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Abalone farming in South Africa: An overview with perspectives on kelp resources, abalone feed, potential for on-farm seaweed production and socio-economic importance

M. Troell [a,*], D. Robertson-Andersson [b], R.J. Anderson [c], J.J. Bolton [b],
G. Maneveldt [d], C. Halling [e], T. Probyn [c]

[a] *Beijer International Institute of Ecological Economics, The Royal Swedish Academy of Sciences, 50005, 104 05 Stockholm, Sweden*
[b] *Botany Department, University of Cape Town, Rondebosch 7701, South Africa*
[c] *Marine and Coastal Management, Private Bag X2, Rogge Bay 8012, South Africa*
[d] *Department of Biodiversity and Conservation Biology, University of the Western Cape, P. Bag X17, Bellville 7535, South Africa*
[e] *Department of Systems Ecology, Stockholm University, 106 91 Stockholm, Sweden*

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Abstract

The South African abalone cultivation industry has developed rapidly and is now the largest producer outside Asia. With a rapid decline in wild abalone fisheries, farming now dominates the abalone export market in South Africa. Kelp (*Ecklonia maxima*) constitutes the major feed for farmed abalone in South Africa, but this resource is now approaching limits of sustainable harvesting in kelp Concession Areas where abalone farms are concentrated. This paper gives an overview of the development of the South African abalone industry and analyses how abalone farming, natural kelp beds and seaweed harvesting are interlinked. It discusses options and constraints for expanding the abalone industry, focussing especially on abalone feed development to meet this growing demand.

Kelp will continue to play an important role as feed and kelp areas previously not utilised may become cost-effective to harvest. There are many benefits from on-farm seaweed production and it will probably be a part of future expansion of the abalone industry. Abalone waste discharges are not at present regarded as a major concern and farming brings important employment opportunities to lower income groups in remote coastal communities and has positive spillover effects on the seaweed industry and abalone processing industry.

Keywords: Abalone; Kelp; *Ecklonia*; Integrated aquaculture; *Gracilaria*; *Ulva*

1. Introduction

The global production of abalone reached 22,600 metric tonnes (including poaching of 3700 metric tonnes) in 2002. Of this, over 8600 metric tonnes was farmed and the total value of the production was estimated as approximately US$ 0.8 billion (Gordon and Cook, 2004). Triggered by a decline in yields from wild fisheries, a rapid development of abalone cultivation took place in the 1990s, and cultivation is now widespread in many countries including USA, Mexico, South Africa,

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* Corresponding author.
E-mail address: max@beijer.kva.se (M. Troell).

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Australia, New Zealand, Japan, China, Taiwan, Ireland, and Iceland (Hahn, 1989; Gordon and Cook, 2001). China is the largest producer in the world with over 300 farms and a total production of approximately 4500 metric tonnes (Gordon and Cook, 2004).

South Africa has become the largest abalone producer outside Asia (FAO, 2004) and over-exploitation of wild abalone stocks by poaching and high market prices have been the main drivers for its cultivation. Access to relatively cheap labour, together with favourable coastal water quality and infrastructure, also facilitated rapid growth of the abalone industry in South Africa. The expansion of the industry is, according to AFASA (Abalone Farmers Association of Southern Africa, Terry Bennett, personal communication), expected to continue. However, access to suitable coastal land and the dependence on wild harvest of kelp for feed may restrict further development in certain areas.

Harvestable kelp occurs on the west coast of South Africa wherever there are rocky shores, and on the south-west coast (between the Cape Peninsula and Cape Agulhas), but not on the south coast (east of Cape Agulhas) (Fig. 1A, B). The large kelp *Ecklonia maxima* has been collected as beach-cast since at least 1953, and shipped to Europe, North America and Asia for alginate production (Anderson et al., 1989). Until the emergence of the abalone farming industry, the only kelp cut from beds was used for a liquid growth stimulant for agricultural crops (Kelpak®, Anderson et al., 2003). The growing demand for kelp by the abalone industry has greatly increased harvesting. According to estimates done by coastal management authorities (Marine and Coastal Management, Department of Environmental Affairs and Tourism, Cape Town) the maximum sustainable yield (MSY) of the kelp was approached in 2003 in parts of the two main nodes of abalone farming; from Quoin Point to Cape Hangklin and in the Cape Columbine area (Fig. 1B). Large increases in kelp harvesting from these areas may impact negatively on kelp ecosystem functions (Anderson et al., 2003, in press). This situation may not be unique for South Africa as potential limitation of kelp supply has also emerged in other abalone farming countries (e.g. USA; McBride, 1998) and in countries where the industry is anticipated to develop rapidly (i.e. Chile; personal communication A. Buschmann, University Los Lagos, Chile). Thus, unless alternatives to wild kelp as feed are utilised to a greater extent, this may constitute a bottleneck for increased abalone production in South Africa. The seaweed industry and the abalone industry bring important economic benefits to South Africa as they both generate export earnings, boost local and regional economies and provide employment among poor coastal communities. For continued growth of the South African abalone industry, from both economic and ecological perspectives, there is a need to identify and analyse the inter-linkages between these two industries and to consider effects on South African coastal ecosystems in general.

This paper describes how natural kelp beds, abalone farming, seaweed harvesting and the abalone-canning industry are interlinked, and identifies potential environmental and resource limitations for continued development of the South African abalone industry. Further aims are: 1) to evaluate different available options for abalone feed, focussing specifically on farm-based seaweed production; and 2) to overview direct and indirect impacts of abalone farming on the seaweed industry and abalone processing industry, with respect to socio-economic benefits for lower income groups.

2. Methods

Data on kelp yields (harvesting and collection of beach-cast) were obtained from the compulsory return statistics sent by commercial seaweed operators in South Africa to Marine and Coastal Management (MCM). Socio-economics, management and production data were obtained from questionnaires that were sent out to 1) all South African abalone farms; 2) all seaweed concession holders; 3) abalone feed manufacturer; and 4) the only canning factory processing farmed abalone at the time. Information was also obtained from industry reports, the results of current research on integrated abalone and seaweed culture, and on coastal resource statistics obtained from coastal management authorities. The open-ended questionnaires were answered by managers at 12 out of 18 abalone farms (a few managers operate more than one farm in an area – therefore total farm number equals 22, Fig. 1B), and by 11 out of 17 seaweed concession holders. Some of the returned questionnaires were not fully completed. The questions asked focused on production, employment statistics (income, gender, races, skills, etc.), on-farm seaweed production and production constraints in the foreseeable future. The information generated by the questionnaires from the abalone farmers and seaweed concession holders is here treated as representative for the overall industry.

3. Development of the South African abalone industry

The present abalone fishery in South Africa is based on subtidal stocks of a single species, *Haliotis midae*.

