Available online at www.sciencedirect.com
SCIENCE DIRECT®
Marine Pollution Bulletin 48 (2004) 1040–1047
MARINE POLLUTION BULLETIN
www.elsevier.com/locate/marpolbul

Minor improvement for intertidal seaweeds and invertebrates after acid mine drainage diversion at Britannia Beach, Pacific Canada

Thalia Zis *, Vera Ronningen, Ricardo Scrosati

Department of Botany, University of British Columbia, Vancouver, BC, Canada V6T 1Z4

Abstract

In December 2001, acid mine drainage (AMD) from an abandoned copper mine at Britannia Beach (British Columbia, Canada) was diverted to flow from Britannia Creek into an outfall at 30 m depth in Howe Sound. Britannia Beach was studied in early 2003 to determine whether AMD diversion resulted in improved conditions for intertidal organisms. Species number and abundance have increased at the intertidal zone since AMD diversion, although they were still lower than at an unpolluted control site nearby (Furry Creek). Survivorship and growth rates of transplanted *Mytilus trossulus* (mussel) have increased since AMD diversion, although they were still significantly lower than at the control site. Transplanted *Fucus gardneri* (seaweed) performed better than before the AMD diversion; at Britannia Beach the chlorophyll *a* concentration in tissues was not significantly different from that at the control site, although the concentration of chlorophyll *c* in tissues and the chlorophyll *c* to *a* ratio was lower than at the control site six weeks after transplantation. Britannia Beach is still subject to leaching of metals from surrounding soils, low levels of AMD coming down the creek, and AMD discharge from the deep outfall. Although there has been an improvement, the intertidal environment at Britannia Beach still seems unable to support normal growth and survival of organisms.

Keywords: Acid mine drainage; Britannia Mine; British Columbia; *Fucus gardneri*; Intertidal community structure; *Mytilus trossulus*

1. Introduction

Britannia Beach is at the mouth of Britannia Creek, in Howe Sound, north of Vancouver, British Columbia, Canada (Fig. 1). Britannia Creek is considered to be the single worst point source of pollution of any mine in British Columbia (McCandless, 1995). In 1902, the Britannia Mining and Smelting Company Ltd. began mining for copper, zinc, and iron ore bodies (Mills, 2003). The mine continued operating under the Anaconda Mining Company until 1974, after which it closed for economic reasons (Mills, 2003). The abandoned mine and the processing grounds around it are a source of toxic levels of metal contamination due to acid mine drainage (AMD). During its 72 years of operation, Britannia Mine extracted approximately 50 million tonnes of ore from 80 km of tunnels and five open pits (Mills, 2003). The metal sulfides in these tunnels and pits have been exposed to air and water, producing sulfuric acid, which leaches out the metals forming AMD (Britannia Mines and Reclamation Corp., 2003). There are two main tunnels from which AMD has been discharged: one is at the 2200 level portal (270 m above sea level) which until December 2001 discharged into Jane Creek and then into Britannia Creek. The other is at the 4100 level portal (67 m above sea level) and discharges AMD to Howe Sound via a pipeline at 30 m depth and 50 m offshore, directly in front of Britannia Creek (Ministry of Water Land and Air Protection, 2003). On 31 December 2001, a concrete plug (2200 Plug) was constructed in the 2200 level tunnel, to prevent discharge of AMD to Jane and Britannia Creeks; it redirects AMD to the 4100 level portal (Meech et al., 2003). Thus, AMD from the tunnel into Jane Creek and Britannia Creek has been halted, and this drainage is now discharged into Howe Sound via the pipeline instead. Prior to the installation of the 2200 Plug, dissolved copper concentration at the Townsite Bridge (mouth of Britannia Creek) was 0.51 ppm, total copper concentration was 0.75 ppm, and the pH was 6.3 (Meech et al., 2003). After the plug was installed, dissolved copper

* Corresponding author. Address: 1998 Matthews Avenue, Vancouver, BC, Canada V6J 2T7. Tel.: +1-604-306-6713; fax: +1-604-875-4477.
E-mail address: thaliaz@interchange.ubc.ca (T. Zis).

0025-326X/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpolbul.2003.12.007

