Can plankton communities be considered as bio-indicators of water quality in the Lagoon of Venice?

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Abstract

This study examines whether plankton of the Lagoon of Venice could be considered as a bio-indicator of areas subjected to various anthropogenic influences. This study was a two year hydrochemical and biological survey in five areas of the Lagoon of Venice, each with different environmental conditions due to pollution from urban, industrial, thermal and agricultural wastes. Phytoplankton associations did not show any promising species. In the different lagoonal areas, this community was differentiated into its major groups. In contrast, the copepod Acartia tonsa Dana could be considered as a target species in highly eutrophic areas.

Keywords: Anthropogenic pollution; Hydrology; Nutrients; Plankton; Bio-indicators; Lagoon of Venice

1. Introduction

In brackish-water ecosystems, planktonic populations are well-known to be influenced by space–time variations in hydrochemical parameters and tidal dynamics (UNESCO, 1981; Cloern et al., 1989). Anthropogenic activities often generate further effects (Campesan et al., 1981; Sorokin et al., 1996; Collavini et al., 2001), which also interfere to a greater or lesser extent with the ecosystem. The Lagoon of Venice receives several types of inputs: urban, industrial and thermal effluents, and agricultural run-off (Perin, 1975; Cironi et al., 1993; Collavini et al., 2001). These have produced significant variations in the trophic state of the ecosystem in question, sometimes accompanied by alterations in specific biological populations. As regards plankton, algal blooms have been described in the central and northern basins of the Lagoon (Voltolina, 1973; Alberighi et al., 1992; Socal et al., 1999), while one species of zooplankton (Acartia tonsa Dana) has undergone explosive increases in numbers, especially in the innermost areas of the Lagoon (Comaschi and Cavalloni, 1995; Comaschi et al., 2000). The question therefore arises as to whether planktonic organisms in the Lagoon can be exploited as bio-indicators of water quality.

Aiming to answer this question, a research program started since 1997. This study consisted of two years of observations in the Venice lagoon, to follow the space–time variations of plankton populations in areas subjected to anthropogenic influences.

2. Materials and methods

Sampling stations, located in the northern and central basins of the Lagoon of Venice (Fig. 1) were chosen so that each one was representative of the variety of habitats subjected to contamination:

- Station 1, S. Giuliano, collects urban waste from the town of Mestre, where phytoplankton blooms often develop (Bianchi et al., 1996; Socal et al., 1999);
- Station 2, Marghera, is influenced by polluting substances of industrial origin (Perin, 1975);
- Station 3, Fusina, is affected by heat emissions from the thermo-electric power plant at Portomarghera (Alberighi et al., 1992; Socal et al., 1999);
- Station 4, Lido, the northernmost inlet of the lagoon, is characterized by Adriatic coastal waters influence;
Station 5, Palude, in the inland marshy area called Palude della Rosa, is a typical lagoonal environment, influenced both by fresh waters entering from the Silone channel and, to a lesser extent, by waters transported this far by tide (Bianchi et al., 1999).

Samples were collected monthly from May 1997 to April 1999. In addition, sampling was carried out every two weeks during summer 1998, to follow intensified biological activity in greater detail. At every station, measurements and sampling were carried out on the surface, at neap tide, in order to minimize the effect of tidal hydrodynamics. The total number of surveys was 30.

The following parameters were measured: transparency, with a Secchi disk; temperature, by a bucket-thermometer; salinity, with a Guildline Autosal laboratory salinometer; dissolved oxygen, according to Winkler’s method; dissolved nutrients (ammonia, nitrates and nitrates, orthophosphates and orthosilicates), filtered through Whatman GF/F fiberglass filters (porosity = 0.7 μm) and analysed with a Systea-Alliance auto-analyser, according to the methods generally indicated by Strickland and Parsons (1972) and Hansen and Koroleff (1999); chlorophyll \(a\), assessed according to Holm-Hansen et al. (1965), after filtering through Whatman GF/F filters and measurement of the acetone extract before and after acidification by means of a Perkin Elmer LS5B spectrofluorometer; particulate organic carbon (POC) and nitrogen (PN), determined on Whatman GF/F filters after elimination of inorganic carbon by HCl, with a Perkin Elmer 2400 CHN elemental analyser, according to Hedges and Stern (1984); phytoplankton, fixed in neutralized formalin and counted on an inverted microscope.