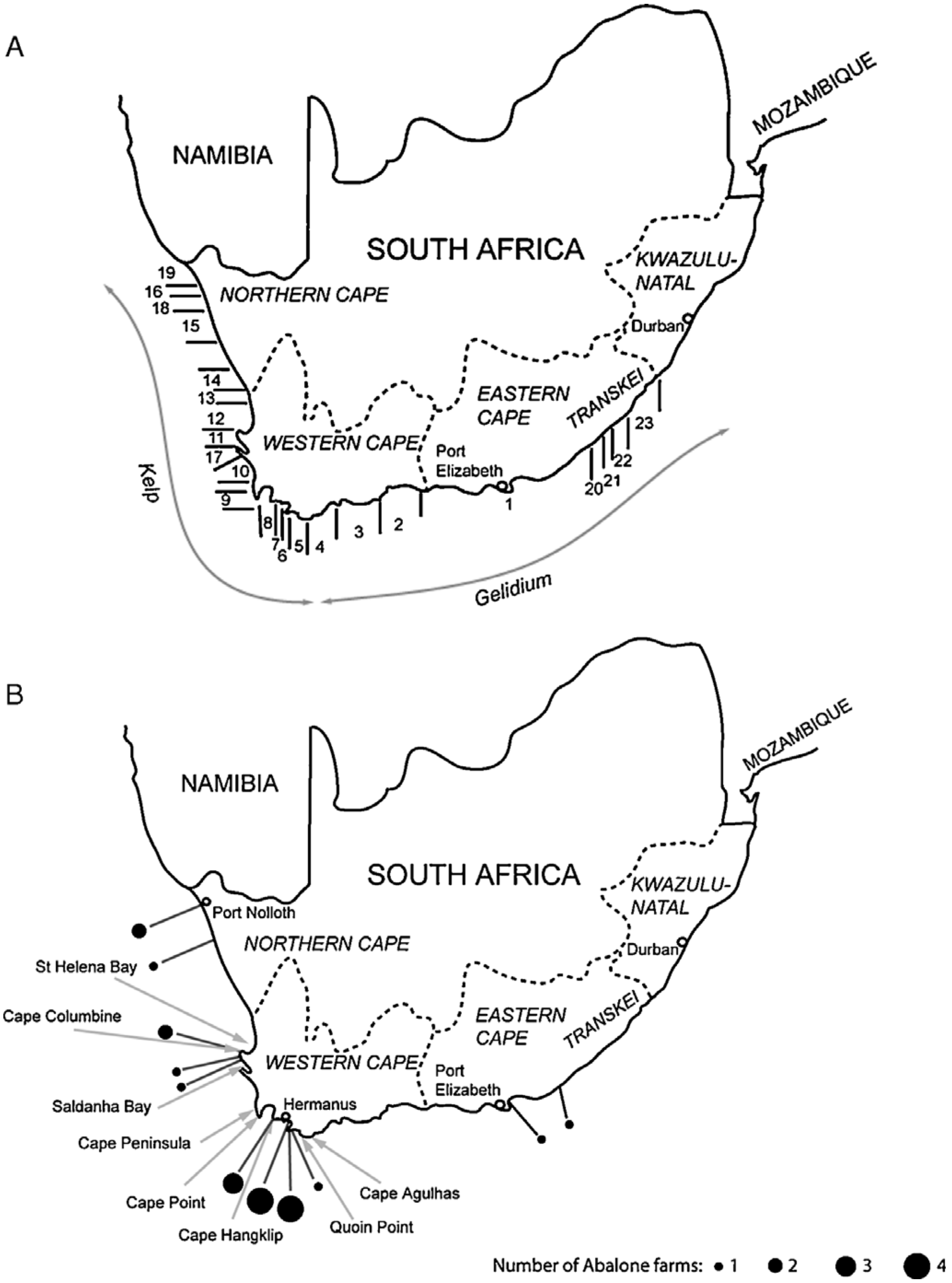

Fig. 1. (A) Map of the South African coast showing Seaweed Concession Areas (after Anderson et al., 2003). *Gelidium* is currently collected from areas 1, 20, 21 22, and 23. There is no current collection of seaweed in areas 2, 3, 4, 10, 20, 22, and 23. Kelp is collected in areas 5–9, 11–16 and 18–19. Lines separate concession areas. (B) Distribution of abalone farms along the coast of South Africa.

Although this species is distributed from at least Cape Columbine in the west to the southern Transkei in the Eastern Cape Province, the traditional commercial fishery is based on about 580 km of coastline between Cape Columbine and Quoin Point (near Cape Agulhas, see Fig. 1B). Mainly small-scale fishing rights are in place and due to unsuitable sandy areas, Marine Protected Areas, or closures to the commercial fishery, not the entire coast is fished. Since 1986, the fishery has been regulated by a minimum legal size of 138 mm shell length (114 mm shell breadth), a restricted fishing season and a strict quota system.

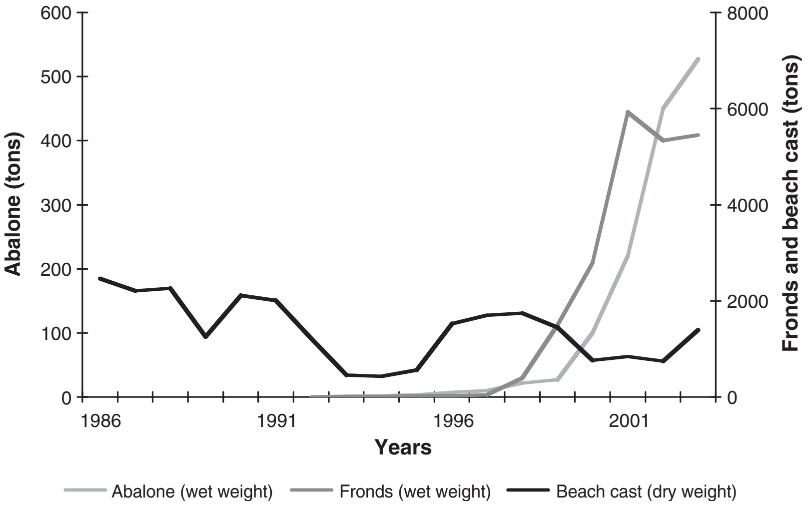

Fig. 2. Graph showing amount of kelp fronds utilised by the abalone farming industry, total amount of beach-cast kelp and abalone production along South African coast.

Despite this, natural stocks and consequently quotas have been steadily decreasing over the last decade. This is a result of severe poaching in all areas (Hauck and Sweijd, 1999), higher-than-expected recreational catches estimated at 850 metric tonnes for 2002 (Gordon and Cook, 2004), and also a massive reduction in abalone recruitment in one particular area (Cape Hangklip to Hermanus), which used to provide the bulk of the commercial yield. This recruitment failure was caused by an unprecedented ingress of large rock lobsters, which have eaten most of the small benthic invertebrates, including juvenile abalone, turbinid snails and sea urchins; these effects on abalone recruitment are compounded by the fact that the very young abalone often live under urchins as a refuge from predators (Tarr et al., 1996; Day and Branch, 2002). The quota for the whole commercial fishery was thus reduced to a little over 230 metric tonnes in 2004 (Rob Tarr, MCM, personal communication) and recreational fishing was stopped in an attempt to combat poaching. It is likely that unless poaching can be controlled, the commercial fishery will have to be closed within a few years. With the high prices being paid for abalone and the worldwide decline in fisheries production, it is not surprising that the economic viability of abalone farming in South Africa is looking promising.

