Impact of mechanical clam harvesting on a benthic habitat: evaluation by means of sediment profile imaging

GUIDO BADINO\textsuperscript{a,}\textsuperscript{*}, FRANCESCA BONA\textsuperscript{a}, ALBERTO MAFFIOTTI\textsuperscript{b}, OTELLO GIOVANARDI\textsuperscript{c} and FABIO PRANOVI\textsuperscript{d}
\textsuperscript{a} Department of Animal Biology, University of Turin, via Accademia Albertina 17, 10123 Turin, Italy
\textsuperscript{b} Department of Environmental Impact Assessment ARPA, Turin, Italy
\textsuperscript{c} ICRM Chioggia, Venice, Italy
\textsuperscript{d} Department of Environmental Sciences, University of Venice, Calle Larga Santa Marta 2137, 30123 Venice, Italy

ABSTRACT

1. Manila clam (\textit{Tapes philippinarum}) harvesting in the Venice Lagoon has increased considerably in the last decade, owing to recently developed collection methods. However, these techniques have negative effects on benthic communities and on the structural and functional characteristics of the sediments.

2. A field survey was carried out in 2000 in the central basin of the Venice Lagoon to evaluate the efficacy of sediment profile imaging (SPI) in investigating disturbances caused by fishing activities and to compare the modifications of bottom sediments induced by different fishing gear (the ‘rusca’, currently used by local fishermen, and a rotating drum).

3. An environmental index, the organism–sediment index, derived from SPI analysis was applied. The efficacy of the SPI camera method in evaluating the disturbance of soft bottoms caused by clam harvesting was confirmed, as was the high degree of disturbance of sediment and benthic communities by mechanical clam harvesting.

4. The experimental hauls strongly modified the sediment features by resuspending the top layer of sediment and bringing the deep anoxic layer near the bottom. These effects could have a severe impact on the biogeochemical cycles and on the possibility of recolonization by benthic organisms in the short term. However, there was less disturbance when the rotating drum fishing gear was used.

KEY WORDS: clam harvesting; sediment quality; sediment profile imaging; benthic disturbance; Venice Lagoon

INTRODUCTION

Fishing is the most widespread method of exploiting marine resources (Jennings and Kaiser, 1998). However, it is currently recognized as a major threat to marine biodiversity (NRC, 1995) and, thus, is one

*Correspondence to: G. Badino, Department of Animal Biology, University of Turin, via Accademia Albertina 17, 10123 Turin, Italy. E-mail: guido.badino@unito.it

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of the most pressing issues in marine conservation. In recent years, scientists have focused on the impact of fishing disturbance on the trophic structure of marine communities. Indeed, the food web of exploited ecosystems is the product of both direct and indirect effects of fisheries, as well as oceanographic changes and cycles, pollution and other disturbances (Cloern, 2001; Jackson et al., 2001; Jennings et al., 2001). Minimization of the negative effects of fishing activities is considered an important component of fishery management plans in heavily exploited ecosystems (Benaka, 1999) and should be one of the main aims of management policies.

The Venice Lagoon is a ‘sensitive area’ affected by various kinds of human activity, such as industrial discharge, inland drainage, urban sewage, canal dredging and intensive fishing (Cossu and De Fraja Frangipane, 1985; Sfriso and Marcomini, 1999; Granzotto et al., 2001). Over the last decade, intensive harvesting of the alien bivalve Manila clam *Tapes philippinarum* (Adams and Reeve, 1850) has seriously threatened the lagoon ecosystem (Libralato et al., 2002; Pranovi et al., 2003a). *T. philippinarum* was introduced into the Venice Lagoon in 1983 (Cesari and Pellizzato, 1985) and quickly spread throughout the basin, replacing the autochthonous *Tapes decussatus* (Linnaeus, 1758). The success of *T. philippinarum* is due to its wide tolerance of several environmental conditions and its high reproduction rate.