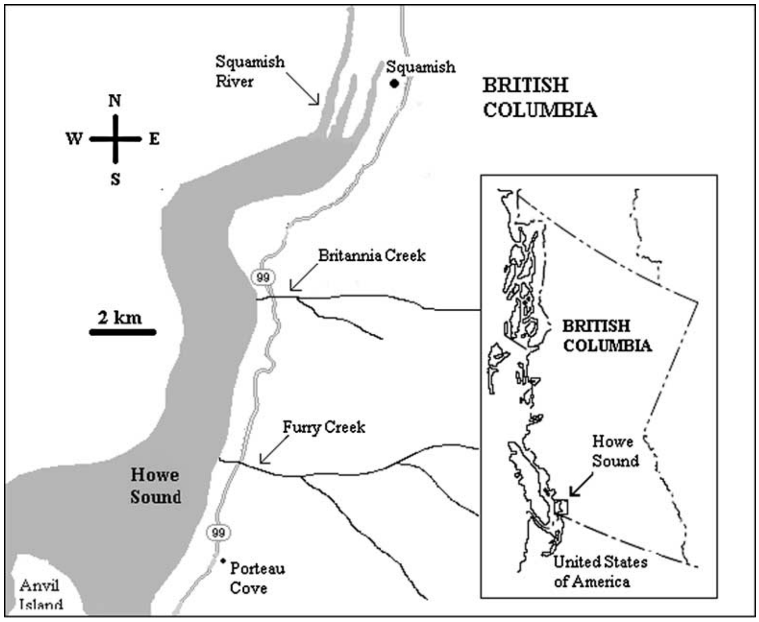

Fig. 1. Map of upper Howe Sound, BC, showing the location of the study site, Britannia Creek, and the control site, Furry Creek.

concentration at the Townsite Bridge was 0.04 ppm, total copper concentration was 0.06 ppm, and the pH was 6.9 (Meech et al., 2003). These measurements were taken in December 2001 (before the plug) and January 2002 (after the plug) (J.A. Meech, Department of Mining Engineering, The University of British Columbia, 6350 Stores Road, Vancouver, BC, Canada V6T 1Z4, personal communication).

The main metal discharged into Howe Sound from Britannia Creek is copper, which, in high concentrations, can be toxic to marine organisms (Barry et al., 2000). Britannia Mine is the largest source of dissolved metals to Howe Sound (Dunn et al., 1992). Howe Sound is an important habitat for young salmon as they migrate to the Pacific Ocean. Intertidal algae such as *Fucus gardneri* provide habitat and food for many marine invertebrates, some of which are food sources for salmon (Marsden, 1999). One of the effects of AMD contamination is reduced primary production, which can have a serious impact on the marine food web (Varela et al., 2000). Since the construction of the new concrete plug and the resulting decrease of AMD and copper in Britannia Creek, no studies have investigated the impact on organisms in the intertidal zone at Britannia Beach. AMD is a long-term problem that can continue for thousands of years, and therefore needs a long-term solution (Environmental Mining Council of British Columbia, 2003).

Several studies were conducted prior to the AMD diversion. High copper concentrations have been measured in surface water, intertidal organisms, and sediments in the Britannia Beach area (Barry et al., 2000; Dunn et al., 1992; Grout and Levings, 2001; Marsden, 1999; Marsden and DeWreede, 2000; Marsden et al., 2003). Previous transplantation studies have shown that the levels of copper at Britannia Beach were lethal to the Chinook salmonids *Oncorhynchus tshawytscha* (Barry et al., 2000), the mussel *Mytilus trossulus* (Grout and Levings, 2001), and the seaweed *F. gardneri* (Marsden, 1999; Marsden et al., 2003). A study by Marsden (1999) found that, apart from a thin layer of green algae, there was no apparent life present within 100 m of Britannia Creek, and no *F. gardneri* within 1000 m north of the creek mouth and 600 m south of the creek mouth. Transplants of *F. gardneri* to within 100 m of Britannia Creek resulted in negative growth rates and high mortality within two months of exposure in the autumn and winter (Marsden et al., 2003). Juvenile mussels (*M. trossulus*) were transplanted to Britannia Beach and it was found that exposure had a detrimental impact on mussel survival and growth rates (Grout and Levings, 2001).

The objectives of this study were to assess the effects of the lowered copper and AMD levels in Britannia Creek since the AMD diversion in December of 2001 on marine intertidal organisms at Britannia Beach, and to determine whether the diversion of the acid drainage improved environmental conditions to allow for successful recolonization and growth of organisms. The amount of AMD entering Howe Sound via Britannia Creek has been reduced, but AMD is being discharged via the deep outfall, and heavy metal contamination is still evident in the soil and groundwater at the foreshore, in the sediments of Howe Sound, and on Britannia Creek fan lands (Ministry of Water Land and Air Protection, 2003). A biological survey was conducted to compare abundance and diversity of intertidal macroalgae and sessile invertebrates at Britannia Creek to that of Furry Creek (an unpolluted creek 6 km south of Britannia Creek). It was hypothesized that (1) there would be signs of recolonization with an increase in species number at Britannia Beach, (2) there would be greater abundance of organisms at Britannia Beach, and (3) that species number and abundance would still be greater at the control site (Furry Creek) than at Britannia Beach.

The growth rate and survivorship of transplanted *M. trossulus* were measured. It was hypothesized that (4) the survivorship and growth rate of transplanted mussels near Britannia Beach would be higher than those found in transplantation experiments prior to the AMD diversion, and (5) that survivorship and growth rate of mussels would be lower at Britannia Beach than at Furry Creek.