South Africa became involved in abalone farming in the 1990s, following awareness of initiatives in New Zealand and California. Initial work by Genade et al. (1988) showed that the South African abalone could be successfully spawned and reared in captivity. Initial research also indicated that growth rates in captivity were much faster than in the wild, and that food conversion efficiency was such that sufficient quantities of kelp would be available to feed the farm stock (Hahn, 1989). The stage was therefore set for a rapid development of farming activities. In 2003 South Africa farmed over 500 mt of abalone (FishStat Plus, 2005).

Most of the abalone farms are located in the Western Cape Province, but others exist as far north as Port Nolloth (in the Northern Cape Province), and also in the Eastern Cape Province (despite the absence of kelp beds) (Fig. 1B). Most farms pump seawater into land-based tanks that are run in flow-through mode, though recirculation technology is also used. Some farms have both hatchery and on-growing facilities whilst others rely on purchasing juveniles from other hatcheries. It takes about 4 years to grow an abalone from seed to market size (approx. 80 g). The abalone-cultivation industry is growing exponentially (Fig. 2) with 22 permits in existence (not all yet exporting) and a further 5 scheduled for development (AFASA, Terry Bennett, personal communication). In addition, several farms are expanding their production.

An interesting offshoot of the industry has been the development of abalone ranching, where hatchery-produced seed are stocked into kelp beds outside the natural distribution (on the northern west coast) (de Waal and Cook, 2001; de Waal et al., 2003). The current objective of ranching operations is the commercial harvesting of the animals once they have grown to market size. The same technology is used for stock enhancement on the east coast, but here the main aim is to rehabilitate over-fished stocks.

4. South African kelp resources

4.1. Kelp beds

Extensive beds of kelp that reach the surface at low tides extend along rocky coasts from near Cape Agulhas, up the west coast and into Namibia (Fig. 1B) (Stegenga et al., 1997). From Cape Agulhas to at least Cape Columbine, the dominant inshore kelp is *E. maxima*, which has a stipe up to 9 m long with a gas-filled bulb at the top, above which the long, strap-like fronds are suspended near the water surface. *Laminaria pallida*, the other dominant kelp, has a stipe up to 2 m long, no hollow bulb, and a digitate frond. It occurs almost entirely as a sub-canopy in the Agulhas to Columbine area, and seldom reaches the surface, often forming extensive beds in deeper water. However, north of Cape Columbine, *L. pallida* develops a hollow stipe, and gradually replaces *E. maxima* as the dominant inshore kelp. Therefore, south of Cape Columbine, most of the harvestable kelp resource comprises *E. maxima*, while in the Northern Cape, the bulk of the resource comprises *L. pallida*. *Ecklonia* is presently preferred by abalone farmers as it is reported to have a lower food conversion ratio (FCR) compared to *Laminaria*. This has been reported by farmers but needs experimental confirmation.

The primary production of kelps in the inshore ecosystem has been studied in some detail in South Africa. Most of the organic material produced by kelp is ingested as particulate matter by filter feeders (Newell et al., 1982). Furthermore, a significant part of the energy fixed by kelp enters the ecosystem as dissolved organic matter, via bacterial pathways (Newell et al., 1988). However, kelps are more than just primary producers, and also provide various ecosystem services (e.g. shelter, shade, and a substratum for attachment, etc.) and interact with the hundreds of other species in the kelp bed in complex ways that are far from understood (Bolton and Anderson, 1997). Therefore, while the recovery of the kelps from harvesting may be easily measured, more subtle ecosystem effects of long-term or excessive harvesting are difficult to measure. Thus there is a need for conservative management. The effects of commercial harvesting of *E. maxima* have been investigated since the late 1970s (Mann et al., 1979; Anderson et al., 1989; Levitt et al., 2002), and kelp biomass has been shown to recover within 2.5 to 3 years of harvesting of the whole sporophyte plant. Harvesting of *E. maxima* did not cause measurable changes in understorey communities over a 3-year period (Levitt et al., 2002), or affect recruitment of juvenile plants over about 1.5 years (Rothman et al., in press). However, populations of three obligate red algal epiphytes that grow on *E. maxima* took at least 2 years longer to recover than the kelp host itself (Anderson et al., in press).

4.2. The seaweed industry

Seaweed harvesting in South Africa started during the Second World War and focused initially only on red seaweeds (i.e. *Gracilaria* and *Gelidium*), which were exported as dry seaweed for agar extraction (Anderson et al., 1989). Collection of beach-cast kelp (*E. maxima* and *L. pallida*) started at the beginning of the 1950s, with most of the material exported for alginate extraction (Anderson et al., 1989). The demand for kelp from South Africa has fluctuated widely. Although an average of about 1000–1500 mt dry biomass has been collected annually, in 1972–1977 collections reached record amounts of more than 4000 mt per year (Anderson et al., 1989, 2003). There have also been periodic slumps, usually lasting 2–3 years, when international market prices and yields fell. In 2003, just over 1000 mt of this dried, beach-cast kelp was exported. Harvesting of *Ecklonia*, with plants cut just above the holdfast by divers, began in the late 1970s, for the production of a commercial plant-growth stimulant (Kelpak), and this operation continues. The first abalone farms were built in the early 1990s and since then the demand for fresh kelp fronds for feed has increased to a total of nearly 6000 mt wet-weight in 2003 (Table 1 and Fig. 2).

Seaweed resources in South Africa are included under the Marine Living Resources Act, 1998, and are managed on an area basis, with 23 Concession Areas between the Namibian border and the eastern border of the Eastern Cape Province (Fig. 1A) (Anderson et al., 2003). In each area, a single company is granted the right to harvest or collect (beach cast) a particular seaweed species or group of species (e.g. “kelp” including *E. maxima* and *L. pallida*; “*Gelidium*” including all commercially useful species of this genus, and *Gracilaria*). The yield reported from the different concession-holders during 1986–2003 is shown in Table 2, which clearly shows a reduction in beach cast collections since about 1999, and increased production of harvested kelp for abalone feed and Kelpak. In some Concession Areas (e.g. 5, 8, and 11) almost no beach-cast is now collected for export. This is because some operators no longer consider it worthwhile, as collecting and harvesting fresh kelp fronds for sale to local abalone farms earn larger and more immediate returns. Thus, at least three of the Concession Areas, that produced substantial amounts of dried kelp before the advent of abalone farms, now produce none.

