MULTIVARIATE ANALYSIS OF COMMUNITY STRUCTURE OVER TEN YEARS FOLLOWING THE *EXXON VALDEZ OIL SPILL*

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ABSTRACT: *A 1990/1991 shoreline ecology program to assess the fate and effects of the Exxon Valdez oil spill in Prince William Sound was updated in 1998 and 1999. This update included a sediment sampling program for organisms at "worst case" sites and at randomly chosen reference sites. Correspondence analysis (CA), a statistical method that examines animal communities in terms of their similarity, was used to define community structure Statistical analysis of the degree of similarity between communities was used to assess effects of site-specific variables (sediment grain size, total organic carbon (TOC) and wave energy), interannual variation, and degree of oiling. Interannual variability had a significant effect on community structure, whereas site specific variables and degree of oiling did not. Differences in communities between 1998 and other years were particularly dramatic. The importance of interannual change demonstrates the importance of multi-year sampling and of appropriate study designs for separating impact effects from the natural occurring environmental factors which affect biological communities.*

Introduction

The March 24, 1989 grounding of the *Exxon Valdez* on Bligh Reef in Prince William Sound (PWS), Alaska, resulted in the release of approximately 258,000 barrels (35,500 metric tons) of Alaska North Slope (ANS) crude oil into the marine environment (Maki, 1991). Approximately 40 percent of the spilled oil stranded on the shores of the sound (Wolfe et al., 1994).

Prince William Sound is an estuarine embayment of the Gulf of Alaska with numerous rugged islands and a mountainous coastline dissected by deep fjords. Prince William Sound is subject to a harsh sub-arctic environment with wide temperature fluctuations (average temperatures range from -12°C in the winter to 20°C in the summer), large tidal range (~5 m), high precipitation (up to 6 m/y), and frequent severe (September to April) storms. A small number of resilient plants and animals, such as rockweed, mussels, barnacles, and littorine snails are abundant and widespread in the intertidal zone. They play a major role in determining the structure of the entire intertidal community (O'Clair and Zimmerman, 1987). Intertidal communities in the sound also are exposed to cyclical changes in temperature and salinity that may produce substantial ecological changes (Muter *et al.*, 1994; Parker *et al.*,1995; Trenberth and Hoar, 1995).

There are 4 major shoreline habitat types in western Prince William Sound, the area affected by the spill: exposed bedrock/rubble; sheltered bedrock/rubble; boulder/cobble beaches; and pebble beaches.

Approximately 16% of the total shoreline of the sound was oiled to some degree in 1989 (Maki, 1991; Neff *et al.*, 1995). As in most oil spills, the shoreline was very discontinuously oiled, with most of the oiling classified as light (< 3m oil band). The length of oiled shoreline decreased from 486 miles in 1989 to approximately 8.7miles in 1993, with 92% of the oiling being very light (< 10% oil coverage). Heavily oiled shoreline areas (> 6m oil band) decreased from 87 miles in 1989 to approximately 0.07 miles in 1993 as a result of cleanup operations and natural processes of recovery, particularly severe storms (Neff *et al.*, 1995).

The shoreline ecology program (SEP) performed in 1990 and 1991 (Boehm *et al.*, 1995; Gilfillan *et al.*, 1995; Page *et al.*, 1995b) included a non-random sampling program in 1990 and 1991, in which heavily oiled sites of special "worst-case" concern were sampled to assess oil persistence and worst-case effects. There was a rapid and ongoing decrease in petroleum concentrations in intertidal sediments at heavily oiled study sites. By 1991, biological effects persisted only at a small number of boulder/cobble (B/C)"worst case" locations, where the initial oiling was very heavy and the substrate was protected by boulder armor from the scouring action of severe storms. Measurements of sediment toxicity performed as part of the 1990 and 1991 SEP showed that, by 1991, the oil had weathered to the point where it was no longer toxic to benthic fauna (Boehm *et al.*, 1995). Neff *et al.* (1995) estimated that there was an approximately 75% overall decrease in surface and subsurface oil *each year* between 1989 and 1993. This yields an estimated environmental half-life of 5 months and is in the range of measured environmental half-life values for oil loss in the spill zone reported by Boehm *et. al.* (1995).

