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## Gradual changes of benthic biodiversity in Comau Fjord, Chilean Patagonia – lateral observations over a decade of taxonomic research

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Due to its huge extension and inaccessibility Chilean Patagonia for the longest time has been seen as a pristine region with never ending marine resources. But as a byproduct of the inaccessibility its ecosystems are still poorly known. During the last two decades, the aquaculture industry brought an unparalleled economic development to the area and the number of small-scale fishermen who go for pelagic and demersal fish and shellfish multiplied. Since 2003, we have been studying the benthic biodiversity of the Comau Fjord, Northern Patagonia. We have compared benthic photos that show large, long-living species down to 40 m depth on a key study site, which were taken in 2003 and again in 2013. Additionally we compared the decapod fauna which was inventoried in 2005/2006 and again in 2011. The analysis of photographs taken during the last ten years of taxonomic studies demonstrated an important decline in abundance in megabenthic species, throughout several taxa.

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### Introduction

The biodiversity of the Chilean Patagonian fjord region is still largely unknown. Since 2003, scientists at Huinay Scientific Field Station have been studying the ecosystems of the region and new species and even new communities are discovered on a regular base (see Häussermann & Försterra 2009). The Comau Fjord ecosystem is characterized by high primary production, high standing stock of benthic biomass, high turn-over rates, combined with high diversity, including abundant presence of scarce and endangered species. The fjord also has important colonies of marine mammals and birds (Häussermann et al. 2012). Situated only 200 km south of Puerto Montt, the capital of the Los Lagos

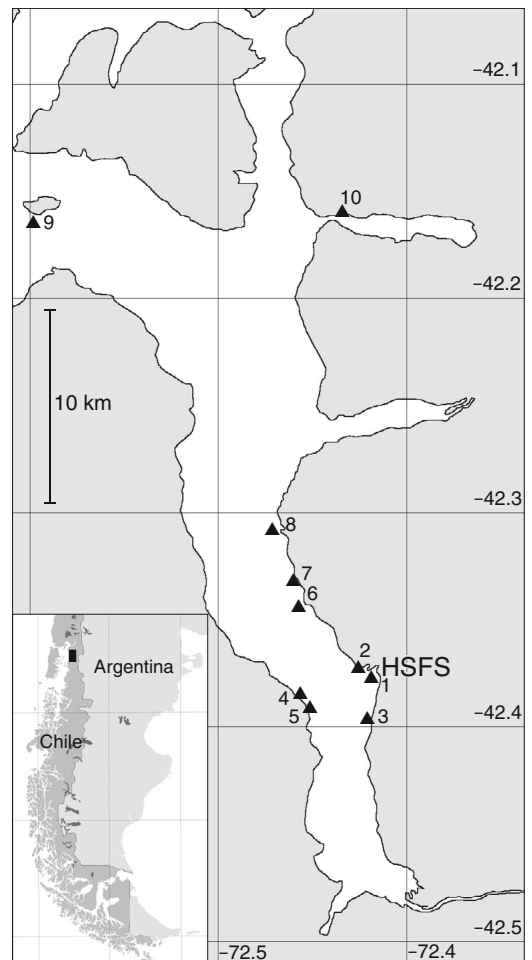
region, the Comau Fjord has less than 100 inhabitants of which the first settled in 1925. Locals mainly live of artisanal fisheries which have been concentrating on pelagic and demersal fish like hake (*Merluzzius australis* (Hutton, 1872)) and congrio (*Genypterus chilensis* (Guichenot, 1848)), and the mytilids *Aulacomya atra* (Molina, 1782) and *Mytilus chilensis* Hupé in Gay, 1854. Fin-fish are caught with long line systems while mytilids are harvested from the intertidal rocks during low tide and to a lower extent in the subtidal with HUKA-diving equipment.

Huinay Scientific Field Station started operating in 2003. At that time, three salmon farms and one mussel farm were situated in the fjord. Fishermen generally reached their monthly fishing quota of 600 kg hake per boat within two to three days (Luis

Hernandez, pers. comm. 2012). In 2012, 42 aquaculture concessions (33 salmon farms and 9 mussel farms) were registered for the fjord of which 23 salmon farms and 9 mussel farms hold installations. Despite rising fishing quotas and a twelve-fold higher number of registered fishermen in 2012 compared to 10 years before (HFFR-2012), fish landings have been constantly decreasing by nearly 60 % between 2004 and 2011. Mytilid landings decreased by more than 90 % (HFFR-2012) between 2007 and 2012. Since 2012 many fishermen abandoned fisheries on hake since the resulting catches did not justify the effort any more (Luis Hernandez, pers. comm. 2013). This situation is representative for Chilean fisheries; in September 2013 the Undersecretary of Fisheries declared that 70 % of the main commercial Chilean fisheries have collapsed (Radio del Mar 2013).