Table 1
Kelp resources along the South African west coast

Concession area	Kelp MSY (f wt)	Kelp harvest (f wt)	Kelp harvest as % of MSY	Beach-cast for abalone (f wt)	Total abalone feed (f wt)	Beach-cast dry (d wt)
5	1165	696	60	354	1050	0
6	2680	897	33	878	1775	362
7	644	348	54	523	871	192
8	956	951	99	0	951	0
9[a]	1030	0	0	0	0	0
10	0	0	0	0	0	0
11	1550	1158	75	112	1270	9
12	15	0	0	0	0	29
13	32	0	0	0	0	126
14	478	0	0	0	0	177
15	784	0	0	0	0	129
16	564	0	0	0	0	77
18[b]	137	0	0	0	0	0
19[b]	364	0	0	0	0	0
Total	10 399	4050		1867	5917	1101

Columns show for each Concession area for 2003: kelp maximum sustainable yields (MSY), kelp harvests, harvests as % of MSY, beach-cast amounts of fronds in fresh wet weight (f wt) supplied as abalone feed, the total f wt of fronds supplied as abalone feed, and dry beach cast material (d wt) (mostly exported for alginate extraction). All weights in mt.

Data from Marine and Coastal Management, Cape Town. Data in mt.

[a] Area 9 kelp harvest is used for production of Kelpak, not for abalone feed, and so harvest figure is excluded from Table 1.

[b] Diamond mining areas – no collecting or harvesting at present.

The principle of allocating a single right-holder per area aims to prevent competitive over-exploitation of these static resources. For kelp, an annual Maximum Sustainable Yield (MSY) is set for each concession area, based on estimates of kelp biomass. In effect the MSY is about 6–10% of the standing biomass (a value similar to the estimated annual natural mortality of the kelp: see Simons and Jarman, 1981). Furthermore, about 10% of each area is set aside as a "non-harvest zone" for the protection of old kelp plants and of kelp epiphytes, which occur mainly on old plants, and are an important food source for certain invertebrates and line-fish (Anderson et al., in press). Estimated MSY for the different Concession Areas, together with amounts of beach cast and harvests shown in Table 1.

The potential supply of fresh kelp fronds for abalone feed is complicated by two main factors: a) the distribution of the kelp resources and b) the distribution of kelp species.

4.3. Distribution of kelp and abalone farms

Abalone farms are concentrated in two main areas, placing localised pressure on the kelp in those areas (Fig. 1B). There are 12 farms just north west of Cape Agulhas and potential annual MSY of kelp along this stretch of coast (Concession Areas 5–8) is 5445 mt fresh weight, and in 2003, 53% of this was harvested (Table 1). More importantly, 99% of the MSY was harvested in Concession Area 8 (Table 1). The second aggregation of farms is in the Cape Columbine area (effectively supplied only by Concession Area 11) where there are three farms at present, and one under construction (Fig. 1B). Here an MSY of 1550 mt is available and, in 2003, 75% of this was harvested, leaving little room for expansion of the industry. Between these two farm nodes (in Area 9), there are 1030 mt (2003 estimates) of *Ecklonia* fronds available on the Cape Peninsula, but only part of this quota is used by the right-holder, for the production of Kelpak. However, no abalone farms operate in the area, probably because of the extremely high land prices and potential conflict with the extensive

Table 2
Commercial yields of seaweed from natural populations on the coast of South Africa, 1986–2003, as reported by concession-holders

Year	*Gelidium*	*Gracilaria* (beach-cast)	Kelp for Kelpak[a]	Kelp (beach cast)[b]	Kelp (abalone feed)
	d wt	d wt	w wt	d wt	w wt
1986	121	155	141	2465	0
1987	144	170	113	2211	0
1988	162	362	150	2258	0
1989	182	28	202	1253	0
1990	169	0	167	2112	0
1991	196	0	224	2004	0
1992	152	191	268	1220	1
1993	157	378	268	454	7
1994	143	272	365	433	10
1995	139	439	316	560	23
1996	139	190	495	1523	26
1997	129	266	426	1704	40
1998	142	270	322	1742	391
1999	148	270	273	1443	1502
2000	125	264	609	759	2784
2001	145	248	641	845	5924
2002	138	65	701	746	5334
2003	114	92	957	1101	5917

The column kelp (abalone feed) comprises only frond material, but includes both harvested amounts and amounts of fresh fronds collected from beach-casts.

These amounts were separated for the first time in 2003: 1101 mt of the total of 5917 mt was reported to come from fresh beach-casts.

All *Gelidium* and *Gracilaria* values are reported by the industry as dry wt: an approximate dry wt percentage of 20% is assumed for commercial purposes. All weights in mt. (w wt=wet weight; d wt=dry weight).

[a] Kelpak is a plant growth stimulant.

[b] Preliminary data for beach cast in 2004 amounts to 936 mt and the first three quarters in 2005 to 192 mt.

Table Mountain National Park area. Further, long-distance transportation of fresh kelp material from Area 9 to existing farms is not feasible under existing economic conditions.

North of Cape Columbine, there are seven Concession Areas (12–16, 18 and 19) with a combined MSY of 2374 mt of kelp (mostly *Laminaria*) fronds, but spread over more than 450 km of the undeveloped coast (Fig. 1B). Furthermore, two of these Concession Areas are effectively unworkable because they lie within high-security, diamond-mining zones. Transportation costs prevent any supply of fresh kelp from this coast to the existing main nodes of abalone farm development. However, small amounts of dried fronds from some of the areas have been supplied to the farms in the Eastern Cape where there are no natural kelp populations.

Inshore kelp beds are north of Cape Columbine increasingly dominated by *Laminaria* rather than *Ecklonia.* Kelp is present in seaweed Concession Areas 5 to 19 (see Table 1) excluding Area 17 (an enclosed bay system where only the red seaweed *Gracilaria* occurs in economic quantities). Beach-cast kelp is collected from eight of these areas and kelp is harvested in substantial quantities, for abalone feed, only from six of them (Areas 5–8 and 11) (Table 1). Within these areas eight companies have permits giving them the right to collect unlimited quantities of beach-cast. However, beach-casts are seasonal and sporadic, because they appear mainly after storms. For actual harvesting (cutting) of kelp there is a limitation to how much they can take out, depending on MSY, and each year an operator can remove 5–10% of the standing stock depending on the harvesting technique (see below).

4.4. Harvest techniques

Harvesting of kelp for abalone feed essentially involves cutting the fronds during low tide. Traditionally, almost all of the harvesting is done from boats, by workers who lean overboard and remove the fronds and primary blade by cutting through the base of the primary blade. The whole “head” of kelp is then pulled aboard, leaving the stipe and holdfast to die. Recovery of the kelp biomass then requires the growth of new sporophytes. Ashore, the fronds are then cut off and the primary blade discarded.