Chlorophyll *a* and *c* concentrations of transplanted *F. gardneri* were measured in order to determine physiological status, which can be used as an indicator of current environmental conditions. Toxic levels of heavy metals such as copper and zinc (which are found in high concentrations in the AMD discharge from Britannia Mine) cause a loss in pigment correlated with a loss in photosynthetic performance of *Fucus* (Rijstenbil et al., 1994). Heavy metals have been found to decrease chlorophyll content in plants and algae, since they inhibit the biosynthesis of chlorophyll pigments and enzymes (Ralph and Burchett, 1998). Since little, if any, AMD enters the marine environment through Britannia Creek, it was hypothesized that (6) chlorophyll *a* and *c* concentrations of *F. gardneri* would be lower at Britannia Beach than at the control site. Chlorophyll *c* to *a* ratios have been found to decrease along with decreasing chlorophyll *c* and *a* content with increasing amounts of heavy metal exposure (Rijstenbil et al., 1994). It was hypothesized that (7) the ratio of chlorophyll *c* to *a* in *F. gardneri* would be lower at Britannia Beach than at the reference site. The physical condition of transplanted *F. gardneri* was also observed and compared to data from before the diversion. It was hypothesized that (8) the physical condition of transplanted *F. gardneri* would be better than that of plants moved before the diversion.

2. Materials and methods

2.1. Selection of control site

The control site chosen for this experiment was the intertidal area at the mouth of Furry Creek, a relatively unpolluted creek (Marsden et al., 2003) about 6 km south of Britannia Creek. Both sites are estuaries similar in salinity, size, topography, and flow patterns (Barry et al., 2000). The slope is gradual at the mouth of the creeks and increases with distance; the creek mouths have mild wave exposure. On the beaches, sandy areas are found near the mouths of the creeks with many rocks increasing in size to boulders with horizontal distance. *M. trossulus* and *F. gardneri* were taken for transplantation from the beach surrounding Magnesia Creek, 20 km south of Britannia Creek, also in Howe Sound. Magnesia Creek and Furry Creek are relatively unpolluted areas and show abundant growth of *F. gardneri*, which is typical of Howe Sound (Marsden et al., 2003).

2.2. Sampling of community structure

Sampling was conducted in February 2003 during low tides. Salinity ranged from 24 to 26 ppt across 100 m zones stretching northwards from the creek mouths. The areas chosen for sampling were in the mid-intertidal zone. Access to the south side of Furry Creek was limited. For reasons of consistency, the north side of Britannia Creek was selected for the study. At each creek, the 100 m zone was divided into four 25-m sections. Ten 0.25-m^2 quadrats were randomly placed in each 25-m section. The quadrat was pre-strung with nylon strings in a grid pattern with 100 25-cm^2 squares (subquadrats). Percent cover for *F. gardneri* (Phaeophyceae, Fucales) was estimated for each subquadrat. Percent cover of barnacles, *Balanus glandula* (Crustacea, Cirripedia), mussels, *M. trossulus* (Mollusca, Bivalvia), *Hildenbrandia* spp. (Rhodophyta), *Enteromorpha intestinalis* (Chlorophyta, Ulvophyceae), and green slime were then estimated by moving the canopy of *F. gardneri* aside and estimating percent cover of each organism in each subquadrat. Samples of the green slime were identified using a compound microscope.

2.3. Organism selection for transplantation experiments

F. gardneri is a sensitive indicator of many elements in the tidal environment (Dunn et al., 1992). *F. gardneri* transplanted to Britannia Beach prior to the AMD diversion was used as a biomonitor; its survivorship, growth rate, and copper content were then examined (Marsden et al., 2003). *M. trossulus* is an intertidal mussel; surveys of natural populations showed an increase in abundance with distance from the Squamish River (the head of Howe Sound), but an absence of mussels within 1.5 km of the mouth of Britannia Creek (Grout and Levings, 2001). Mussels are often used as biological indicators for examining the effects of human activity on the marine environment and, because of their sedentary nature, they can concentrate metals from the water column (Grout and Levings, 2001). Caged mussels have been used in transplant studies to define areas of metal pollution (Grout and Levings, 2001).

2.4. Experimental design

Rocks covered with *F. gardneri* and *M. trossulus* were randomly selected for transplantation from the shoreline adjacent to Magnesia Creek. Two of each of the rocks containing the species of interest were placed inside wire cages (to prevent predation from seabirds and benthic invertebrates) and randomly positioned on the substratum on the north side of each creek mouth. There were a total of two rocks per cage and a total of eight cages per treatment for each species. The greatest horizontal distance between any two cages was 3 m. The location of the cages was similar at both sites; the goal was to maintain as natural an environment as possible. Transplants were carried out during low tides, when the organisms would normally have been out of the water, and the total time of transportation of organisms was always less than 1 h. The length of the experiment was two months, from 16 February to 16 April 2003.

2.5. Monitoring

Mussels used to monitor growth rate were chosen from a relatively narrow range of shell length (17–36 mm; mean 25.8 mm) to minimize initial differences in size-dependent growth (Grout and Levings, 2001). Test mussel shells were painted with nail polish. At the end of the experiment, mussels that had closed shells at low tide were considered survivors. Shell lengths were recorded for the selected mussels ($n = 16$). Observations were made on the condition (attachment strength) of the transplanted mussels.