### Material and methods

Since 2003 we have regularly undertaken numerous dives at ten different locations in the Comau Fjord (Fig. 1) to establish species inventories for all benthic macro-invertebrates as a baseline (see Häussermann & Försterra 2009). VH and GF established four long-term study sites (see Fig. 1): at two sites several photo transects down to 30 m depth have been taken in 2003 and 2004 (sites nr. 2 and 7) and are being repeated for comparison in an ongoing study, and at two other sites (sites nr. 5 and 9) recruitment plates have been installed in 2009 which are photographed approx. every 3 months. Punta Llonco is located at the tip of a small peninsula at the eastern shore of the Comau Fjord, where tidal currents can get significant. Punta Llonco was declared as “no touch” site by the field station with strongly restricted diving activity and no extractive sampling, because of the presence of one of the largest banks of cold-water corals in shallow water in the Comau Fjord, an accumulation of several species of large deep-sea anemones, and extensive coral banks down to at least 120 m depth (observed during a ROV transect in February 2005 down to 188 m). This way community changes through scientific sampling as observed at other field stations could be excluded. In 2003 and 2004, we have been opportunistically photographing benthic habitats with large and long-living sessile mega-fauna at Punta Llonco down to 40 m depth (Fig. 2). In October 2007, we carried out two ROV transects at Punta Llonco (down to 200 m), one close to a salmon farm north of Punta Llonco (down to 68 m), and one 1.4 km north at SWALL (down to 180 m) (Fig. 1). To find out if the benthic macro-fauna has changed at Punta Llonco, we revisited the site in 2012 and 2013, taking photographs of the same spots and compared them to the photos taken in 2003/2004 (Fig. 2). Primnoid gorgonian densities were estimated by counting the gorgonian densities on four randomly selected estimated 1 m<sup>2</sup> areas within a sea whip field and taking the average density.



**Fig. 1.** Regularly visited study sites in the Comau Fjord system; with lateral fjords Quintupeu (north) and Chahuelmo (south). Legend: HSFS: Huinay Scientific Field Station. Long-term study sites with transects: nr. 2: Punta Huinay and nr. 7 SWALL; long-term study sites with recruitment plates: nr. 5: X-Huinay S and nr. 9: Lilihuapi Island; nr. 6: Punta Llonco.

RMel and RMey made detailed surveys on the occurrence and abundance of decapod crustaceans during stays in 2005 and 2006 for altogether 6 weeks with between one and three dives per day including numerous night dives, and again in 2011 during a stay for ten days with one to three dives per day (Fig. 3). Abundance and diversity comparisons were based on effort (dive hours)/species numbers and effort/individual numbers ratios.

## Results

### Benthic communities at Punta Llonco

The exponentially increasing marine aquaculture in the Comau Fjord leads to increased sedimentation and to nutrient enrichment, at least in the vicinity of farms (Hargrave 2010). Since 2006/2007 there are two salmon farming concessions approx. 100–200 m south and north of Punta Llonco, respectively, which were producing rainbow trout at irregular intervals during the last years. In mid 2013, only the concession north of Punta Llonco was active.

### Mytilid banks down to 15 m depth

The Comau Fjord had been known for its old and thick mytilid banks and its good larval recruitment of mytilids (Luis Hernandez, pers. comm. 2012). Basically all hard surfaces from the mid intertidal down to 15–20 m were covered by mussel banks. At all ten study sites which we had visited regularly between 2003 and 2004, we documented mytilid banks with close to 100 % coverage down to approx. 15–20 m depth with up to 20–30 cm mussel canopy, diverse age structure and plenty of associated fauna (Fig. 2A1). The mytilid bank at Punta Llonco was representative for the entire fjord at that time: down to more than 15 m depth the rocks were covered with multi-layered mytilid banks, up to 30 cm thick, dominated by *Mytilus chilensis* in the intertidal and *Aulacomya atra* in the subtidal. Mussels were densely covered by the gastropod *Crepidula* sp. and specimens of the sea anemone *Anthothoe chilensis* (Lesson, 1830) (Fig. 2A1). A diverse infauna composed of sea cucumbers (e.g. *Heterocucumis godeffroyi* (Semper, 1868)), polychaetes (e.g. *Hypsicomus phaeotaenia* (Schmarda, 1861) and *Perinereis gualpensis* Jeldes, 1963), sea anemones (e.g. *Paranthus niveus* (Lesson, 1830) and *Anthopleura hermaphroditica* (Carlgren, 1899)) and small gastropods (e.g. *Tonicia atrata* (Sowerby, 1840)) lived between the mussels.