Fig. 1. Lagoon of Venice: sampling stations.

3. Results

3.1. Hydrology, nutrients and particulate matter

Water transparency was minimal at station 1 (S. Giuliano) and at station 5 (Palude); this was attributed respectively to freshwater inputs and intense shipping movement which cause resuspension of bottom sediments (st. 1) and to draining caused by tides on boundary shoals (st. 5). Maximum transparency was found at coastal station 4 (Lido; Table 1). The influence of warm wastewater was observed at station 3 (Fusina), due to the proximity of the thermo-electric power plant, and station 2 (Marghera), located along the same main channel (Table 1). As regards salinity, diluted waters were found mainly at S. Giuliano, Fusina and Palude, due to the presence of freshwater channels draining water from inland (Table 1). Lido and Marghera had typically marine-coastal salinity value (respective averages = 32.8 and 29.2 PSU, with a range of 22.6–36.2 PSU).

Dissolved oxygen saturation percentages were on average higher at Marghera (118%), with peaks exceeding 170% in summer 1998, when phytoplankton blooms occurred. Fusina had values around 100%, similar to results found during previous studies (Bianchi et al., 1996). At S. Giuliano, oxygenation was on average under saturation levels (range = 67–141%; Table 1), probably due to the resuspension of anoxic sediments, caused by shipping, and/or to the degradation processes of suspended organic matter present in great quantity.

Concentrations of dissolved nutrients stayed at low levels at Lido (Table 1), whereas loads were significantly greater in the innermost areas. The terrigenous origin of orthosilicates was evident at S. Giuliano and Palude (means higher than 50 μM). Total dissolved inorganic nitrogen (DIN, as sum of ammonium, nitrite and nitrate) showed peaks corresponding to the areas subjected to industrial, urban and agricultural wastes, DIN values being very high at Fusina, Marghera, S. Giuliano and Palude (Table 1). The nitrate form always prevailed, with mean percentages varying between 60% (S. Giuliano) and 79% (Lido); ammonia ranged between 17% (Lido and Palude) and 35% (S. Giuliano). Similarly, orthophosphates were higher in the industrial (Marghera) and urban (S. Giuliano) areas, where an absolute
peak of 7.9 µM was measured; minima were observed at Lido and Palude.

POC and PN concentrations were very high at S. Giuliano, with intermediate values at Marghera, Fusina and Palude (Table 1). Chlorophyll $a$ had the same behaviour (Table 1). At Marghera, a maximum of 71.7 µg chl $a$ dm$^{-3}$ was measured in July 1998, resulting from a community of nanoflagellates with abundances exceeding $7 \times 10^6$ cell dm$^{-3}$. At Lido, chlorophyll $a$ concentrations typical of Northern Adriatic coastal waters were measured (mean = 2.0 µg dm$^{-3}$), whereas Palude and Fusina had more or less similar means, around 5-6 µg dm$^{-3}$. POC/chlorophyll ratios exceeded 200 in all stations, highlighting how the contribution of the biogenic detritus to organic particulates was high.

### 3.2. Phyto- and zooplankton abundances and taxonomy

The phytoplankton component revealed abundances which were on average higher at S. Giuliano and Marghera (Table 1, Fig. 2); the minimum of $124 \times 10^3$ cell dm$^{-3}$ was found at Lido.

The interannual variability of phytoplankton appeared very high everywhere, being abundance trends quite heterogeneous in time and space (Fig. 2). Qualitatively, phytoplankton was mainly composed of diatoms (mean...
values ranged from 52% to 74% of total), except at Marghera, where microflagellates prevailed (avg = 52% of total; Fig. 2). Other classes were found occasionally: coccolithophorids, typical of marine environments, were mainly observed at Lido, but always in very small percentages (max 1%). Chlorophyceans and euglenophyceans, typical freshwater forms, were found in stations influenced by inputs from the innermost areas. The phytoplankton populations of Palude were typically both marine and brackish, confirming the transitional nature of this area. During summer, S. Giuliano and Palude had diatom blooms in both 1997 and 1998. At S. Giuliano in June 1997, 92% of the phytoplankton was composed of *Chaetoceros cfr. compressus* (21 × 10⁶ cell dm⁻³) and *Cylindrotheca closterium* (29 × 10⁶ cell dm⁻³), whereas, in June 1998, 70% of the total was represented by *Thalassiosira* sp. (22 × 10⁶ cell dm⁻³). In Palude, in August–September 1997 and 1998, a *Nitzschia frustulum* bloom was observed, with abundances respectively of 30 × 10⁶ and 15 × 10⁶ cell dm⁻³.