F. gardneri thalli were observed at three time intervals (every two weeks post-transplantation). Chlorophyll *a* and *c* extractions were taken from three plants per cage. The tips of *F. gardneri* thalli were collected and brought to the lab for chlorophyll extractions. Tips without receptacles were randomly chosen, removed, and transported to the lab in a cooler, and extracted immediately. We followed standard extraction procedures. In brief, the tips were blotted with tissue paper to remove any excess moisture from the plant surface. The tips were then placed on a weigh scale to determine tissue mass (in g). The tips of the transplanted *F. gardneri* plants were extracted in 8 ml of 90% acetone solution by grinding followed by vacuum filtration. The final volume of chlorophyll extract was adjusted to 8 ml with 90% acetone. Spectrophotometric determination was performed according to Jeffrey and Humphrey (1975). The absorbance of chlorophyll extracts was read at 664 and 630 nm against a 90% acetone blank, using a spectrophotometer. The amounts of chlorophyll *a* and *c* ($c_1 + c_2$) were calculated in the extract according to the following equations:

$$\text{mg Chlorophyll } a/\text{g tissue} = \frac{[11.47 \ * \text{E664} - 0.4 \ * \text{E630}] \times \text{Volume}}{\text{Mass of tissue}}$$

$$\text{mg Chlorophyll } c(c1 + c2)/\text{g tissue} = \frac{[24.36 \ * \text{E630} - 3.73 \ * \text{E664}] \times \text{Volume}}{\text{Mass of tissue}}$$

In the above equations, "E" represents the extinction at the wavelength indicated, "Volume" the final volume of the chlorophyll extract in liters, and "Mass" the mass in grams of the tissue extracted. Observations were also made on the physical appearance of the transplanted thalli.

2.6. Data analysis

All statistical tests were conducted using SYSTAT (version 5.03). Data was first tested for normality with normal probability plots. For the ANOVA and *t*-test, assumptions are equal variance and normal distributions. Some violations of these assumptions were detected, but the ANOVA and *t*-test are very robust to departures from normality and equality of variances (Zar, 1999). Thus, they were used despite occasional violations of assumptions.

Percent cover of each species was compared for each 25-m section between the two creeks using *t*-tests. In some sections, certain measurements yielded values of zero. These measurements could not be analyzed by ANOVA, because they have no variance. These sections were omitted from the ANOVA. However, the results can be interpreted based on their obvious contrast with sections with non-zero values for the measurement in question.

M. trossulus survivorship scores yielded a proportion of mussels surviving on each rock. Growth rate of mussels ($n = 16$) was calculated by dividing the difference between the initial and final shell lengths by the duration of the experiment (two months) and also by initial length, to standardize for size. Survivorship and growth rate were compared between sites using a *t*-test. *F. gardneri* chlorophyll *a* and *c* concentrations, and the chlorophyll *c* to *a* ratio were derived from the data. The mean chlorophyll concentration was calculated for each rock and the two treatments were compared using a *t*-test.

3. Results

3.1. Community structure

The percent cover of barnacles, *M. trossulus*, *F. gardneri* and *Hildenbrandia* spp. within each 25 m

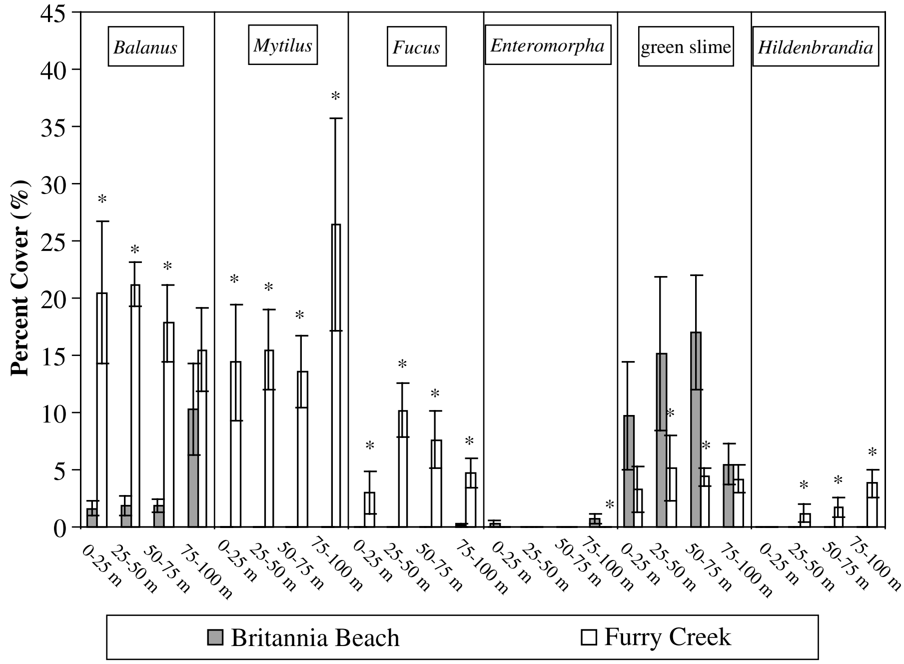

Fig. 2. Percent cover (mean ± S.E.) of species at Britannia Beach and at Furry Creek, in 25-m sections increasing with distance from the creek mouths. $n = 10$ for all sections. $^*p < 0.05$ at Furry Creek compared with Britannia Beach (t-test).

distal to each creek mouth was higher at Furry Creek than at Britannia Beach, while, for *E. intestinalis* and green slime, percent cover was lower at Furry Creek (Fig. 2). It was found that the green slime is a combination of the xanthophyte algae *Vaucheria* and several chlorophyte species including the genera *Blidingia* and possibly a young *Enteromorpha*.