In 2006 the mytilids in the rocky lower and mid-intertidal of Punta Llonco have been harvested exhaustively; this band is bare of mytilids since (Fig. 4A). In 2012 and 2013 we observed that mussel banks have largely disappeared in the subtidal rocks, where now specimens of the sea anemone *Anthothoe chilensis*, small sea urchins of different species (*Arbacia dufresnii* (Blainville, 1825), *Pseudechinus magellanicus* (Philippi, 1857)) and specimens of *Crepidula* sp. (Fig. 2A2, 2SA) dominate the benthos. During the same time we observed very patchy mussel banks with large gaps of bare rock, especially at the upper limit, homogenized age structure and significantly reduced associated fauna at all regularly visited dive sites (Fig. 2A2, 2SA).

### Anthozoans-dominated communities between 15 and 40 m depth

During a ROV transect in October 2007 next to the salmon farm north of Punta Llonco, besides white bacteria mats, accumulations of pellets, large amounts of general trash and dumped structures and cables (own observation), we have observed gorgonians covered by filaments of white bacteria (Fig. 4B). During a SCUBA dive in March 2008 at SWALL (1.4 km north of Punta Llonco; Fig. 1), Keith Hiscock observed dead gorgonians covered with fine organic sediment (K. Hiscock, pers. comm. 2008).

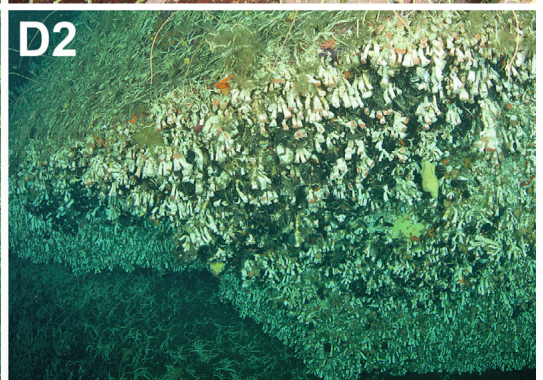
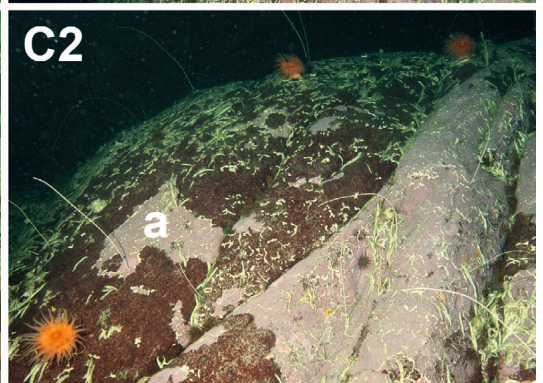
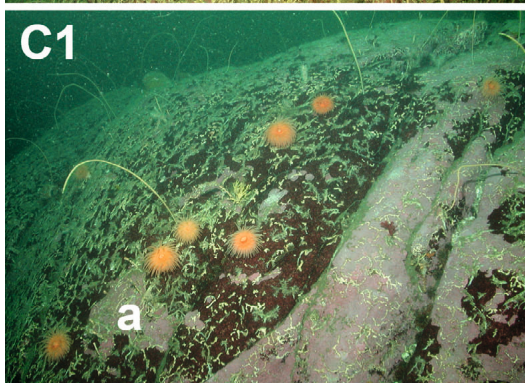
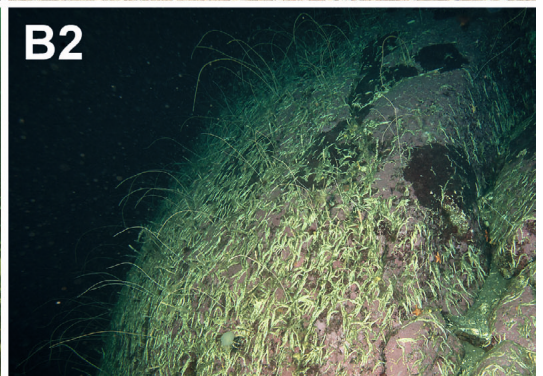
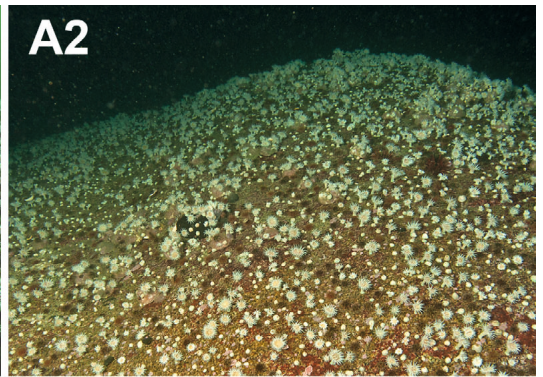
The comparison of photos taken at Punta Llonco in 2003/2004 and 2012/2013 revealed the following:

1. The density of gorgonians of the species *Primnoella chilensis* (Philippi, 1894) which were abundant on moderately steep to vertical rock below 20 m depth throughout the fjord was significantly reduced between 2003 (Fig. 2B1) and 2013 (Fig. 2B2). From the photos, we estimated a reduction in density by 70 % (27 gorgonians per m<sup>2</sup> in 2003 and 8 in 2013). The average length of the specimens also seems reduced, although we could not quantify this reliably from the photos.

