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Spr</td>
<td>75.4</td>
<td>27.49</td>
<td>14.3</td>
<td>1.91</td>
<td>56.10</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>81.8</td>
<td>31.29</td>
<td>9.3</td>
<td>2.32</td>
<td>56.84</td>
<td>0.18</td>
</tr>
<tr>
<td>Ulva (Offshore)</td>
<td>Aut</td>
<td>88.3</td>
<td>26.14</td>
<td>19.6</td>
<td>3.65</td>
<td>50.20</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>Win</td>
<td>86.4</td>
<td>27.26</td>
<td>22.8</td>
<td>3.06</td>
<td>46.90</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>Spr</td>
<td>84.5</td>
<td>23.17</td>
<td>12.1</td>
<td>2.01</td>
<td>62.72</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>76.2</td>
<td>21.46</td>
<td>7.8</td>
<td>2.21</td>
<td>68.48</td>
<td>0.14</td>
</tr>
<tr>
<td>Ulva (GSW)</td>
<td>Aut</td>
<td>88.1</td>
<td>23.21</td>
<td>30.5</td>
<td>4.44</td>
<td>42.02</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>Win</td>
<td>88.2</td>
<td>24.23</td>
<td>25.6</td>
<td>4.74</td>
<td>45.81</td>
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</tr>
<tr>
<td></td>
<td>Spr</td>
<td>77.8</td>
<td>23.37</td>
<td>9.7</td>
<td>2.71</td>
<td>64.08</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>88.5</td>
<td>30.51</td>
<td>21.0</td>
<td>5.33</td>
<td>42.98</td>
<td>0.36</td>
</tr>
</tbody>
</table>

*NFE = Nitrogen Free Extract, consisting of carbohydrates, sugars and starches.

**P = Phosphorous.
Discussion and Recommendations

Abalone culture

Survival
One of the key issues associated with farming in offshore environments is the vagaries of climatic extremes that can limit regular access to cages and also place demands on equipment and culture systems.

The survival of abalone in the current study may have been closely related to water quality. This was especially the case for the onshore culture system where overall survival was nearly half that observed in other systems. The onshore culture system experienced high and variable water temperature, high ammonia concentrations and low dissolved oxygen concentrations in the warmer months.

Water temperature above optimal conditions for abalone can result in stress leading to increased incidence of disease and death. Braid et al. (2005) found that, at high temperatures, red abalone (Haliotis rufescens) exhibited a greater prevalence, but not a greater intensity, of infection. The optimum temperatures for growth of Tasmanian blacklip abalone (H. rubra) and greenlip abalone (H. laevigata) are 17.0°C, and 18.3°C, respectively (Gilroy and Edwards 1998). Water temperatures in the onshore system peaked at 25°C during summer.

Both high ammonia concentrations and low dissolved oxygen concentrations have been found to reduce the growth in juvenile greenlip abalone (Harris et al. 1998, Harris et al. 1999).

The survival of the 120 tagged abalone in the control raceway system over the entire trial period was 77%. However, under general farm practices for abalone in the age range used in the current trial, survival rates in raceways are expected to be at least 95% per year. The lower survival rate observed in the current study was attributed to abalone losing identifying tags rather than mortality. In comparison, a substantial number of abalone in cages lost tags (onshore - 19%, offshore – 10%).

Growth
Growth rates of abalone reared in cages offshore were generally lower than for abalone reared onshore. Although temperature can affect growth of abalone (Britz et al. 1997, Gilroy and Edwards 1998), the differences in temperature between offshore and onshore systems during the trial were minimal (Table 4). The growth rates were higher in each of the systems during the summer months and slowed through winter. This was more pronounced in the offshore cages and may be accounted for by the increased biofouling seen through winter.

Abalone in both the experimental systems were originally stocked at relatively low densities (0.046 m² Shelter Surface Area – SSA). However, as the trial continued the high levels of mortality in the onshore system meant that the density was reduced (0.092 m² SSA). This could account, in part, for the higher growth rates seen onshore versus offshore. Abalone reared in cages at low densities (0.66 m² SSA) have been shown to grow significantly faster than those grown at higher densities (Fermin and Mae Buen 2002).

Biofouling of aquaculture cages can limit growth of farmed shellfish (Alcantara and Noro 2006, Dürr and Watson 2010, Ingram et al. 2013), and was an issue for cages at the offshore site. Biofouling may have affected growth by reducing water exchange rates. Onshore cages were cleaned more frequently, and food was replaced with fresh food more often, than in offshore cages.

Harris et al. (1998) showed that juvenile greenlip abalone (weight 4.48g) were highly sensitive to ammonia, which reduced growth rates. In the current study, hybrid abalone in the onshore system were exposed to elevated levels of ammonia in the effluent water from traditional abalone culture raceways, but their growth was similar to abalone reared in the culture raceways.