When considering the entire 100 m areas, barnacle cover was significantly higher at Furry Creek (18.8% ± 2.0%, mean ± S.E.) than at Britannia Beach (3.9% ± 1.2%, $p < 0.05$). The barnacles within 75 m of Britannia Creek were generally smaller than those at Furry Creek; many (about half) were hollow and several broke easily when pushed with a finger. No mussels were found at Britannia Beach, while they were abundant at Furry Creek (cover = 17.5% ± 2.9%). The only *F. gardneri* thalli found at Britannia Beach were a few small individuals at about 90 m from the creek mouth (cover = 0.01% ± 0.04%), while thalli were significantly more abundant at Furry Creek (6.4% ± 1.1%, $p < 0.05$). *E. intestinalis* was only found at Britannia Beach (cover = 0.25% ± 0.1%). Green slime was found at both creeks, but its abundance was significantly higher at Britannia Beach (cover = 11.8% ± 2.5%) than at Furry Creek (4.3% ± 0.9%, $p < 0.05$). The slime was most dense in and around both creek mouths. It reached into the intertidal zone and about 100 m up both creeks. No *Hildenbrandia* was found at Britannia Beach, while it was found at Furry Creek (cover = 1.7% ± 0.5%).

3.2. Survivorship of *Mytilus trossulus*

Survivorship of *M. trossulus* was significantly lower at Britannia Beach (89.9% ± 1.2%, mean ± S.E.) than at Furry Creek (99.4% ± 0.2%) two months after transplantation ($p < 0.005$, $n = 16$).

3.3. Growth rate of *Mytilus trossulus*

The relative growth rate of transplanted *M. trossulus* was significantly lower at Britannia Beach (0.30 ± 0.05 month^{-1}, mean ± S.E.) than at Furry Creek (0.85 ± 0.07 month^{-1}, $p < 0.005$, $n = 16$).

3.4. Attachment changes in *Mytilus trossulus*

M. trossulus at Britannia Beach were more easily dislodged from their holdfast compared to those transplanted to Furry Creek.

3.5. Chlorophyll concentration in *Fucus gardneri*

Mean chlorophyll *a* concentration of transplanted *F. gardneri* at Britannia Beach (0.25 ± 0.02 mg/g tissue, mean ± S.E.) was statistically similar to that for Furry Creek (0.30 ± 0.02 mg/g tissue, $p = 0.171$, $n = 8$). Mean chlorophyll *c* concentration of transplanted *F. gardneri* was significantly lower at Britannia Beach (0.13 ± 0.01 mg/g tissue) than at Furry Creek (0.18 ± 0.02 mg/g tissue, $p < 0.05$, $n = 8$). Mean chlorophyll *c* to *a* ratio of transplanted *F. gardneri* was significantly lower at Britannia Beach (0.50 ± 0.02 mg/g tissue) than at Furry Creek (0.60 ± 0.03 mg/g tissue, $p < 0.05$, $n = 8$).

3.6. Changes in appearance in Fucus gardneri

By the end of the transplantation period, *F. gardneri* transplanted to Britannia Beach was more brown when compared with the olive green color of plants that were transplanted to Furry Creek and plants at nearby sites. The plants at Britannia Beach also became softer in texture relative to the plants at Furry Creek.

4. Discussion

4.1. Species number and abundance

Species number and abundance at Britannia Beach have increased compared to prior to the AMD diversion, when Marsden (1999) reported that no marine algae, mussels, or barnacles were present within 100 m of the mouth of Britannia Creek. However, species number and abundance at Britannia Beach are still much lower than at the control site. *Hildenbrandia* was only found at Furry Creek, possibly because *Hildenbrandia* may not be tolerant of heavy metal toxicity or low pH. *E. intestinalis* was only found at Britannia Beach. *E. intestinalis* can tolerate higher concentrations of AMD than *F. gardneri* (Marsden and DeWreede, 2000); this may be the reason for its growth much closer to the creek mouth at Britannia Beach. *Enteromorpha* spp. have been found to be more tolerant of copper than other algae (Correa et al., 1996), and copper-polluted areas have been found to be dominated by *E. intestinalis* (Castilla, 1996). Green slime appears to grow well at both creeks, although its abundance is significantly higher closer to the creek mouth. Chlorophytes have been shown to be highly resistant to environmental stress, showing tolerance of copper, with optimum growth rates in the presence of elevated copper levels, and tolerance of a wide range of pH (Blackwell and Gilmour, 1991). Percent cover of green slime at Britannia Beach may be higher due to lack of competition or predation by other species. Barnacles were found at both creeks although they were more abundant at Furry Creek. Prior to the AMD diversion, no barnacles were present within 100 m of the mouth of Britannia Creek (Marsden, 1999). Barnacles are tolerant of, and are capable of, accumulating heavy metals, which makes them useful indicators of heavy metal toxicity (Rainbow, 1987).