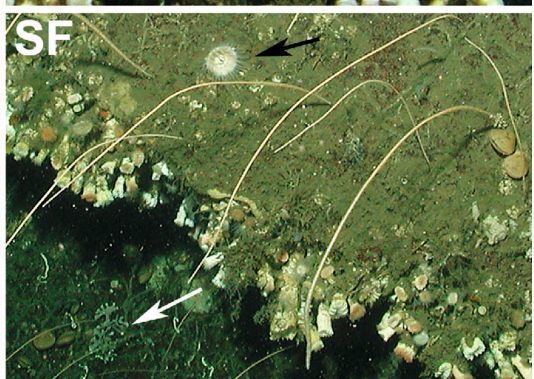
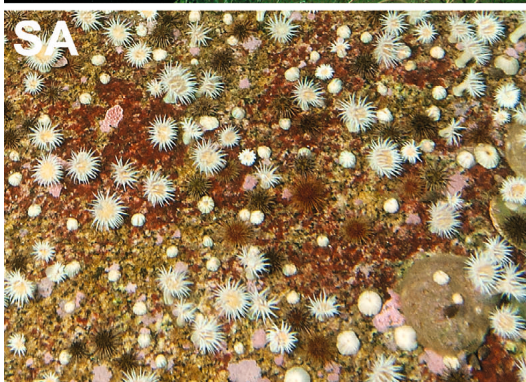
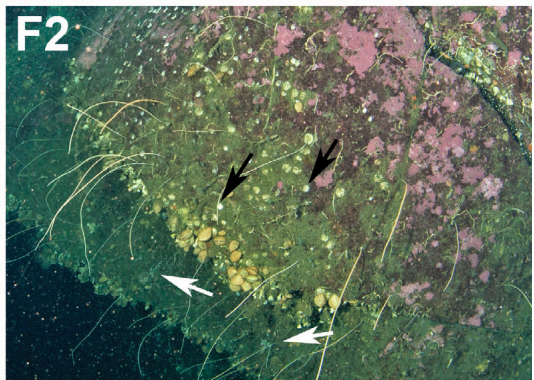
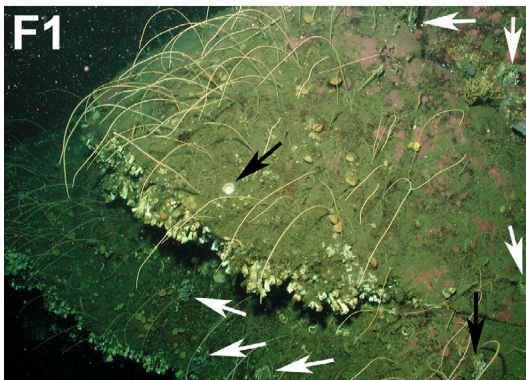
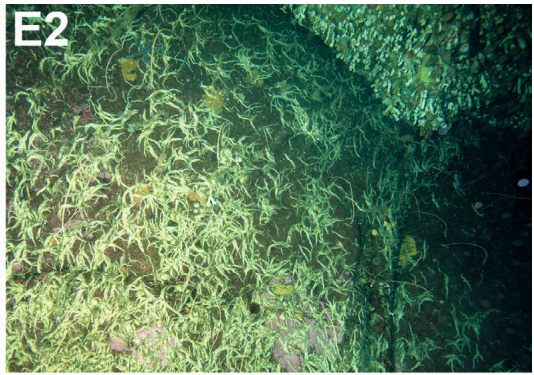
2. In February and March 2003 we documented eight large specimens of the deep-sea anemone *Actinostola chilensis* McMurrich, 1904 on a defined section of the wall north of the coral bank in 22–25 m (Fig. 2C1). This long-living species is found on exposed rocks below 20–25 m depth throughout Chilean Patagonia (Häussermann 2004 and Erratum 2005). In August 2003, we detected one additional specimen on the left margin of the section (large *Actinostola* specimens rarely change sites and if, don't move far). In March 2004, one specimen had disappeared, on the left side two specimens were attached some decimeters above their original place (probably they had moved up); all others were still at the same place. In 2013, no specimen was found at the same place as before; three larger specimens