Analysis of population structure, carried out by applying Margalef’s diversity index (Margalef, 1957), gave further information on water quality. The seasonal trends of this index (Fig. 3) were more or less similar in all stations: (i) Marghera almost always had lower diversity values, revealing a reduction in total species numbers; (ii) Lido showed a more constant seasonal trend, with no dominance on the community; (iii) the trend at Fusina underwent a decrease in diversity during winter, probably due to a community adapted to the increased temperatures influenced by a thermal waste.

Zooplankton data (Table 1) shows that: (i) the mean of numerical abundances was very high at S. Giuliano, followed by Lido; (ii) peaks were observed at S. Giuliano (21,205 ind m⁻³) and Palude (11,506 ind m⁻³), the nearest areas to the edge of the lagoon; (iii) the taxonomic composition of zooplankton was almost exclusively represented by the copepod *A. tonsa*, except for Lido, where the congener *Acartia clausi* had higher numerical abundances (Fig. 4); (iv) time trends closely followed temperature trends (Fig. 4), both as regards total zooplankton and its major constituent, *A. tonsa*; (v) while the typical high trophic state of Marghera indicated that zooplankton abundances should have been high, observed values were far lower, only reaching a mean of 308 ind m⁻³ and a peak of 1644 ind m⁻³.

3.3. Statistical analyses

In order to highlight relations existing between environmental parameters and biological populations, the data set of 14 variables, for a total of 136 samples, was statistically processed.

To order the variables, a principal components analysis (PCA R-mode) was applied, resulting in a series
of eigenvalues, of which the first two overall explained more than 60% of the total variance—a highly significant percentage, considering that biological variables also occurred in the examined system (Clarke and Warwick, 1994). The contribution of each variable is shown in Table 2: in the first component, chlorophyll, POC, PN, phytoplankton and temperature had a positive influence; in the second, salinity positively, and nitrates, phosphates, ammonia and nitrates negatively. These variables fell in the plane of the first two principal components, identifying three groups: (A) relative oxygenation, zooplankton, temperature, phytoplankton, chlorophyll, POC and PN; (B) salinity and transparency; (C) dissolved nutrients (Fig. 5). Substituting single observations to the variables, the following may be observed in the same ordering model (Fig. 5): group A contains samples from S. Giuliano, Marghera, Fusina and Palude, collected from May to September; group B contains all observations at Lido in all seasonal situations, together with some in winter at Fusina and Palude; group C includes samples from S. Giuliano and Marghera in winter, together with the remaining winter

Table 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>I component</th>
<th>II component</th>
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<tbody>
<tr>
<td>Transparency</td>
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<td>0.510</td>
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<tr>
<td>Temperature</td>
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<tr>
<td>Salinity</td>
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<tr>
<td>Relative oxygen</td>
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<td>0.537</td>
</tr>
<tr>
<td>N–NH₃</td>
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<td>-0.742</td>
</tr>
<tr>
<td>N–NO₂</td>
<td>0.049</td>
<td>-0.836</td>
</tr>
<tr>
<td>N–NO₃</td>
<td>-0.312</td>
<td>-0.707</td>
</tr>
<tr>
<td>Si–SiO₄</td>
<td>-0.240</td>
<td>-0.531</td>
</tr>
<tr>
<td>P–PO₄</td>
<td>0.111</td>
<td>-0.764</td>
</tr>
<tr>
<td>POC</td>
<td>0.868</td>
<td>-0.136</td>
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<td>PN</td>
<td>0.898</td>
<td>-0.096</td>
</tr>
<tr>
<td>Chlorophyll a</td>
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</tr>
<tr>
<td>Phytoplankton</td>
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</tr>
<tr>
<td>Zooplankton</td>
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<td>0.367</td>
</tr>
</tbody>
</table>