Dense populations of *F. gardneri* have been observed at creek mouths at Watts Point and at creek mouths in the Woodfibre Creek area (north of Britannia Creek and therefore closer to the Squamish River), which has higher turbidity and lower salinity than Britannia Beach during freshet (Marsden et al., 2003). Therefore, salinity and turbidity appear to be unlikely explanations for the low species number and abundance at Britannia Beach.

4.2. Mussel survivorship and growth rate

Survivorship of transplanted mussels was significantly lower at Britannia Beach compared with Furry Creek. The reduced survival of transplanted mussels at Britannia Beach is further supported by the absence of natural mussels in the transplanted area. The conditions may still be too toxic for mussels to survive at Britannia Beach or it may be that not enough time has passed for their successful recruitment. Survivorship of mussels was higher than previously recorded. In 1998, prior to the AMD diversion, survivorship of mussels at different stations near Britannia Beach ranged from 0% to 42% in "low survival zones" (that is, within 3.8 km of Britannia Creek) after 41 days (Grout and Levings, 2001), while, in our study, average mussel survivorship at Britannia Beach was 89.9% after 60 days. The relative growth rate of transplanted *M. trossulus* was significantly lower at Britannia Beach (0.30 month^{-1}) than at Furry Creek (0.85 month^{-1}). Mean growth rate of mussels at Britannia Beach was significantly lower than at Furry Creek. The growth rate of mussels from a study prior to the AMD diversion also found mussel growth rates to be lower at Britannia Beach than at nearby reference stations (Grout and Levings, 2001). Mean mussel growth rates in "low survival zones", prior to the AMD diversion, ranged from 0 to 0.16 mm month^{-1} in the different zones (Grout and Levings, 2001). In contrast, since the AMD diversion, the mean growth rate of transplanted mussels at Britannia Beach was 0.8 mm month^{-1}, which is about 10 times higher than previously recorded. These differences in results between our study and the Grout and Levings study may be due to ecological effects and/or methodological effects. In the Grout and Levings (2001) study, mussels from an aquaculture operation were placed in mesh tubes and divided into individual compartments which were hung in cages below floats anchored in approximately 10 m of water, less than 50 m offshore (Grout and Levings, 2001). In our study, rocks with mussels were placed in cages in the intertidal zone in order to create an environment as natural as possible. Therefore, it is possible that different experimental conditions may account at least in part for the different mussel survivorship reported in the previous study.

4.3. Fucus condition and chlorophyll analysis

The concentration of chlorophyll *c* as well as the ratio of chlorophyll *c* to *a* were significantly lower at Britannia Beach compared with the reference site. High concentrations of dissolved metals have been known to decrease chlorophyll *c* concentrations, and to decrease the ratio of chlorophyll *c* to *a* in brown algae and plankton exposed to various amounts of copper, cadmium, and zinc (Rijstenbil et al., 1994). The toxic effects of heavy metals, such as copper, involve a reduction in mass-growth and pigment content in brown algae; the chloroplasts exhibit morphological changes upon exposure to cadmium, copper, and zinc (a few $mg\,l^{-1}$) (Pellegrini et al., 1993). Rijstenbil et al. (1994) found that chlorophyll *a* and *c* proved to be sensitive to copper (3–126 nM range) and their reduction coincided with the decrease of photosynthetic activity and the enlargement, deformation and breakage of cells in the marine planktonic diatom *Ditylum brightwellii* (Rijstenbil et al., 1994). They found that copper was an oxidative stressor and that the lack of antioxidant defense causes oxyradical damage in chloroplasts and inhibition of algal photosynthesis. We found that the concentration of chlorophyll *a* in transplanted *F. gardneri* at Britannia Beach did not differ significantly compared with Furry Creek; this may suggest that the reduction of AMD in the creek has allowed for some improvement in the condition of *F. gardneri*, although not enough for successful growth. Prior to the AMD diversion, *F. gardneri* was not found less than 1 km north of Britannia Creek and 600 m south of it (Marsden, 1999; Marsden and DeWreede, 2000). Since the AMD diversion, *F. gardneri* is growing closer to the creek mouth (within 100 m north of the creek mouth), suggesting a possible improvement in habitat conditions. However, at Britannia Beach, no *F. gardneri* was found closer than 90 m from the creek mouth; this may be an indication of continued pollution from the creek and the deep outfall, and leaching from the surrounding grounds, or it may be that there has not been enough time for recovery. In 1997 and 1998, prior to the AMD diversion, *F. gardneri* transplanted to Britannia Beach was found to have a high mortality and low growth rate attributed to a gradient of AMD from Britannia Creek (Marsden et al., 2003). In that study, it was also found that, within 14 and 30 days after it was transplanted to the Britannia Creek area, *F. gardneri* thalli turned reddish brown, produced large amounts of exudate, became very soft in texture compared with *F. gardneri* at Furry Creek, and tissue even began falling off of the thalli tips (Marsden et al., 2003). In our study, transplanted *F. gardneri* did take on a more brown color and also became softer in texture relative to the plants at Furry Creek and other nearby areas within six weeks. However, the production of exudate and the loss of tissue was not observed at Britannia Beach since the AMD diversion. Our results may indicate that AMD is still present in concentrations that do not allow for successful growth of *F. gardneri* at Britannia Beach.