**Fig. 2.** Benthic mega-fauna of Punta Llonco 2003 (1) and 2013 (2): **A.** Mytilid bank; 15 m. **B.** Meadow of primnoid gorgonian *Primnoella chilensis*, rocks covered with polychaetes of the genus *Spiochaetopterus patagonicus* Kinberg, 1867; 20 m. **C.** Rocky wall with deep-sea anemones *Actinostola chilensis*; 22–25 m. As point of reference, see red algae patch (A). **D.** Coral bank with the matrix species *Desmophyllum dianthus* under overhanging rock; 25 m. **E.** Steep rock with sea anemones *Bolocera occidua* and *Boloceropsis platei* (white arrows in 1 mark white specimens and one of the many dark brown specimens); 26–30 m. **F.** Double ridge with sea anemones *Hormathia pectinata* (black arrows), bryozoans *Aspidostoma giganteum* (white arrows) and *Primnoella chilensis*; 35–40 m. **SA, SD, SE, SF:** close-up section from figure A, D, E, F.











were attached to the rock close by (two within the defined area, and one outside, just below: still visible in Fig. 2C2).

3. In 2003, a few scattered mytilids were growing close to the upper margin of the large coral bank at 25 m depth (Fig. 2D1) which were only visible on close-up photos. On photos taken in 2006, the coverage of mytilids within the coral bank had not changed significantly. In 2013 however, the percentage of mytilids within the coral bank was much higher, visible by extended dark patches (Fig. 2D2, 2SD).

4. In 2003, the steep wall below the coral bank in 25–30 m depth was inhabited by dozens of specimens of the sea anemone species *Boloceroopsis platei* McMurrich, 1905 and *Bolocera occidua* McMurrich, 1893 (Fig. 2E1, 2SE, white and brown spots). In 2013 at the same place, we found no sea anemones (Fig. 2E2; the dark spot is a sea urchin *Arbacia dufrenoyi*).

5. In 2003, the top of a double ridge which is situated between 35 and 40 m depth north of the large coral bank, was inhabited by several specimens of the calcified bryozoan *Aspidostoma giganteum* Busk, 1854 (arrows in Fig. 2F1, 2SF) and at least one specimen of the deep-sea anemone *Hormathia pectinata* (Hertwig, 1882) (white line, see Fig. 2F1, 2SF). In 2013, of the seven specimens of *A. giganteum* found in 2003, only three were left, all of which inhabit the lower ridge. The specimen of *H. pectinata* is attached at exactly the same spot, and a second specimen is visible on the upper ridge (it might have already been there in 2003, retracted below the fine sediment layer). The density of *Primnoella chilensis* at this spot has been reduced by 53 % since 2003 (in average 15 gorgonians per m<sup>2</sup> in 2003 and 8 in 2013).

### Decapod surveys

Compared to the first stays at Huinay Scientific Field Station in 2005 and 2006, a decline in crustacean abundance in all previously common, large and well detectable species was observed in 2011. In particular, *Cancer edwardsi* Bell, 1835 (Fig. 3A) was very common in 2005 and 2006 (more than 30 specimens per one hour and diver), but rare in 2011 (altogether three specimens in twenty dives were observed). A drastic decrease was also observed for *Campylonotus vagans* Bate, 1888 (Fig. 3B). While in 2006 during each night dive several specimens were recorded, in 2011 a total of only two specimens were seen during five night dives. A very conspicuous decrease in abundance was also observed for *Pagurus villosus* Nicolet, 1849 (Fig. 3C). This previously very common hermit crab was the most abundant decapod in 2005 and 2006 with observed aggregations of more than 50–60 specimens (Fig. 3D). In 2011, less

than 10 specimens were observed per dive. Other decapod species that were abundant in 2005 and 2006 but only sporadically found in 2011 are *Propagurus gaudichaudi* H. Milne Edwards, 1836 (Fig. 3E), *Pagurus edwardsi* (Dana, 1852) (Fig. 3F), *Pilumnoides perlatus* (Poeppig, 1836) (Fig. 3G) and *Nauticaris magellanica* (Milne Edwards, 1891) (Fig. 3H).

## Discussion

### Effects of extractive activities on biodiversity of mytilid banks in Comau Fjord

With a twelvefold multiplication of registered fishermen in the Hualaihué Province over the past ten years (from 52 in 2002 to 649 in 2011) (HFFR-2012) and a rising number of boats coming from other Provinces to harvest in Comau Fjord (Luis Hernandez, pers. comm. 2012), the pressure on the mussel banks has increased strongly. Mytilid landings in Hualaihué have constantly decreased over the past ten years by more than 90 % (HFFR-2012).