About 600 boats are used for clam harvesting in the Venice Lagoon, operating in the absence of a real management policy (in a sort of free-access system of exploitation) (Provincia di Venezia, 1999). They use mechanical dredges (locally named ‘rusca’) which can substantially modify the characteristics of the sediment surface, with a severe impact on the benthic community. In 1997, a peak of 40 000 MT of Manila clams were collected in the lagoon (Provincia di Venezia, 1999). The impact of this activity on the seabed is enormous, involving the loss of fine sediment through resuspension (Pranovi and Giovanardi, 1994; Provincia di Venezia, 1999; Da Ponte, 2001). Clam harvesting directly or indirectly influences many other compartments of the lagoon ecosystem, such as seagrass meadows (*Cymodocea nodosa*, *Zostera* spp.) and fish reproduction (sea bream *Sparus auratus*, sea bass *Dicentrarchus labrax*, mullet *Liza* spp. and *Mugil* sp., sole *Solea solea* and flounder *Platichthys flesus*) (Libralato et al., 2002; Pranovi et al., 2003a).

Therefore, mechanical clam harvesting is now a major cause of environmental stress in the Venice Lagoon. For this reason, it would be useful to evaluate the possibility of new fishing gear to replace the currently used ‘rusca’, as part of a management policy to reduce the impact of this fishing activity on the lagoon ecosystem.

In the present study, sediment profile imaging (SPI) was used to investigate in situ the disturbance of lagoon sediments caused by mechanical clam harvesting. SPI allows a fine-scale analysis of physical, chemical and biological features (Smith et al., 2003), so it can give a detailed view of the possible changes induced by trawl fishing gear on the first bottom layers. Our aim was to evaluate the effects of mechanical clam harvesting on the benthic habitat by comparing the ‘rusca’ and an experimental prototype called ‘rotating drum’. This is one of the first applications of SPI to assess the impact of trawl fishing in the Mediterranean Sea (Rosenberg et al., 2003).

**METHODS**

The ‘rusca’ consists of an iron cage, 60 cm wide, with two sledges that prevent it from sinking into the sediment and a net bag that collects the clams. The digging action is produced by an outboard engine propeller located on the side of the boat; it forces water onto the sediment, suspending the clams which are then collected in the net bag. The rotating drum extracts clams from the sediment by means of three rows of iron teeth fitted on a drum; the clams are washed into the drum by the rotating action and then transferred to the boat by a conveyor belt. The boat is advanced by winching against an anchor.

This study was carried out in October 2000 in an area (100 m × 300 m, depth 0.7 m) of the central basin of the Venice Lagoon, on the east side of Sacca Sessola island. Before the experimental treatments, six random
stations were sampled (each with three replicates) with the SPI system (see details below). The area was then divided into two sections, one treated with the rotating drum (section ‘P’) and the other with the ‘rusca’ (section ‘R’).

Immediately after the clam harvesting, five stations in each section were sampled with SPI (three replicates); this was carried out using a sediment-profile camera apparatus, designed by AMBIO Srl for shallow waters and used in previous studies in the Venice Lagoon (Bona et al., 1994, 2000), equipped with a Minolta 9001 camera and standard photographic slide film (35 mm, 100 ASA).

SPI is a benthic sampling technique providing undisturbed, vertical cross-section photographs (profiles) of the upper 20–25 cm of the seafloor (Rhoads and Germano, 1982). SPI measurements were made via computer image analysis using a slide digitizer (Epson Perfect 1200 Photo) and specific software (Global Lab Image release 3, Data Translation Inc., 1994).

The range and major mode of sediment grain size were estimated from the photograph by overlaying a grain-size comparator based on the Udden–Wentworth size classes (Wentworth, 1922).

The apparent redox potential discontinuity (aRPD) depth, i.e. the boundary between the light aerobic near-surface sediment and the underlying grey to black hypoxic or anoxic sediment, was measured via computer image analysis. For the statistical analysis, two aRPD measures were considered: the minimum and mean value of each sediment profile. The minimum value is related to the presence of sediment surface anoxia, and the mean value is used to calculate the multivariable Organism–Sediment index (OSI). Benthic colonization was estimated from the sediment images, based on the theory of Pearson and Rosenberg (1976, 1978) adapted for SPI (Rhoads and Boyer, 1982; Rhoads and Germano, 1982). At the end of the image analysis, the multivariable OSI was calculated to characterize the quality of the benthic habitat. The OSI ranges from −10 (severely disturbed sediment with no macrofauna) to +11 (undisturbed sediment with mature benthic community) and is related to the successional stages of the benthic fauna, according to the model proposed by Pearson and Rosenberg (1978).