4.4. General discussion

The present study indicates that, although there has been an improvement in environmental conditions in the intertidal area at Britannia Beach since the AMD diversion, conditions are not yet supportive of successful establishment and growth of organisms. The final diversion of AMD took place only one year and two months prior to this study, which may not have been enough time for the intertidal area at Britannia Beach to recover. Britannia Creek is still not free of metal contamination. In 2002, after the plug was installed, dissolved copper concentration measured at the mouth of Britannia Creek was 0.04 ppm, total copper concentration was 0.06 ppm and the pH was 6.9 (Meech et al., 2003); these values of copper are higher than throughout Howe Sound, and the pH values are lower than throughout Howe Sound (Britannia Mines and Reclamation Corp., 2003). Thus, there may still be an AMD gradient from the creek outflow and from the deep outfall, which could be affecting local species growth and abundance. Heavy metal contamination is still evident in the soil and groundwater at the foreshore and sediments of Howe Sound, and on Britannia Creek fan lands because of landings where tailings and concentrates have contaminated soil and are still leaching heavy metals into the creek and foreshore (Ministry of Water Land and Air Protection, 2003). High copper concentrations have been measured in surface water, intertidal organisms, and sediments in the Britannia Beach area (Grout and Levings, 2001; Barry et al., 2000; Marsden et al., 2003).

Another possible explanation for the partial improvement so far is that there is a possibility that the submerged outfall has become a relatively more important source of pollution. With the plug now in place, more drainage is flowing through the submerged outfall. The surface circulation pattern in Howe Sound is driven by a major outflow of fresh turbid water of glacial origin from Squamish River (mean annual discharge 242 $m^3\,s^{-1}$) (Chretien, 1997; Grout and Levings, 2001). This outflow of fresh water produces a 5 m deep layer of fresh, cold surface water overlying the warmer saltier waters at depth, giving rise to a pycnocline that limits vertical mixing and isolates the surface water during the spring and summer months (Barry et al., 2000). However, in late fall and winter, the pycnocline is weakened, allowing the AMD discharge to come to the surface (Chretien, 1997) and the surface currents carry some of the discharge back to the foreshore areas of Britannia Beach (refer to Grout and Levings, 2001, for a figure of upper Howe Sound surface circulation). Thus, increased AMD drainage flowing through the outfall may have a significant impact on the intertidal community.

While some pollution-control measures have been implemented at Britannia Beach, such as the sealing of contaminated grounds and the AMD diversion pipe, these are temporary solutions. Future research is required on the effects that the diversion of AMD has had on the benthic community, and the progress of recovery should be followed. Several remediation and mitigation options for Britannia Beach have been examined, yet as of the time of this study, none of them have been implemented. These include a proposed treatment plant (in 2004), sealing of abandoned mine tunnels and shafts, and bioremediation using algae. The results of this study could serve as a comparison for future investigations following the recolonization of organisms at Britannia Beach, and could lead to further measures in order to control the pollution.

Acknowledgements

Many thanks go to Dr. Robert DeWreede of the Botany Department at UBC for his advice and loan of equipment. We would like to thank Dr. Santokh Singh of the Botany Department at UBC for allowing the use of his laboratory and for his advice. We would like to acknowledge Dr. A.G. Lewis of the Department of Earth and Ocean Sciences at UBC for kindly reviewing the manuscript and for his comments. Thanks to Fanie Zis for taking time to assist in data collection. Finally, we would especially like to thank Todd Mitchell for his enthusiasm and for his time in assisting with transplantation and collection of data, and for providing transportation.

References

Barry, K.L., Grout, J.A., Levings, C.D., Nidle, B.H., Piercey, G.E., 2000. Impacts of acid mine drainage on juvenile salmonids in an estuary near Britannia Beach in Howe Sound, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 57, 2032–2043.

Blackwell, J.R., Gilmour, D.J., 1991. Stress tolerance of the tidal pool chlorophyte, *Chlorococcum submarinum*. British Phycology Journal 26, 141–147.

Britannia Mines and Reclamation Corp. (BMARC), 2003. History. Retrieved February 5, 2003 from the World Wide Web: http://www.britanniamine.info/Reports_and_%20Maps.htm.

Castilla, J.C., 1996. Copper mine tailing disposal in northern Chile rocky shores: *Enteromorpha compressa* (Chlorophyta) as a sentinel species. Environmental Monitoring and Assessment 40, 171–184.