Harvest of natural mussel banks means the removal of the entire epi-benthic biomass on large areas, which later is sorted on board. All no-target species are cleaned off the mussels and discarded, with minimal chances of survival. While in the subtidal mytilid recruitment on the cleaned areas may take place within few years, the higher in the intertidal this technique is applied and the larger the horizontal extent of the harvesting site, the longer it takes until mussel recruitment can be observed, and at some sites no mussel recruitment was observed until 2013. Since 2004 the upper limit of intertidal harvesting has successively raised (Fig. 4A2). The reported strong decline in mytilid seed production (by nearly 80 %) and recruitment in Northern Patagonia in 2012 could be connected to the decline in plankton in the Ancud Gulf in 2010/2011 (Feldman & McClain 2013) but also to the low density of larvae (Mundo Acuicola Pesquero 2013) through the lack of old mussel banks. After the crisis in mytiliculture through the decline in mussel recruitment, the Undersecretary of Fisheries announced to fund a study on the effect of Cypermethrin and Deltamethrin (used against sea lice) on mytilid aquacultures (Mundo Acuicola Pesquero 2012).

### Effects of aquaculture on biodiversity

For a variety of reasons, marine aquaculture of predatory species in general and intense net pen farming in coastal areas with restricted water exchange is controversially discussed (Grant 2010). Buschmann et al. (2012) state that environmental threats and human health risks are unacceptably



high and salmon farming in Chile does not meet any reasonable definition of sustainability. The effects of eutrophication and increased organic sedimentation on benthic communities resulting in reduced diversity and altered macrofauna in the vicinity of the farms have been extensively studied (Hargrave 2010); in the vicinity of the net pens only benthic taxa tolerant to suboxic conditions can survive (Vaquer-Sunyer & Duarte 2010). Far-field effects exist (Wildish & Pohle 2005) but are much less known and more difficult to detect.

In Chile, chemicals are extensively used in fish farming (Buschmann et al. 2009, 2012): e.g. the amount of antibiotics used in Chile in 2007 was more than 1400 times the amount used in Norway calculated for the same amount of produced salmon (732 and 560 versus 0.02 and 0.07 g/t production), which in Chile is done in a quarter of the area (Buschmann et al. 2006, Burrridge et al. 2010). Marine Harvest in its Sustainability Report (2008) declares to use 8200 (2008) to 36600 times (2007) more antibiotics in their farms in Chile compared to their farms in Norway. There is a significant potential that the chemical inputs also affect the diversity of the local fauna (Burrridge et al. 2010), which has already been observed in some cases in Chile (Buschmann et al. 2006). Data on chemical uses have not been made public at all until 2010; enforcement is inadequate and the illegal use of banned products and the poorly controlled application of others are controversially discussed (Buschmann et al. 2006, Burrridge et al. 2010). Since 2011, some information on the presence of the three main salmonid diseases and on the use of some chemicals is available (however, without data neither on the actually used amount nor on the frequency of treatment). All salmonid diseases known for Chile are present in the Comau Fjord, but our request for information about the chemicals used in the Comau Fjord was rejected by the Undersecretary of Fisheries arguing that the companies see this as strategic, commercially sensitive information and its dissemination would affect their commercial and economic rights (HFFR-2012).

The increasing effects of the salmon farming industry on the natural environment are poorly studied: although Chile is on the top of the list of salmon producing countries, it produces only 2–5 % of the scientific publications on the topic (Buschmann et al. 2009). This is the first publication which includes comparisons of benthic fauna over time.

### Anthozoans

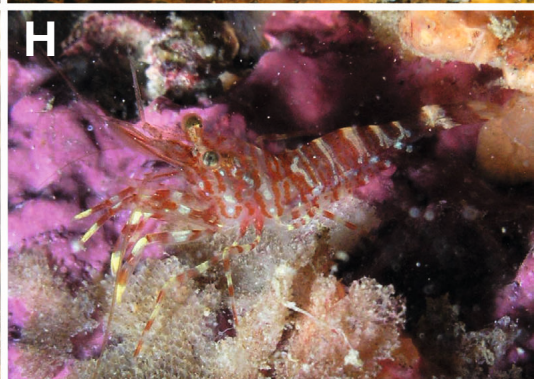
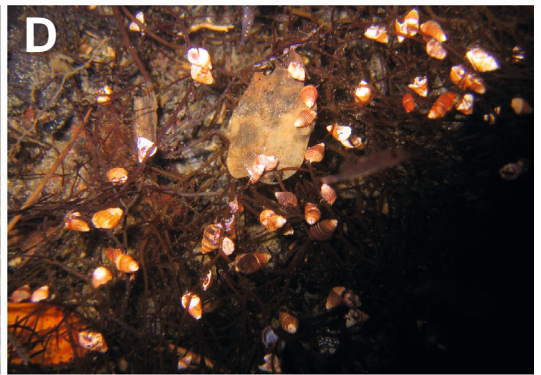
Gorgonian corals are long-lived, slow-growing species exhibiting slow population dynamics. They are known to be affected by increased sedimentation

(Rogers et al. 1990), and to be more prone to diseases when their environment is nutrient-enriched (Bruno et al. 2003). The reduced densities of gorgonians might be connected to elevated sediment stress and increase in nutrients.