Fig. 5. Principal components analysis: ordination model, with rotation of Varimax axes, of variables (above) and stations (below), in plane of first two principal components. Three main groups (A, B and C) are identified.
Table 3
Ridge regression analysis

<table>
<thead>
<tr>
<th>Dependent variables</th>
<th>Variables related with dependent ones</th>
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<tr>
<td>Phyttoplankton</td>
<td>Temperature, Salinity, DIN</td>
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<tr>
<td>$F = 8.578$, df = 5, 136, $p \leq 0.0001$</td>
<td>0.263, $-0.150$, $-0.100$, $-0.080$, 0.042</td>
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<tr>
<td>Copepods</td>
<td>Temperature, Salinity, POC, PN</td>
</tr>
<tr>
<td>$F = 7.375$, df = 4, 139, $p \leq 0.0001$</td>
<td>0.197, 0.026, 0.085, 0.118</td>
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<tr>
<td>Acartia clausi</td>
<td>Temperature, Salinity, POC, PN</td>
</tr>
<tr>
<td>$F = 2.314$, df = 4, 139, $p = \text{not sign.}$</td>
<td>0.106, 0.109, $-0.480$, 0.287</td>
</tr>
<tr>
<td>Acartia tonsa</td>
<td>Temperature, Salinity, POC, PN</td>
</tr>
<tr>
<td>$F = 18.355$, df = 4, 139, $p \leq 0.0001$</td>
<td>0.261, $-0.030$, 0.136, 0.158</td>
</tr>
</tbody>
</table>

$F$-test values, degrees of freedom (df) and significance levels ($p$) shown for each dependent variable (left). Bold type: variables with coefficient values significantly correlated with respective dependent variables.

observations at Fusina and Palude. These results indicate that temperature and salinity are the main factors contributing to the distribution of plankton in the Lagoon of Venice. This is shown by: (i) the cycle of both phyto- and zooplankton, found abundantly in less transparent and less salty waters, is linked to temperature; (ii) nutrients in diluted, colder and less transparent waters make up a separate group.

However, the set of variables making up environmental characterization often do not act independently, generating self-correlation phenomena: to avoid this, some authors recommend applying a ridge regression analysis (Draper and Smith, 1981), the results of which are shown in Table 3. Interesting confirmations and observations derived from it include: (i) phytoplankton depends positively on temperature, again demonstrating the seasonality of its cycle, and negatively on salinity and DIN, showing the greater affinity for diluted waters and its uptake towards this nutrient; (ii) zooplankton: the main group of copepods is only sensitive to temperature, a parameter which heavily influences its lifecycle (however, not all species belonging to this group behave in the same way); (iii) *A. clausi* does not appear to depend either on fundamental hydrological variables or on organic particulates, which do not constitute its preferential source of food; (iv) instead, *A. tonsa* is heavily dependent on temperature and, as a trophic resource, on organic particulates.

4. Discussion and conclusions

The ecosystem consisting of hydrochemical and biological variables of the Lagoon of Venice is extremely complex, partly due to the strong influence of the many different sources of pollution—industrial, thermal, urban and agricultural—as well as the intensity of tidal inflow and outflow. In this frame, chemical parameters, considered independently, may not be sufficient to furnish a complete picture of the environment. Therefore, examination of biological components, in this case plankton, may supply further elements determining the quality of lagoon waters.

Our results show that the most eutrophic stations are those heavily influenced by urban (S. Giuliano) and industrial inputs (Marghera and, to a lesser extent, Fusina), with high concentrations of dissolved nutrients and organic particulates. Large-scale trophic oscillations were found at Palude, greatly influenced both by run-off waters from surrounding land, mainly under intensive agriculture, and by the incoming tidal flow, which makes saltier waters reach these more distant parts (salinity maximum here = 31.7 PSU). A medium/low trophic level has always been observed at the marine station of Lido, where typical coastal waters of the northern Adriatic were found.