A non-lethal harvesting method is being tested commercially in one concession area. This method is based on the experiments of Levitt et al. (2002), who showed that by excising only the distal parts of the secondary blades, and leaving at least 20–30 cm of their bases (with the basal meristems intact) attached to the primary blade, the fronds could be repeatedly re-harvested. The primary blade and stipe are left undamaged, and the yield of frond material over time was reported to be about five times higher than if the sporophytes were killed (Levitt et al., 2002). Although this allows a higher yield, there is evidence that frond re-growth rates decline as the sporophytes age, and it may prove necessary to carry out periodic lethal harvests to allow new plants to enter the population (Rothman et al., in press).

5. Abalone farm effluents

Over the last decade aquaculture has more than doubled its production and today 30% of total world fish and shellfish supply is produced through farming (FAO, 2004). This rapid growth has resulted in a growing awareness by scientists, industry, the public and politicians about environmental impacts of certain types of aquaculture (Naylor et al., 2000; Chopin et al., 2001). A future major challenge for the aquaculture industry is therefore to develop systems that minimise untreated effluents, habitat destruction, spreading of pathogens and non-indigenous species, and that have low dependencies on finite fishmeal resources. Although abalone farming represents an intensive flow-through system, it releases, compared to e.g. fish cage farming, only limited amounts of nutrient wastes (Robertson-Andersson, 2003; Samsukal, 2004; Njobeni, 2006). The main reason for this is feeding mainly kelp or feeds with low fishmeal content. Due to the high-energy coasts of South Africa, with massive mixing and naturally high levels of upwelled nutrients, nutrient effluents from farms most likely have insignificant effects on the coast. To date, there are no specific guidelines for effluent water from land-based mariculture operations in South Africa. However, the Department of Water Affairs and Forestry has produced water-quality guidelines for coastal marine waters that are intended for protection of the natural environment (DWAF, 1996). These guidelines can be applied to receiving waters around pipeline discharges, accepting that a zone of non-compliance, or mixing zone, in the immediate vicinity of the outfall(s) may need to be defined. Where sufficient data are available, these guidelines specify numerical values for various physico-chemical properties that have been derived from national and international effects-level tests. Of relevance to abalone farm effluents are the guidelines for maximum ammonium concentrations (43 μM as NH_3+NH_4) and other nutrients such as inorganic P for which there are no default values but which should not be present at “levels capable of causing excessive or nuisance growth of algae or other aquatic plants”. In addition, concentrations of suspended solids (including both organic and inorganic constituents) in the outflow water should not “exceed ambient levels by more than 10%”.

A preliminary study characterising effluents from seven west coast abalone farms (Samsukal, 2004) concluded that dissolved nutrients were in accordance with the recommended standards outlined in the Department of Water Affairs and Forestry water quality guidelines (DWAF, 1996) and within the calculated range or lower than Australian and New Zealand Environment Conservation Council (ANZECC) guidelines (ANZECC, 1999). The particulate loading (sizes less than 63 μm) was, however, found to be significant, as were the numbers of herbivorous crustaceans released from the farm during cleaning. The implications of this for the environment were, however, not studied. A preliminary study by Potgieter (2005) showed that approximately 100 kg of particulate waste per tonne of abalone is released annually from tank cleaning operations. This is a significant release but many times less than fish cage farming. Any effect from such release is probably of local nature.

The tube-dwelling polychaete worm *Terebrasabella heterounicinata* affects abalone growth negatively and it can occur in high densities at farms (Simon et al., 2004). It is not known if effluent from polychaete infested farms increase the infestation rate for wild abalone living in close proximity to the farm.

6. Abalone feed alternatives

The growing South African abalone industry depends on a steady supply of feed resources. The industry used approximately 5900 t of kelp (Table 1) and about 180–200 mt of Abfeed™ in 2004 (extrapolated from Questionnaires). As for most other cultured species, it has been shown that different abalone diets produce significantly different growth rates (Leighton, 1974; Britz, 1996; Guzmán and Viana, 1998; Shpigel et al., 1999; Boarder and Shpigel, 2001; Bautista-Teruel et al., 2003; Naidoo et al., in press). Abalones are generalist, opportunistic herbivores that readily accept a wide range of diets. In the wild they prefer specific seaweeds, and a number of abalone species have been reported to favour red algae (Barkai and Griffiths, 1986; Tutshulte and Connell, 1988; Shepherd and Steinberg, 1992; Stepto and Cook, 1993; Fleming, 1995). Today, many farms are investing in research to find suitable combinations (ratios) of feeds and new feed formulations, and the following are some of the local feed alternatives: kelp (*E. maxima* and sometimes *L. pallida*), red seaweeds (e.g. *Gracilaria* spp., *Gracilariopsis* spp., *Gelidium* spp., *Plocamium corallorhiza*), green seaweeds (e.g. *Ulva* spp.) and formulated feeds such as Abfeed™ (fishmeal as the primary protein source) and Midae Meal™ (a seaweed-based formulated feed). For logistic reasons, no kelp, either fresh or dry, is imported. However, many brands of international formulated feed are being tested locally.

6.1. Seaweed-based pellets

The only commercially available all-seaweed feed in South Africa is a formulated dried feed called “Midae Meal MM-1c” (Eric-Piet (Pty) Ltd, Luderitzbucht, Namibia) being manufactured for Taurus Products (Pty) Ltd. The ingredients are mainly *Laminaria* spp. and *E. maxima* (stipes and fronds) but they also contain *Graciliaria* spp., *Gelidium* spp. (including the epiphyte *Gelidium vittatum*, formerly known as *Suhria vittata*), *Porphyra capensis* and “agar-agar”. The wet seaweed to dry pellet ratio is between 6–7:1 and protein content is around 18% (Taurus Products (Pty) Ltd, personal communication).

6.2. Kelp

Although abalone prefer fresh kelp, dried kelp pellets are also being tested as a feed source by the abalone industry. Only two companies presently supply dried kelp (Taurus Products (Pty) Ltd, Rivonia and Kelp Products (Pty) Ltd, Simon’s Town).

6.3. Abfeed™

Abfeed™ (Marifeed Pty Ltd, South Africa) is a formulated feed containing mainly fishmeal, soya bean meal, starch, vitamins and minerals. It previously contained *Spirulina* sp. (*Arthrospira* sp.) but not anymore due to supply problems. Abfeed™ contain about 35% protein, 43% carbohydrates, 5% fat, 1% crude fibre, 6% ash and ~10% moisture (Marifeed Pty Ltd, personal communication). A cheaper, low protein (26%) form of Abfeed™ (K26) formulated for large abalone (>50 mm shell length) is currently also in production. At present Abfeed™ is only sold locally, although the product is being tested abroad (e.g. Australia, Chile, Taiwan and New Zealand) against other formulated feeds (Marifeed Pty Ltd, personal communication).