For both onshore and offshore sites, treatments that included formulated feeds produced higher growth rates than those that received seaweed only. The feed treatment that alternated Ulva and formulated feed produced the highest specific growth rates in both trial systems. This indicates that abalone fed this combination receive enhanced nutrition compared to abalone fed solely seaweed or formulated feeds.

In the offshore site, abalone that were fed diets that contained red seaweeds grew better than those fed other types of seaweed. This supports the contention that Australian abalone prefer red seaweed (Fleming 1995) and that red seaweeds can provide for good abalone growth (Mai et al. 2003).
Abalone culture

1994, Mai et al. 1995, Mai et al. 1996, Rosen et al. 2000, Demetrupolous and Langdon 2004. Australian brown seaweed appear to have a higher concentration of unpalatable polyphenolic compounds compared to northern hemisphere kelp (Stepto and Cook 1993) and so are less utilized by abalone.

Abalone in the current study that were fed a mix of different seaweed types grew better than those fed a single seaweed species. This result is consistent with other studies that have shown that abalone grow better on a varied seaweed diet (Simpson and Cook 1998, Gordon et al. 2006, Naidoo et al. 2006, Qi et al. 2010, Viera et al. 2011). A mixed diet may better meet the nutritional requirements of abalone than can be provided by a single species. Proximate and lipid fraction analysis of abalone indicated significant differences in composition associated with seaweed types.

**Biomass gain**

The significantly greater biomass gain in the control raceway system was attributed to a combination of high growth and high survival compared to onshore and offshore cages. The survival rate in the raceway during the study was 77%, however, if the industry supplied figure for survival during raceway grow-out is 95%, then this biomass gain would be 555g for 20 abalone (28g/abalone). This system has been developed over many years and is monitored daily. In comparison, the experimental systems were designed on a small scale and were monitored less regularly.

The two treatments that were replicated at both onshore and offshore sites (Diet U and AU) had lower growth rates but higher biomass gains offshore compared to onshore. This shows the importance of maintaining health and reducing mortality to the overall production of a viable abalone culture system. The offshore site provided for good biomass gains with certain dietary treatments (i.e. alternating formulated and Ulva feeds).

There were increased gains in biomass for the abalone fed the biscuit formulated feed (A) compared to other diets. This could be attributed to its concentrated beneficial nutrient profile compared to seaweed and greater water stability than the pelleted formulated feed. With further developments, this type of formulated feed could be utilised in offshore abalone culture.

**Health**

The condition indices of the abalone in the current study indicated that abalone were converting more energy into their shells than to their muscle mass. The abalone in the control raceway system converted even amounts of energy into both muscle and shell mass.

The high condition index and low muscle to shell ratio of the abalone fed brown seaweed only (Diet P) in the offshore system indicated this diet was nutritionally deficient. This has been attributed to its low protein content, which reduces the uptake of amino acids by the abalone (Britz 1996).

**Proximate Composition**

Proximate and lipid fraction analyses of abalone highlighted significant differences in composition of abalone associated with diet. These differences may have accounted for variations to the growth of abalone observed in this trial. Abalone fed diets used in cages had significant different proximate analysis and lipid fraction analyses compared to the control abalone.

Of the seaweed diets, abalone fed Ulva only had a significantly different composition to abalone fed other diets, including those that were a mix of Ulva and seaweeds.

Differences in abalone composition were also apparent in diet treatments (U and AU) that were used at both onshore and offshore sites. These differences may have been due to the different conditions under which Ulva was cultured (see Table 10). Onshore, only Ulva reared on site was used for the trial, whereas Ulva used offshore was from various sources.

**Feed rate and FCR**

Abalone in the current study were fed to excess and uneaten food was included in FCR calculations. This means that FCR’s were generally high, especially in offshore cages (FCR’s >10). In comparison, abalone fed excess red seaweed Gracilaria sp. had FCR’s of 26–27 in another study (Fermin and Mae Buen 2002). In contrast, FCR’s in normal onshore raceway culture systems are typically about 1.2 (industry comments). Feeding to excess was done to ensure that food was always available to the abalone when less frequent feeding was occurring.

In onshore cages, the FCR was better for the seaweed (Ulva) diet than for the formulated diets. However, the slow growth rates produced on this diet treatment meant that the cost per
kilogram of growth was similar across all treatments.

In the offshore trial, FCR’s were best for the feed treatments that contained red seaweed or formulated feeds. This is in alignment with the growth data. Further reductions in FCR’s could be made by improved, more regular, monitoring of the cages and reducing the amount of excess feed.