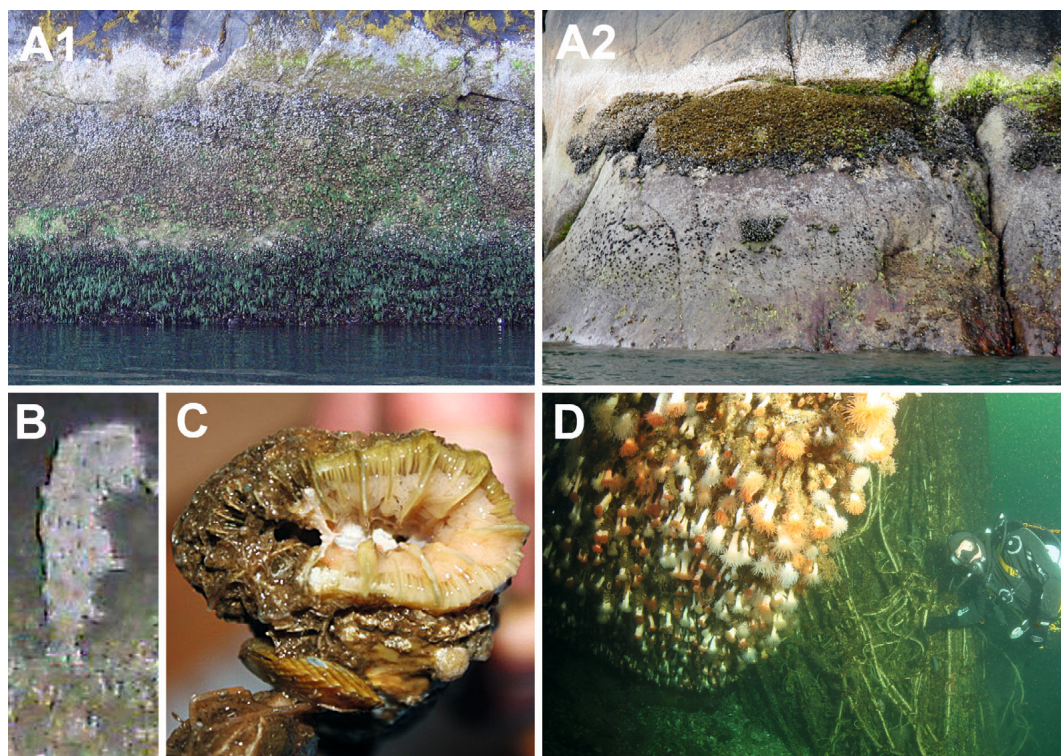
Some species of intertidal anemones are known to live up to 50 or more years (Shick 1991), and larger deep-water anthozoan species hold records of longevity (Roark et al. 2009), thus large deep-water anemones such as *Actinostola chilensis* and *Bolocera occidua* can be expected to be also long-living. No predators are known for these anemones once they reach larger sizes. Consequently, decreases in population densities can most probably be explained through changes in the environment.

The unique cold-water corals in shallow water of Chilean Patagonia (Häussermann & Försterra 2007) face several threats, some of them are natural:

1. In 2008, the eruption of the Chaitén volcano brought high amounts of sediment to the neighbouring Reñihué Fjord.
2. Between April and May 2012, around the two sites at X-Huinay (Fig. 1) along at least 650 m of shoreline we observed a mass die-off of all specimens of the scleractinian coral *Desmophyllum dianthus*, probably caused by elevated cold seep activities (Försterra et al. in review).
3. Elevated sedimentation (e.g. through aquaculture) is known to be the main human-made threat to scleractinian corals (Rogers et al. 1990) since it increases the expense on energy necessary to produce cleaning mucus: in 2012, we observed *D. dianthus* specimens in the neighbouring Reñihué Fjord with the sides directed towards a nearby salmon farm covered with fine slimy organic sediment and died off (Fig. 4C). During a ROV dive at Punta Llonco in October 2007, we observed higher amounts of sediment on the basal portion of the corals that are not covered by polyp tissue anymore, compared to 2005.
4. In 2007, lost nets and lines got entangled in a coral bank at Lilihuapi Island, Comau Fjord and broke off a large fraction of corals, from the remaining corals many died subsequently, probably due to reduced water flow through the net (Fig. 4D).
5. In 2008, after the eruption of the Chaitén volcano, several weak earthquakes affected the area, which might have caused the breaking off of corals. Subsequently, mussels have successfully occupied the free space between the corals where they are less accessible for their main predator, the starfish *Cosmasterias lurida* (Philippi, 1858) (Fig. 2D2, 2SD). Since earthquakes are common in this area the coral/mussel ratio in coral banks may be subject to cyclic fluctuations, but eleva-