6.4. Other seaweed species

Other seaweed species besides *Ecklonia* that are currently being used as feed include *Gracilaria*, *Gelidium*, *Ulva* and *Porphyra*. They are used in very low quantities and are generally only fed to the brood stock. This is because either they occur in very low quantities naturally or their supply (including production from open water and on-farm cultivation) is erratic. However, on-going research into their use for smaller abalone size classes is being tested at a number of farms. Data on the biomass of various species can be found as follows: *Porphyra* (Griffin et al., 1999), *Gelidium* (Anderson et al., 2003; Tronchin et al., 2003), *Gracilaria* (Anderson et al., 1989; 2003).

6.5. Growth performance and diet choice

Research on the effectiveness of different diets has mainly dealt with single seaweed species fed in culture (mainly kelp), and more recently also the effectiveness of formulated feeds (animal-based and seaweed-based) (Simpson and Cook, 1998). However, the fact that wild abalone generally feed on a broad selection of algae, normally with at least two species being found in the gut content at any one time (Barkai and Griffiths, 1986, 1987), could imply that abalone preferentially choose a mixture of algae. The literature on “choice” should, however, be approached with caution. Abalones are sedentary and in the wild they wait for a piece of drift alga to come along which they them clamp down on and consume. So gut contents probably reflect the composition of available drift algae rather than an active selection. The situation is, however, probably different under farm conditions where the abalone more actively choose their feed when provided a choice. Naidoo et al. (in press) tested the effects on growth of various diets, including mixed diets consisting of kelp with combinations of both the green seaweed *Ulva* sp. and the red seaweed *Gracilaria* sp. These diets were also compared with animal-based Abfeed™. It was shown that dried kelp in any form (blades, stipes, and pellets) produced poor growth compared to various fresh seaweed treatments, including fresh kelp. Furthermore, Naidoo et al. (in press) showed that fresh kelp fortified with protein-enriched (farm grown) *Gracilaria* or *Ulva* performs best; even better than Abfeed™. These growth trials support other studies (Owen et al., 1984; Day and Fleming, 1992; Fleming, 1995; Simpson and Cook, 1998) that have shown that “mixed” diets produce better growth rates than single-species diets.

Kelp is low in protein (ca. 15%) and has an unbalanced amino acid profile. Abalone growth on dry kelp is therefore predictably quite poor. However, feeding abalone fresh kelp results in significantly better growth compared to using dry kelp. Possible reasons for this may include the contribution of bacteria associated with fresh kelp to digestibility and assimilation of nutrients, and/or that the drying process renders the protein and other nutrients much less available to the abalone (P. Britz, Rhodes University, South Africa, personal communication).

The use of kelp or other seaweeds versus artificial feed on an abalone farm is related to a number of possibly conflicting aspects such as price of feed, availability and accessibility of fresh seaweed, food conversion ratio (FCR), cost of handling and storage and final quality of abalone and culture environment. Kelp (ca. ZAR 900 per mt, based on prices for June 2005) is cheaper than Abfeed™ (ca. R1400 per mt), but has a higher FCR (between 1:12 and 1:17) compared to Abfeed™ (around 1:5–1:9) (Hahn, 1989; Britz, 1996). Based on these figures, feed would cost ZAR 10 800-ZAR 15 300 to produce a tonne of abalone fed on kelp, and ZAR 7000 to ZAR 12 600 to produce a tonne of abalone fed on Abfeed™ (July 2005, 6.5 ZAR was equivalent to 1 USD). These figures are surprisingly similar, and because feeding with artificial feed is simpler it would seem that there must be benefits to be gained by feeding with kelp, as most farms use kelp when it is available. In general, abalone grow faster on Abfeed, at least until they reach 50 mm shell length, and most farms use it in the early stages of growth. After 50 mm farmers tend to prefer kelp or a combination of Abfeed and kelp for two reasons: 1) Abfeed promotes a higher incidence of sabellid infection as they feed on the more nutrient-rich faeces produced; and 2) shell growth rates tend to be higher on kelp. New Abfeed formulations based on dried kelp are being tested (Abfeed K26) and preliminary tests show equivalent or better growth compared to fresh kelp in the >50 mm size classes (P. Britz, personal communication). As kelp is relatively low in protein, abalones tend to display good shell growth but relatively low gain in meat weight. With Abfeed, meat weight gain is high but shell length gain tends to lag. Kelp is 25% ash on a dry-weight basis, and is probably a rich source of minerals for the shell. The low protein K26 Abfeed formulation was developed in response to the sabellid problem and to improve growth rates (P. Britz, personal communication). Now the “old” high protein Abfeed is used for the early juveniles and the low protein pellet will probably be used for the >50 mm size classes.

7. Integrated seaweed-abalone farming

Integrated cultivation has been suggested to increase production and sustainability of aquaculture (Folke and Kautsky, 1992; Newkirk, 1996; Brzeski and Newkirk, 1997; Naylor et al., 2000; Lüning and Pang, 2003; Troell et al., 2003). Integration involves co-cultivations of different organisms where the wastes from one are utilised by the other. This has the potential to reduce the dependence on external ecosystems for food and energy, build up of waste products and negative environmental impacts from waste release. Seaweeds have been found suitable for biofiltration as they have a high capacity for nutrient uptake and are themselves valuable products (e.g. Neori, 1996; Chopin et al., 2001; Troell et al., 2003; Neori et al., 2004). Some *Ulva* spp., for example, are able to remove up to 90% of dissolved nitrogen from aquaculture effluent (Neori et al., 1998) increasing their protein content as much as 10-fold (Shpigel et al., 1999; Boarder and Shpigel, 2001; Robertson-Andersson, 2003). Farm-grown (on-farm), protein-enriched *Ulva* has subsequently been shown to improve abalone growth, in for example *Haliotis tuberculata* (Neori et al., 1998; Shpigel et al., 1999), *Haliotis discus hannai* (Shpigel et al., 1999), *Haliotis roei* (Boarder and Shpigel, 2001), and more recently *H. midae* (Naidoo et al., in press).