As shown in previous studies in the Venice Lagoon (Bona et al., 1994, 2000; Maffiotti and Bona, 1995), OSI values less than +3 indicate a disturbed habitat, values between +3 and +6 indicate intermediate quality (moderately disturbed), and values greater than +6 indicate an undisturbed benthic habitat.

To test for significant differences among the two treatment sections and control area, we performed a univariate analysis of penetration, minimum and mean aRPD depth and OSI with the non-parametric Wilcoxon test (comparison between the two treatments) and Kruskal–Wallis test (three-sample comparisons). We also carried out multivariate analyses of the following parameters: penetration, minimum, mean and maximum aRPD, and OSI. The data were Z-standardized to avoid effects due to range differences and then tested by discriminant analysis. All statistical analyses were performed with Systat version 10 (SPSS Inc., 2000).

RESULTS

In total, 48 sediment profile images were taken and analysed: 18 control, 15 section P (rotating drum), 15 section R (rusca). Figure 1 shows three examples of the images. Results for the main SPI metrics and statistical analyses are reported in Tables 1 and 2 and Figures 2 and 3.

Penetration

Penetration of the SPI camera into the sediment is inversely related to the compactness of the bottom (Rhoads and Germano, 1982). In the initial control samplings, the mean penetration depth was 23.66 ± 2.41 cm. The univariate statistics showed significant differences among the three groups (P = 0.008, d.f. = 2). After the ‘rusca’ dredging, the penetration depth decreased to 16.82 ± 0.93 cm, whereas it
remained roughly the same after the action of the rotating drum. The Wilcoxon test applied to the results for the experimental sections showed a significant difference ($P = 0.043$) in penetration depth after the two treatments.

**Grain size**

Grain size seemed to be unaffected by dredging, the prevailing fraction being clay in both treated areas. However, there was a slight shift towards coarser fractions in section R. These results agree with the Coulter counter analysis of sediment cores collected before and after the experimental hauls, which showed no significant difference in grain size (as percentage by weight) between layers of the same core or between treatments (Pranovi et al., 2003b).

**The aRPD depth**

In the control samplings, the mean aRPD depth was $3.34 \pm 0.44$ cm, indicating a low sediment oxygen demand and generally good conditions for infauna. None of the 18 control images showed ‘low DO’, an OSI metric signifying anoxia in the surface sediment.

Dredging modified the aRPD data, although the effect varied from station to station. Section-R stations showed a significant decrease of both the minimum and mean aRPD depths ($0.14 \pm 0.20$ and $0.37 \pm 0.27$ cm respectively); in one case, ‘low DO’ (surface anoxia) was detected. Section-P stations showed a smaller decrease in aRPD depth (minimum $0.46 \pm 0.30$ cm; mean aRPD: $2.30 \pm 1.63$ cm), corresponding to an index sub-value of 4. The high variability recorded in the rotating drum area should be noted.

**Benthic stage**

Control sediments were colonized by Stage I and Stage III organisms, with the presence of feeding voids and appreciable bioturbation by infauna (see Figure 1(a)).

In section R, benthic conditions became very critical. The prevailing stage was defined as ‘azoic’, with no benthic fauna activity being detectable (Figure 1(c)).
A significant benthic community deterioration was also recorded in section P (Figure 1(b)). The benthic fauna was limited to the surface sediment except for station P05, where sediment conditions were similar to those of the control samplings.

Table 1. Mean values and standard deviations (or range) for sediment penetration, grain size, aRPD depth, benthic stage, and OSI