**Fig. 4.** **A1.** Mytilid bank in the mid to high intertidal in January 2005. **A2.** The same mytilid bank in 2011. **B.** *Primnoella chilensis* covered with white bacteria; photos taken with ROV under salmon farm north of Punta Llonco in October 2007, 60 m. **C.** *Desmophyllum dianthus* polyp with side directed towards a salmon farm died off; Reñihué Fjord, August 2012, 25 m. Photo Rhian Waller. **D.** Coral bank at Lilihuapi Island entangled with lost nets and lines from mytilid cultures; December 2007, 25 m.

ted sediment load and eutrophication of the fjord may shift environmental conditions, favoring mussels.

6. A road project is planned along the eastern shore of the Comau Fjord through extremely steep slopes covered with primary forest. Rock material that is dumped into the sea and enhanced sedimentation from the unpaved road (Anderson & Potts 2007) will affect the benthic communities, especially cold-water corals. In a steep area with little organic overlay and high precipitation, a horizontal transection of the root system can increase landslide frequencies and can increase the risk of local tsunamis (Bornhold et al. 2001) which is already evaluated as high in the area (Sepúlveda et al. 2011).

## Decapods

Studies found that benthic crustaceans were significantly reduced in biodiversity below and close to salmon farms in Scotland, despite the presence of strong currents, probably due to the combined effects of organic wastes and the use of pesticides (which in Scotland are used in much smaller amounts compared to Chile) to combat parasitic copepods (Hall-Spencer et al. 2006, Hall-Spencer & Bamber 2007). Pyrethroid toxins which have been extensively used against sea lice in Comau Fjord since at least 2010 (PFFR 2012) are known to affect in particular decapods (Burridge et al. 2010) and when used over a longer time can have diverse negative effects on the environment (Furci 2009). This could explain the decline of benthic decapods in the fjord. Further

◁ **Fig. 3.** Decapod fauna of the Comau Fjord: **A.** *Cancer edwardsi* on mytilid bank. **B.** *Campylonotus vagans*. **C.** *Pagurus villosus*. **D.** Crowd of *P. villosus* observed in the year 2006. **E.** *Propagurus gaudichaudi*. **F.** *Pagurus edwardsii*. **G.** *Pilumnoides perlatus*. **H.** *Nauticaris magellanica*.

studies need to confirm these hypotheses. Studies are necessary to examine the effect of pyrethroids on pelagic crustaceans (zooplankton), since this would affect the entire food chain.

## Conclusions

We conclude that significant gradual changes occurred during the last decade in Comau Fjord. The high amount of organic waste produced by the accumulation of many aquaculture concessions, the accompanying eutrophication of the fjord and the poorly controlled use of large amounts of chemicals, and the uncontrolled harvest of natural mytilid banks are threats to the unique cold-water fauna of Comau Fjord which is dominated by filter-feeders. Other fjords of Northern Patagonia (Reloncavi Fjord, east coast of Chiloe Island) (HFFR-UF 2012), have even higher densities of aquaculture installations than Comau. Nevertheless, without having compared the photos from Punta Llonco from 2003/2004 and 2012/2013, and the crustacean data from 2005/2006 and 2011 we would not have been aware of the magnitude of change. This phenomenon of unnoticed rapidly shifting baseline within one generation is called personal amnesia (Papworth et al. 2008).

Although Chilean scientists mention these problems since many years, the topic is still neither widely discussed nor taken sufficiently into consideration by the responsible institutions. As a consequence many politicians and the broader public are still largely unaware of the threat that the current practices may mean to local wildlife, fisheries and the development of sustainable tourism (Vester & Timme 2010). With shifting base lines the awareness on the call for action is even less. Human impacts in the ocean are more severe and persistent than previously thought, and loss of shallow-water marine habitats is proceeding as fast as on land (Roberts 2003). To reverse this trend, and to preserve true base lines, we need to establish networks of marine protected area, for which the proposed marine protected area in Comau Fjord maybe a first step.

## Acknowledgements

This is publication nr. 95 of Huinay Scientific Field Station.

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