7.1. Seaweed integration with abalone aquaculture in South Africa

In South Africa presently only two abalone farms depend on their on-farm seaweed cultivation for abalone feed. Both are situated in the Eastern Cape where there is no access to fresh kelp supply. Their seaweeds are successfully grown in the wastewater from the abalone tanks. Some other abalone farms carry out experimental seaweed farming, building on the knowledge gained since the research on integrated seaweed-abalone (initially *Gracilaria gracilis* and later species of *Ulva*) culture started in 1993 by the University of Port Elizabeth. Since then numerous studies show upon that seaweeds grow better in abalone effluents compared to natural seawater (Fourie, 1994; Friedlander and Levy, 1995; Smit, 1997; Hampson, 1998; Steyn, 2000; Robertson-Andersson, 2003; Njobeni, 2006). Seaweeds being used for on-farm cultivation come mainly from populations in sheltered waters (bays or harbours) where they grow naturally unattached. Furthermore, these species grow vegetatively and do not become reproductive in the system, making control of seaweed life history unnecessary. Both nitrogen and phosphorous content of the seaweeds cultured in abalone effluents increase compared to same species growing in their natural habitat (Fourie, 1994; Friedlander and Levy, 1995; Smit, 1997; Hampson, 1998; Steyn, 2000; Robertson-Andersson, 2003; Njobeni, 2006). Although seaweed growth rates in tanks vary seasonally and usually decrease with an increase in tank size (Table 3), D-ended raceways (40×8 m^2) (Friedlander and Levy, 1995) receiving abalone wastewater are used successfully in the Eastern Cape (by Wild Coast Abalone and Marine Growers). One of the Eastern Cape farms did meet 60% of their feed requirement (35 mt abalone farm) from cultured seaweed (*Gracillaria* and *Ulva*) with the balance made up of formulated feed and a supplement of dry kelp (P. Britz, personal communication).

South Africa has three species of ‘stringy’ gracilarioids which could be useful for aquaculture (Iyer et al., 2004, 2005). It appears that most material used thus far has been *G. gracilis* collected from Saldanha Bay on the west coast, although *Gracilariopsis longissima* is the main species in the neighbouring St. Helena Bay. These two species have been shown to grow in an almost identical fashion in floating aquaculture on rope rafts (Wakibia et al., 2001), and have only been seen to be fertile on very few occasions (Iyer et al., 2005). *Gracilariopsis funicularis* (Wakibia et al., 2001) is rare in South Africa, but common in northern Namibia. It may be useful for aquaculture in the future, particularly as it generally has abundant reproductive structures in Namibia, which may give more scope for the selection of strains useful for culture.

Table 3
Seasonal growth rates for two different seaweed species: *Ulva* sp. and *Gracilaria* sp., cultured in different sized tanks (growth in % day^{-1})

Tank size (L)	*Ulva*		*Gracilaria*		References
	Summer	Winter	Summer	Winter	
95	4.4	3.8–4.9	3.1–5.5	4.7–7.5	Steyn, 2000; Hampson, 1998
100	8–12.1	4.2–4.8	3.0–3.5	2.7–2.8	Robertson-Andersson, 2003; Njobeni, 2006
400	6.5–11.2	1.9–5.0	3.0–3.2	2.6–2.8	Robertson-Andersson, 2003; Njobeni, 2006
3150	4.5–8.1	2.3–4.1	4.5–6.8	1.5–2.1	Robertson-Andersson, 2003; Njobeni, 2006
1 800 000	0.2		0.2		Robertson-Andersson unpublished

Most of the *Ulva* grown in experimental and economic aquaculture systems on South African abalone farms appears to be *Ulva lactuca*, a globally widespread species which probably contains many genetic entities (Kandjengo, 2002; Hayden et al., 2003). *Ulva rigida* has also been cultured in South African, and can replace *U. lactuca* in tank culture in reduced light conditions (Robertson-Andersson, 2003).

There are multiple benefits from co-culture of seaweeds and abalone. The use of the same water for the seaweeds and the abalone cultures can, if the seaweed units are gravity-fed from the abalone tanks, maximise returns from the single large expense of pumping water from the sea. Biofiltration by seaweeds reduces nutrients, but fertilisers may be added which besides stimulating growth also improve feed quality by reducing infestations of *Ulva* by the epiphytic brown alga *Myrionema strangulans*. Thus, the overall result may be an increase of nutrient outflow from the farm instead of a net removal (Robertson-Andersson, 2003).

If water is re-circulated, seaweeds in the system can reduce build-up of toxic by-products from the abalone (NH_3 and NO_2). Recirculation has the added benefit of increasing water temperature in cold water environments, such as off the west coast of South Africa, thereby improving abalone growth. There is always a risk of build-up of both dissolved and particulate matter in a re-circulation system, and possibly also bacteria, parasites and herbivores. However, preliminary studies suggest that the build-up of dissolved nutrients and the degree of abalone parasitic infection is no different between 25% recirculation and flow-through conditions (Robertson-Andersson, unpublished data). Performance during higher re-circulation rates still needs to be evaluated.

An additional advantage of re-circulation may be to avoid pumping seawater containing high densities of toxic algae into the farm. Blooms of toxic algae occur frequently on the west coast of South Africa (Pitcher, 1998), and even if such blooms only occasionally affect abalone farms (Pitcher et al., 2002), the risk of great losses exists. The algal toxin adheres to the epithelial lining on the abalone making it unsuitable to for sale in live form. The option left is evisceration, cleaning and canning the infected abalone, leading to loss in revenue compared to live sales.

A further important benefit from on-farm seaweed cultivation could be reduced harvesting from kelp beds. This would, however, require a large production of on-farmed produced seaweeds.

8. Socio-economic effects of the abalone industry

In the post-apartheid South African society, social equity and transformation are critical current goals of fisheries management (van Sitterta et al., 2006; van Sitterta and Hauckc, 2006). In order to follow the process of transformation, the South African government, and other South African institutions, collect information, including in official censuses, using the categories utilized by previous governments. Thus 'black' denotes 'black Africans', whereas 'coloured' denotes "a diverse group of people descended largely from slaves, indigenous Khoisan peoples and other black people who had been assimilated to colonial society by the late nineteenth century" (van Sitterta et al., 2006), as well as others of 'mixed race'. We consider it important, bearing in mind the potential benefits of this transformation process, to briefly present the social position of the abalone industry and its workforce using these categories.

Unemployment in South Africa is high and is considered to be one of the most critical socio-political challenges for the South African government (Kingdon and Knight, 2003). The abalone industry in South Africa generates direct permanent employment and particularly benefits poor coastal communities. Coastal resources that may be utilised by the poor are limited, leaving few alternatives for their livelihoods. The abalone industry not only includes direct employment at the farm level, it also indirectly supports interlinked businesses such as the seaweed and abalone processing industries. Furthermore, contract workers from local firms are needed during initial and expansion phases.

Cultivating abalone is labour intensive. An average South African farm employs 60 people and the total industry employed about 1390 people in 2004 (based on Questionnaires, AFASA, Terry Bennett, personal communication). The number of employees per tonne of abalone produced ranges between 0.46 and 1.62, with larger farms having fewer employees per output. As maximum production capacity is not reached within the first 5 years of abalone growth, farms will have fewer employees per tonne once full production capacity is reached. Although wages constitute the largest expenditure for a farm, the abundance of cheap labour in South Africa is of obvious benefit to the farmer (Gerber, 2004). The average wage for a typical unskilled farm worker is around US$ 270 per month. The high fixed capital investment needed for abalone farming, ranging between ZAR 1.6 million and ZAR 30 million for 15 and 120 mt farms, respectively, prevents many prospective entrepreneurs from starting a farm. However, as

Table 4
Comparison of skill levels and employment form in different development phases within the South African abalone industry

	Development phase	
	Build up	Mature
Unskilled	50	73
Semi-skilled[a]	40	17
Skilled[b]	10	10
Part time	25	
Full time	75	100

Data in % and based on information from eight abalone farms.