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean penetration (cm)</th>
<th>Grain size range</th>
<th>aRPD (cm)</th>
<th>Benthic stage range</th>
<th>OSI mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modal value</td>
<td>Range</td>
<td>Min</td>
<td>Mean</td>
<td>Modal value</td>
</tr>
<tr>
<td><strong>Reference site</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>REF01</td>
<td>26.22</td>
<td>I</td>
<td>I–II</td>
<td>0.29</td>
<td>3.84</td>
</tr>
<tr>
<td>REF02</td>
<td>25.18</td>
<td>I</td>
<td>I–II</td>
<td>0.64</td>
<td>3.90</td>
</tr>
<tr>
<td>REF03</td>
<td>24.59</td>
<td>I</td>
<td>I–II</td>
<td>1.27</td>
<td>3.06</td>
</tr>
<tr>
<td>REF04</td>
<td>19.29</td>
<td>II</td>
<td>I–II</td>
<td>0.40</td>
<td>3.03</td>
</tr>
<tr>
<td>REF05</td>
<td>23.45</td>
<td>I</td>
<td>I–II</td>
<td>1.10</td>
<td>2.86</td>
</tr>
<tr>
<td>REF06</td>
<td>23.22</td>
<td>I</td>
<td>I–II</td>
<td>0.64</td>
<td>3.32</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>23.66</td>
<td>–</td>
<td>0.72</td>
<td>3.34</td>
<td>–</td>
</tr>
<tr>
<td><strong>St dev/range</strong></td>
<td>2.41</td>
<td>I–II</td>
<td>0.39</td>
<td>0.44</td>
<td>I–III</td>
</tr>
<tr>
<td><strong>Section R</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A01</td>
<td>15.36</td>
<td>I</td>
<td>I–II</td>
<td>0.12</td>
<td>0.29</td>
</tr>
<tr>
<td>A02</td>
<td>17.44</td>
<td>I</td>
<td>II</td>
<td>0.06</td>
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<tr>
<td>A03</td>
<td>16.40</td>
<td>I</td>
<td>I–II</td>
<td>0.03</td>
<td>0.25</td>
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<tr>
<td>A04</td>
<td>17.56</td>
<td>I</td>
<td>I–II</td>
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<tr>
<td>A05</td>
<td>17.33</td>
<td>I</td>
<td>II–III</td>
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<tr>
<td><strong>Mean</strong></td>
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<td></td>
<td>0.14</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td><strong>St dev/range</strong></td>
<td>0.93</td>
<td>I/III</td>
<td>0.20</td>
<td>0.27</td>
<td>AZOIC/I</td>
</tr>
<tr>
<td><strong>Section P</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B01</td>
<td>24.95</td>
<td>I</td>
<td>I–II</td>
<td>0.12</td>
<td>0.40</td>
</tr>
<tr>
<td>B02</td>
<td>25.41</td>
<td>I</td>
<td>I–II</td>
<td>0.58</td>
<td>3.18</td>
</tr>
<tr>
<td>B03</td>
<td>25.99</td>
<td>II</td>
<td>I–II</td>
<td>0.17</td>
<td>0.66</td>
</tr>
<tr>
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<td>23.33</td>
<td>I</td>
<td>II</td>
<td>0.75</td>
<td>3.69</td>
</tr>
<tr>
<td>B05</td>
<td>20.21</td>
<td>II</td>
<td>II</td>
<td>0.69</td>
<td>3.58</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>23.98</td>
<td></td>
<td>0.46</td>
<td>2.30</td>
<td></td>
</tr>
<tr>
<td><strong>St dev/range</strong></td>
<td>2.33</td>
<td>I/I–III</td>
<td>0.30</td>
<td>1.63</td>
<td>I/I–III</td>
</tr>
</tbody>
</table>

Table 2. Univariate statistics (nonparametric Kruskal–Wallis test between the three groups and nonparametric Wilcoxon test between the two treatments) for sediment penetration, aRPD, and OSI

<table>
<thead>
<tr>
<th>Variable</th>
<th>Kruskal–Wallis test</th>
<th>Wilcoxon test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>d.f.</td>
<td>KW</td>
</tr>
<tr>
<td>Penetration</td>
<td>2</td>
<td>9.771</td>
</tr>
<tr>
<td>RPD min</td>
<td>2</td>
<td>7.292</td>
</tr>
<tr>
<td>RPD mean</td>
<td>2</td>
<td>8.765</td>
</tr>
<tr>
<td>OSI</td>
<td>2</td>
<td>10.710</td>
</tr>
</tbody>
</table>

A significant benthic community deterioration was also recorded in section P (Figure 1(b)). The benthic fauna was limited to the surface sediment except for station P05, where sediment conditions were similar to those of the control samplings.
The OSI values were very high in the control samplings (mean $10.17 \pm 0.75$), due to the high sediment oxygenation (deep aRPD, no ‘low DO’, no bubbles of reduced gas) and extensive benthic colonization. In contrast, OSI values in section R varied from $-3$ to $+3$ (mean $0.25 \pm 2.22$). The disturbance was not as great in the rotating drum section, with OSI values ranging from $2$ to $10$ (mean $4.00 \pm 2.31$).
Nonparametric comparisons showed that the three groups of stations differed significantly; the difference between the two harvested sections was also significant (Table 2).