**Feed costs.**

This study showed that feed costs for feeding seaweeds to abalone in cages offshore were substantially greater than for feeding abalone onshore. In order for abalone fed seaweed to be produced at a cost comparable to those fed formulated feeds onshore, green seaweeds, such as *Ulva*, need to be produced at $1.30/kg, while red seaweeds, such as *Gracilaria*, need to be produced for $2.70/kg. Producing seaweeds at a lower cost is achievable through better collection techniques of beach cast seaweed or the cultivation of fast growing, nutritious seaweeds. Alternatively, offshore abalone culture systems could be developed that require reduced feeding rates and/or frequency.

For example, seaweed, especially the kelp *Laminaria japonica* and *Undaria pinnatifida* constitutes the major feed for farmed abalone in north China (Nie and Wang 2004, Zhang et al. 2010), because they are readily available and produce good growth rates for local abalone species. *U. pinnatifida*, is exotic to Australia and although it has the potential as a food for abalone, its noxious status will limit its use in offshore abalone farming in Port Phillip Bay.

**Cost benefit analysis**

Cost benefit projections undertaken in the current study clearly showed that labour costs are a significant influence on the cost of production. With current feed prices at $2.75 for formulated feeds and $1.70/kg for seaweed, farms with an output of 20 tonne would have to be able to maintain between 238 000 and 356 000 abalone with only 2 full time staff. This is even less feasible using formulated feeds because, despite the higher growth rates, feeding needs to occur 2 to 4 times more regularly than for abalone on seaweed feeds. In order to be profitable, an offshore abalone farming system must be carefully designed to allow minimal maintenance and labour.

Using seaweed as a feed in offshore abalone farming has its benefits and concessions. The slow growth rates of abalone fed seaweed diets mean that a farm that only utilizes seaweed feeds requires 1.5 times the number of abalone than a farm that utilizes solely formulated feeds. A farm that uses a combination of seaweed and formulated feeds needs 1.4 times the number of abalone than a farm that utilizes solely formulated feeds. The quantity of feed required for a farm that utilizes formulated feeds rather than seaweeds is also significantly lower. The low cost of producing seaweed, and the reduced labour involved with using it, means that despite the need for large quantities of seaweed (36 tonne/year to maintain a 5 tonne farm), the total feed and operational costs is comparable to using formulated feeds.

Developing cheaper feeds is also possible, particularly with regard to seaweed feeds. The cultivation of seaweed has not been developed in Australia and as such, the costs of production for seaweed in Australia are currently unknown. The cost of seaweed used in these projections is based on hand collection of beach cast seaweed only.

**Seaweed culture**

The preliminary seaweed culture trials undertaken in the current study provided information that can be used to further develop seaweed culture methods. However, these trials did not produce seaweed in the amounts that were required to undertake the offshore abalone culture trial. As such, beach cast seaweed was primarily used in the abalone trials, while seaweed culture trials were suspended.

While seaweed culture is still in its infancy in Australia, its cultivation is practiced widely around the world to produce a range of products (see Andersen 2005). At total of 19.9 mil. tonne of seaweed was produced globally in 2010, which was the second largest aquaculture sector after freshwater fishes (33.7 mil. tonne) (http://www.fao.org/fishery/statistics/en). The integration of seaweed culture into abalone culture has been shown to have a positive effect on both the bioremediation of system water and the productivity of the system (Troell et al. 2006, Robertson-Andersson et al. 2008, Abreu et al. 2009, Marinho-Soriano et al. 2009, Abreu et al. 2011). Consequently, further research on seaweed culture will be continued through a University of Wollongong PhD study (by Will Mulvaney). This study will explore the potential for growing seaweeds on ropes that can then be easily harvested and transferred into abalone culture systems. Tumble culture of *Ulva* will also be further developed.
In order to be financially viable it is necessary to produce seaweed at a low cost. This means that culture systems need to be developed that have low labour and set up costs. Seeding and harvesting techniques require minimal labour if they are to be viable.

**Challenges of offshore abalone farming:**
This study identified a number of key challenges that face further development of offshore abalone farming. These were:

1. **Feeds and feeding**
Providing a reliable feed supply for abalone in offshore cages is one of the key challenges facing the industry, due to the irregularity of offshore feeding regimes (on account of weather, etc.). Formulated feeds can currently be accessed and are a reliable feed source, however current formulated feeds require changing every 3-4 days in order to maintain optimal growth conditions for abalone.

Seaweeds are currently not produced in sufficient quantities in Australia to provide for abalone culture (e.g. 1 tonne abalone: 7 tonne seaweed) and there availability is affected by seasonality.