Examination of biological components, such as plankton, may supply further elements determining the quality of lagoon waters. As regards phytoplankton, its abundance, closely depending on nutrient distribution, turned out to be an indirect index of water trophism. In the course of the sampling period, no species prevailed in highly trophic areas, and when algal blooms occurred, they had a point source, did not last very long, and were often composed of various organisms. Species diversity supplied useful elements characterizing the five stations. The Margalef’s index appliance showed: (i) peaks in winter–spring and minima in summer; (ii) a flattening at Lido, signal of a well-balanced community, with no particular species prevailing; (iii) low diversity at Fusina in winter, probably due to the constantly warmer water, which influences taxonomic compositions; (iv) a reduction of diversity at Marghera, accompanied by different species composition, mainly represented by microflagellates.

As regards zooplankton communities, in this study the largest abundances were observed in the innermost area (Palude). The unusually high values were due to the massive presence of *A. tonsa*, a recent arrival here (Comaschi and Cavalloni, 1995; Comaschi et al., 2000), which numerically dominated the samples collected in the more internal stations. Other studies (Roman, 1984;
Paffenhofer and Stearn, 1988; Bianchi et al., 1999) show that the life-cycle of this copepod closely depends on the quantity of food available and that, the greater the trophic supplies, the more growth is accelerated. When the physical–chemical conditions of the waters show coastal features, abundances of *A. tonsa* decrease, and the congener *A. clausi*, which has greater affinity for these waters, occupy the area of distribution, as demonstrated by our data.

A minimal quantity of zooplankton was recorded at Marghera. In view of the high trophic load found here, it was reasonable to expect explosive growth of opportunistic species, but this did not occur. We believe that, in this area, polluting substances of industrial origin interfere with the life-cycle of zooplankton and of some phytoplankton groups, such as diatoms. Toxic substances detected in this site include mainly heavy metals and polyaromatic hydrocarbons (i.e. some average data measured at Marghera in May 1993 in flood and ebb tide: 1.8–2.5 μg Cu dm⁻³, 11.0–23.5 μg Zn dm⁻³; Cleary et al., 1999). Their effects on the plankton associations, despite the wide natural variability of the biological response, cannot be neglected.

Among phytoplankton, diatoms, in spite of the heterogeneous sensitivity which several classes (and several species inside the same class) show towards various kinds of toxic substances (Walsh, 1986), present high mortality towards organotin compounds (Walsh et al., 1985), pesticides (Walsh, 1983) and heavy metals such as Cu and Cd (Visviki and Rachlin, 1991). Consequently, the reduced numbers of diatoms in the samples from Marghera may be ascribed to the presence of one, or more, polluting substances. For microflagellates, highly abundant at Marghera, it should be recalled that this category comprises many taxonomic groups, small in size, difficult to identify under the microscope, and belonging to various classes, each of them with a different sensitivity level. Because of the few literature data on the biological response of microflagellates towards toxic compound (these organisms are not used as targets in toxicity tests), it is difficult to make hypotheses regarding their sensitivity. The low species diversity observed at Marghera highlighted that microflagellates are less affected by situations of environmental stress—unlike diatoms, the relative abundances of which are reduced.

*Acartia tonsa*, the dominant species in the inner Lagoon, is a widely studied organism in ecotoxicology, due to the important role played by copepods in marine and brackish-water ecosystems (Sosnowski and Gentile, 1978; U’ren, 1983; Tester and Costlow, 1981). The acute and chronic effects caused by some heavy metals on this organism have been studied in similar estuarine ecosystems, like Chesapeake Bay (Sunda et al., 1990), where high concentrations of Zn and Cu, comparable to those of the Lagoon of Venice (Cleary et al., 1999), are responsible for the high mortality of *A. tonsa* populations exposed to them.

In conclusion, our data suggested that the plankton in the Lagoon of Venice could be considered as a bio-indicator of water quality in several areas subjected to anthropogenic disturbance. Among zooplankton, the target species identified is *A. tonsa*, generally found in large numbers in eutrophic waters. Its scarce presence in the industrial area is probably caused by a depression of its life-cycle induced by different polluting substances. Further studies need to confirm this assessment. The situation of phytoplankton is different. Although no particular species emerges, phytoplankton species composition is equally interesting as bio-indicator. On one hand, high trophic levels favour massive explosions of single species (blooms), while, on the other, the presence of industrial wastes may inhibit the growth of some taxonomic group (e.g. diatoms), highlighting increasing percentages of other classes (microflagellates).

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**References**