Correa, J.A., Gonzalez, P., Sanchez, P., Munoz, J., Orellana, M.C., 1996. Copper–algae interactions: inheritance or adaptation? Environmental Monitoring and Assessment 40, 41–54.

Chretien, A.R.N., 1997. Geochemical behaviour, fate and impacts of Cu, Cd and Zn from mine effluent discharges in Howe Sound. Ph.D. Thesis. University of British Columbia, Vancouver, Canada.

Dunn, C.E., Percival, J.B., Hall, G.E.M., Murdoch, A., 1992. Reconnaissance geochemical studies in the Howe Sound drainage basin. In: Levings, C.D., Turner, R.B., Ricketts, B. (Eds.), Canadian Data Report of Fisheries and Aquatic Sciences No. 1879, pp. 89–101.

Environmental Mining Council of British Columbia, 2003. An End to Metals Contamination? Retrieved January 30, 2003 from the World Wide Web: http://www.miningwatch.org/emcbc/news/britannia.htm.

Grout, J.A., Levings, C.D., 2001. Effects of acid mine drainage from an abandoned copper mine, Britannia Mines, Howe Sound, British Columbia, Canada, on transplanted blue mussels (*Mytilus edulis*). Marine Environmental Research 51, 265–288.

Jeffrey, S.W., Humphrey, G.F., 1975. New spectrophotometric equations for determining chlorophylls a, b, c_1 and c_2 in higher plants, algae and natural phytoplankton. Biochemie und Physiologie der Pflanzen 167, 191–194.

Marsden, A.D., 1999. The effects of acid mine drainage at Britannia Beach, BC, on *Fucus gardneri* and associated intertidal algae. M.Sc. Thesis. University of British Columbia, Vancouver, Canada.

Marsden, A.D., DeWreede, R.E., 2000. Marine macroalgal community structure, metal content, and reproductive function near an acid mine drainage outflow. Environmental Pollution 110, 431–440.

Marsden, A.D., DeWreede, R.E., Levings, C.D., 2003. Survivorship and growth of *Fucus gardneri* after transplant to an acid mine drainage-polluted area. Marine Pollution Bulletin 46, 65–73.

McCandless, R.G., 1995. The Britannia Mine: Historic landmark or environmental liability? The BC Professional Engineer, April, 4–7.

Meech, J.A., Scoble, M., Wilson, W., Pakalnis, R., Klein, B., Veiga, M., Hall, R., Ghomshei, M., Baldwin, S., Lavkulich, L., Suttle, C., Mortensen, J., Weis, D., Smith, L., Hall, K., Dixon, D., Tromans, D., Dreisinger, D., Dunbar, S., Pawlik, M., Morin, M., Cullen, W., Teschke, K., Gibson, G., Ulansky, R., Hinton, J., Wickland, B., Bissiri, Y., Lang, B., 2003. CERM3 and its contribution to providing sustainable research for the mining industry. CIM Bulletin 96, 72–81.

Mills, C., 2003. The Former Britannia Mine, Mount Sheer/Britannia Beach, British Columbia. Retrieved on January 30, 2003 from the World Wide Web: http://www.infomine.com.

Ministry of Water Land and Air Protection, 2003. Britannia Mine Remediation Project: Background on Pollution and Remediation Issues. Retrieved February 5, 2003 from the World Wide Web: http://wlapwww.gov.bc.ca/sry/p2/britannia/background.htm.

Pellegrini, M., Laugier, A., Sergent, M., Phan-Tan-Luu, R., Valls, O., Pellegrini, L., 1993. Interactions between the toxicity of the heavy metals cadmium, copper, zinc in combinations and the detoxifying role of calcium in the brown alga *Cystoseira barbata*. Journal of Applied Phycology 5, 351–361.

Rainbow, P.S., 1987. Heavy metals in barnacles. Crustacean Issues 5. Barnacle Biology, 405–418.

Ralph, P.J., Burchett, M.D., 1998. Photosynthetic response of *Halophila ovalis* to heavy metal stress. Environmental Pollution 103, 91–101.

Rijstenbil, J.W., Derksen, J.W.M., Gerringa, L.J.A., Poortvliet, T.C.W., Sandee, A., Van Den Berg, M., Van Drie, J., Wijnholds, J.A., 1994. Oxidative stress induced by copper: defense and damage in the marine planktonic diatom *Ditylum brightwellii*, grown in continuous cultures with high and low zinc levels. Marine Biology (Berlin) 119, 583–590.

Varela, D.E., Barry, K.L., Guo, M., Piercey, G.E., Mehelenbacher, N.M., Harrison, P.J., Levings, C.D., 2000. Water quality and oceanographic data near a deep water outfall discharging acid mine drainage from Britannia Mine into Howe Sound, British Columbia. Canadian Data Report of Fisheries and Aquatic Sciences No. 1063.

Zar, J.H., 1999. Biostatistical Analysis. Prentice-Hall, Upper Saddle River, NJ.