**Multivariate analysis**

Figure 3 shows the results of the discriminant analysis of a set of four variables (penetration, minimum aRPD depth, mean aRPD depth, OSI). Stations appear to be well grouped, and there is complete correspondence between predicted and observed group assignments, with the exception of one station belonging to section P. Axes 1 and 2 explain more than 94% of the total variance and are significantly (and negatively) correlated with OSI and penetration depth respectively.

**DISCUSSION**

SPI is a method to observe and quantify *in situ* the net result of animal–sediment relationships without disrupting the organism–sediment coupling. Used for the study of disturbance by fishing gear (mechanical clam harvesting), it allows the description of changes in the benthic habitat which mediate the indirect effects on benthic organisms and subsequent recolonization dynamics.

The control samples revealed a number of features typical of an advanced successional assemblage, such as high bioturbation of the sediment profile and a deep aRPD. These factors are reflected in the high OSI values, amongst the highest recorded in the Venice Lagoon (Maffiotti and Bona, 1995; Bona *et al*., 2000).

The comparison between the control and treatment areas confirmed the view that demersal fishing gear causes significant changes to sediment habitats. As highlighted by Nilsson and Rosenberg (2003) and Rosenberg *et al*., (2003), trawling and dredging reduce the benthic habitat quality indices, reflecting the combined effects on surface structures, subsurface structures and redox conditions.

Our data for the Venice Lagoon confirm the results of earlier SPI studies (Lindeboom and de Groot, 1998; Smith *et al*., 2003) showing that trawling decreases the roughness of the seabed and increases its compaction: the penetration was significantly lower immediately after the treatment in both the experimentally dredged areas (indicating more compact sediments). Moreover, there was a shallower aRPD in images taken from treated areas with a disturbed sediment surface, in agreement with the findings of Nilsson and Rosenberg (2003).

Changes in sediment compactness and oxygenation will alter the magnitude and rate of biogeochemical cycling (e.g. fluxes of nitrogen and phosphorus between sediment and the overlying water) and may influence the structure and dynamics of the micro-, meso- and macro-benthic communities. Depletion of the oxidized sediment layer, recorded after the experimental dredging, could be an obstacle to reburrowing by infaunal organisms displaced by the fishing gear.

The direct effects of the fishing gear on the macrobenthic community were assessed on the basis of the successional stages theory (Pearson and Rosenberg, 1978; Rhoads and Boyer, 1982). After the experimental dredging, the bottom sediments were classified as 'azoic' or 'stage I'. These results are consistent with those reported by Pranovi *et al*., (2003b), who compared samples collected before and immediately after the experimental haul and found a significant decrease in the total abundance of macrobenthic organisms. Moreover, the results seem to confirm that the harvesting gear causes both direct and indirect effects extending to a depth of about 10 cm, i.e. beyond the gear digging depth (about 7 cm; Pranovi *et al*., 2003b).

The univariate and multivariate analyses showed significant differences among the three areas; the section dredged with the rotating drum is clearly situated between the other two along axis 1, which is correlated with the OSI values. This suggests that adoption of the rotating drum instead of the ‘rusca’ could mitigate the environmental changes. However, the catch efficiency ratio between the ‘rusca’ and rotating drum is about 3:1 (Pranovi *et al*., 2001), which means that a fisherman using the latter would have to sweep
an area three times as large in order to achieve the catch level of the ‘rusca’. This would probably result in a comparable total impact.

In the long term, mechanical clam harvesting could have negative effects on the entire Venice Lagoon and destabilize the sediments throughout the area. Resuspension of the top sediment layer could aggravate the natural erosion of shallow bottoms, which is currently a major topic in plans for protection of the Venice Lagoon (Consorzio Venezia Nuova, 1996).

The current study confirms that SPI is a useful tool to study the disturbance caused by demersal fisheries (Nilsson and Rosenberg, 2003), as it is a rapid method to record the direct and indirect physical impact on the bottom fauna. It could be used on a mesoscale to map the sediment status of the clam-harvesting grounds and to obtain useful information for future fishery management plans.

Moreover, use of the SPI approach (mainly with time-lapse cameras; see Solan and Kennedy (2002)) to test changes in bottom sediments induced by demersal fishing gear could add an interesting perspective to studies of the recolonization processes and dynamics.

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REFERENCES