2. **Culture system design**
The cages used in this study were relatively small and so required disproportional effort to feed and clean a small amount of abalone. The corflute base that provided the floor to the cages restricted the flow of waste out of the cage.

Several cages were lost due the rusting of the clips that attached them to the long lines as well as the high-energy environment they were placed in. Replacing the clips regularly significantly reduced cage loss.

3. **Biofouling**
Significant fouling occurred in the cages within 2 months of being placed at sea. This restricted water flow in the cages, and affected the shells of the abalone; in some cases their respiratory holes were covered.

4. **Labour**
The labour and boat costs involved with this offshore abalone culture trial were significantly higher than any other cost (including feed). This is, in part, due to the small cages and disproportionate effort required to feed and clean a small number of abalone. The experimental system required 3 people and a boat to feed and clean the abalone fortnightly.

**Conclusions and recommendations**
Increased investment in offshore abalone culture systems in Victorian aquaculture zones, and associated production of diets (seaweed and artificial foods), has the potential to increase overall production of the industry. The present pilot-scale study provided baseline information of the culture of hybrid abalone reared in cages and fed different diets of seaweed and formulated feeds. This information may be used to guide further research and development into offshore abalone farming and associated production of seaweed as either a direct or indirect food source.

**Recommendations for offshore abalone farming**

**Feeds and feeding**
Due to the irregularity of offshore feeding regimes, feed sources that can be delivered remotely or that will remain stable and active for extended periods of time need to be developed.

The use of binders can extend the stability of the formulated feeds. However, some studies have shown a negative correlation between binder strength and feed palatability and growth rates (Uki et al. 1985, Gorfine 1991, O’Mahoney et al. 2011). The biscuit formulated feed (Diet A) was a promising feed source in the current study trial as it produced good growth rates, was easy to dispense and allowed the abalone to continue to graze for longer periods of time. This diet should be further developed as a formulated feed for use offshore.

Use of seaweeds exclusively, or in combination with a formulated feed, should be further explored. An advantage of seaweed over currently available formulated feeds is that they remain functional as a food for abalone for a longer time by not degrading. However, a reliable source of the seaweed needs to be found or developed. This study showed the benefits of feeding mixed seaweed diets to abalone, a generalist opportunistic herbivore. Red seaweeds (*Gracilaria*) and *Ulva* provided for the best growth rates.

A combination of formulated and seaweed feeds produced the best growth rates in the offshore system. There were also several health benefits to the abalone being fed seaweeds (better condition indices, adapting to environmental...
stresses). This feeding approach should be further developed.

**Culture system design**

Cages need to be designed to provide adequate shelter for the abalone while still allowing for water flow. They also need to be easy to access for abalone feeding, cleaning and harvesting.

Cage design should be investigated, particularly with regard to shape and size of cages and mesh size, as well as anchoring systems that should be engineered to withstand both the tidal and wave action.

Other factors that can influence abalone growth and survival in cages that should be investigated further include, size at stocking, stocking density and the ratios of shelter surface area to cage volume (SSA:CV).

**Biofouling**

Biofouling may be reduced by more frequent cleaning or replacement of cages. Having a higher density of abalone in each cage may also limit the growth of biofouling organisms. By studying the water currents of the selected farming area, it may be possible to locate an abalone farm within an area that would be affected less by biofouling.

**Labour**

Offshore farming systems will need to be carefully designed to reduce the amount of time needed to service the abalone. A system such as the one used in this experiment is not appropriate. There are several offshore culture systems that have been designed and are commercially produced around the world in areas that use such systems extensively. These designs should be explored and tailored to an individual locations’ requirements, reducing the labour and boat costs involved with its operation. Marketing opportunities such as advertising the abalone as ‘sea-reared’ and potentially having better omega-3 profiles (subject to proximate composition analysis) could allow the abalone to be sold at a premium price. This would allow for higher operational costs.

**Recommendations for seaweed culture:**

In order to be financially viable it is necessary to produce seaweed at a low cost.

Culture systems need to be developed to have low labour and set up costs.

Further development of the tumble culture method for *Ulva* growth would result in greater production.

*Gracilaria* production (set up and harvesting) may be improved in both onshore and offshore environments, if an efficient means of threading this algae onto ropes is realised.

Seaweed culture could be integrated into abalone culture systems for bioremediation and to increase the growth and protein content of the seaweeds.

Further seaweed growth trials are being performed at the University of Wollongong utilising *Ulva* and *Gracilaria* that have been seeded (*Ulva*) or threaded (*Gracilaria*) onto ropes. Seaweeds will also be cultured in an abalone farms effluent water to ascertain the bioremediation potential and growth rates that can be achieved in this environment.
Acknowledgements

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Appendix I - Project poster presented at the International Abalone Symposium (Hobart, May 2012)