[a] Semi-skilled = read, write.

[b] Skilled = some form of tertiary education.

most of the jobs offered at a farm do not require educational or apprenticeship credentials they can be taken up by people from poorer communities. In terms of full- versus part-time employment, and unskilled versus skilled jobs, farms in the start-up phase require more part-time and more skilled workers than when established (Table 4). Unskilled employees are mainly maintenance workers and those involved in harvesting, processing and security. Personnel working with engineering, administration and finances, research and management are usually semi-skilled or skilled. The majority of the workforce for the farms resides within 0–30 km of their place of work. Black and coloured unskilled and semi-skilled labour dominates (Table 5), and the majority have no tertiary education. There is a difference in the distribution of gender during the development of the industry, with new, non-producing (i.e. not yet exporting) farms having almost 100% male workers while established farms have about 78% males. The reason for this inequality is the heavy manual labour required in raceway maintenance. Grading and sorting occur on established farms, which allows more females to move into the industry. With hatcheries becoming more common on farms, this also increases employment opportunity for female workers.

The seaweed industry was an important source of employment for poorer coastal communities long before the abalone farming industry developed. Production peaked during the 1970s, but since then it has been rather erratic due to fluctuations in the global seaweed market. The introduction of kelp as abalone feed has created a new market and undoubtedly stimulated the local seaweed industry by increasing profitability for companies located near abalone farms. Calculated on a dry weight basis, the price obtained for fresh kelp as abalone feed is more than double that for dry kelp that is exported for alginate production. However, a proper comparison must take into account capital and operational costs, and is subject to price fluctuations in the international kelp market. At present, the seaweed industry in South Africa employs around 400 people of which most are unskilled labourers. In addition to this, because beach-cast kelp occurs periodically extra pickers are hired after major beach cast events, but their numbers are difficult to estimate. Unlike in the abalone industry, most workers are females, but the employment levels above labourer are usually male dominated. Black and coloured workers make up almost the entire labour force, but higher echelons involving more responsibilities are usually white-dominated. There have been attempts since the change of the political system in 1994 to carry out social transformation, involving changing racial profiles, particularly in ownership, in many industries, including the seaweed industry (Share et al., 1996; Sauer et al., 2003).

The potential for increasing employment in the present seaweed industry is limited by several factors. All sectors involving export of dried seaweed for processing are limited by available resources (i.e. total beach-casts of kelp), international prices (and the strength of the South African currency), and often, localised issues of access to sections of the resources. Sectors that can process relatively small amounts of raw material locally into high-value products (e.g. Kelpak and other kelp-based plant growth stimulants) are probably limited mainly by marketing considerations. Potential for expansion of the abalone-feed (fresh kelp) sector is at present limited by proximity to abalone farms and by MSY. The growth of the abalone farming industry has also created some employment in the production of artificial feeds in South Africa, although the bulk of the production of artificial feeds takes place abroad. There is also a link between the abalone processing industry and the farming industry. Increased abalone poaching has resulted in decreased quotas for wild fisheries and this has made the link even stronger. Thus the processing factories will become increasingly dependent on the supply of farmed abalone. Furthermore, it is reasonable to assume that the building and maintenance of abalone farms has stimulated construction and allied industries in certain areas. This is

Table 5
Distribution of races and skills within the South African abalone farming industry

	Employed	Skilled	Unskilled
Races			
Black	45	13	87
Coloured	38	29	71
White	17	99	1

Data in % and based on information from seven abalone farms.

however, difficult to estimate. At present many abalone farms also provide training and training incentives for employees, including basic life skills education.

9. Future research

The development of abalone farming has stimulated research into abalone digestive physiology, the application of animal feed science principles to abalone, abalone feeding behaviour, on-farm seaweed production, performance of different seaweed as feed, and the optimal use of both natural and formulated diets under intensive culture conditions (Britz et al., 1994; Sales and Britz, 2001; Robertson-Andersson, 2003; Njobeni, 2006). New developments include investigations into gut bacteria in *H. midae* capable of hydrolysing a variety of complex polysaccharides in algae. Endogenous polysaccharases of abalone fed either *E. maxima* or *Gracilaria verrucosa* have been found to vary in response to diet (Erasmus, 1996; Erasmus et al., 1997). A probiotic research programme to use bacteria to enhance feed digestion in abalone is underway at the University of Cape Town, South Africa (Vernon Coyne, personal communication). Bacterial isolates included in diets containing *E. maxima* and *G. gracilis* extracts have been shown to improve growth in abalone (ten Doeschate et al., 2000). The "probiotic" can be added to artificial feed, improving its nutritional value for abalone (Macey and Coyne, 2005).

The abalone farms situated on the east coast have noticed a problem when canning their abalone, with the abalone having an "off taste" and "petroleum" or "seaweed- or kelp-like" smell in animals that are fed an exclusive *Ulva* spp. diet. This seems to be caused by dimethylsulfide, a volatile breakdown product of dimethysulphoniopropionate (DMSP). A potential remedy for this is presently being investigated and would involve feeding the abalone a low DMSP diet prior to harvest (Robertson-Andersson et al., 2005). Further research on this is needed as it may become important for utilization of such seaweeds as feed and also for on-farm seaweed production. New systems designed for on-farm production of seaweeds (including re-circulation systems with seaweeds) need to be further studied, especially with respect to their production capacity and overall economic performance.

10. Conclusions

Abalone aquaculture continues to expand in South Africa and with it the demand for high quality and effective feeds. Kelp is today the dominant feed input but current MSY estimates of kelp beds only allow for the annual harvesting of between 6% and 10% of the standing stock, a limit that has been approached for some Concession Areas. It is unlikely that greater kelp harvests will be allowed in the foreseeable future and therefore alternative feeds need to be developed. Artificial feed is available (Abfeed™) and is being increasingly used either alone or in combination with kelp. Abfeed™ generates a lower FCR compared to kelp but has the potential to affect culture water quality negatively. Kelp is therefore increasingly being added to formulated diets as a feeding stimulant and to reduce problems with sabellid growth. Greater use of seaweeds in dry form would make harvest of kelp from areas further away from the abalone farms more cost-effective. Thus the overall pressure on coastal kelp beds would increase. On-farm production of seaweeds constitutes a viable alternative for continuous supply of high quality feeds. This has the added benefits of improved water quality and abalone growth. It is clear that the abalone industry generates important direct and indirect employment, which is of particular relevance to the poorer coastal communities. As the industry expands in the future, it is important that the close inter-linkage between abalone farming and the seaweed industry is maintained for the benefit of both sectors.

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