The purpose of this paper is to assess the relative importance of natural and oil spill effects on community structure over a ten year period, 1990 - 99. We used Correspondence Analysis (CA) (Ter Braak 1986 a,b) to define community structure. CA compares samples according to taxonomic composition. CA compares communities in 2 contrasting ways (Axis 1 and Axis 2). Each sample is assigned a score on each of the axes. Samples with similar compositions will lie close together on each axis. Scatter plots for the 2 axes were created and grouped by year. CA was carried out using CANOCO for the Macintosh (Microcomputer Power, 111 Clover Lane, Ithaca, NY 14850). Density ellipses are used to visually interpret changes in communities over years. Scores on each axis are analyzed with multivariate and univariate analysis of variance (MANOVA and

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ANOVA, respectively) to test effects of site-specific variables, years, and degree of oiling on community structure.

Study design and methods

A shoreline chemistry and biology program was performed in June 1998 (Page *et al.,* 1999) and July of 1999 (Gilfillan *et al.,* 2000) to update the 1990-1991 SEP in a quantitative manner. The sampling plan and field and analytical methods were the same as those in the 1990, 1991 and 1998 SEP as described in detail elsewhere (Gilfillan *et al.,* 1995; Page *et al.,* 1995a,b). Figure 1 shows the locations of the sampling sites that were studied in 1990, 1991, 1998 and 1999.

At each sampling site, only the intertidal stations were sampled. At each site, quantitative samples of sediments under the overlying B/C armoring were sampled along three transects perpendicular to the shoreline and 10 m apart at the upper, middle, and lower intertidal zone. Separate sediment samples were collected for chemistry and biology at each sampling location and stored in precleaned plastic jars.

Biological sampling was performed as described by Gilfillan *et al.* (1995). The population density of those species found in more that 20% of the samples in each of the 4 years sampled was analyzed using Correspondence Analysis (CA), and multivariate and univariate Analysis of Variance (MANOVA, ANOVA). The species constituting the groups that were analyzed have been described elsewhere (Gilfillan et al., 2001).

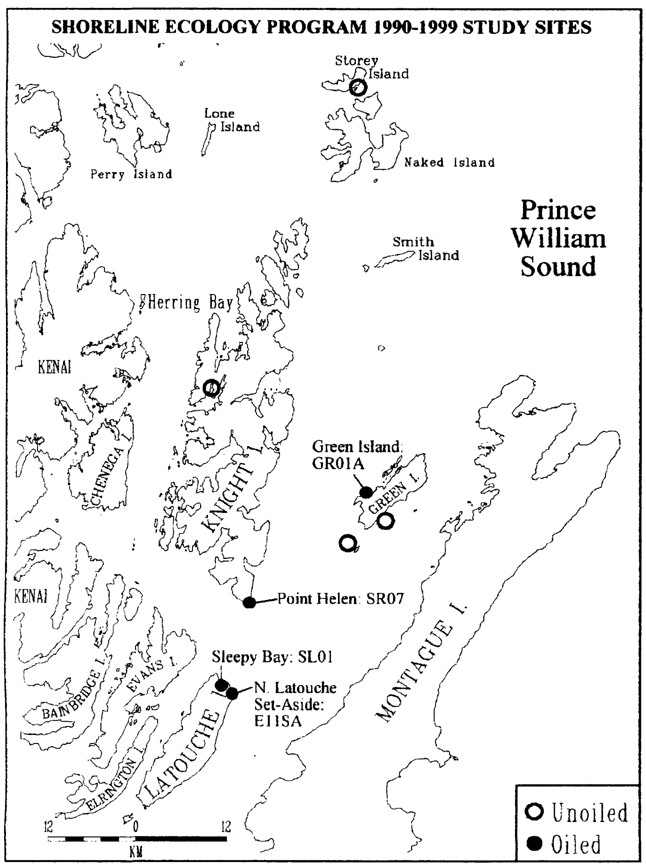

Figure 1. Sites in Prince William Sound sampled in 1990, 1991, 1998 and 1999.

Because a possible effect of year was observed in the plots of CA scores, a multivariate analysis of variance (MANOVA) on the scores for axes 1 and 2 was used to test for effects of site specific variables (total organic carbon content of sediment (TOC), wave energy, the proportions of sand and of silt), year, degree of oiling, and the year-by-oil degree interaction. Site specific variables take into account natural differences among sites and help overcome imperfect matching between oiled and reference sites. Because communities differ among intertidal zones, upper, middle, and lower intertidal zones were treated separately. Results from MANOVA showed that mean CA scores for axes 1 and 2 differed significantly among years. A one-way ANOVA. Post-hoc Student's t-tests were used to differences CA scores among years.

Results

Population densities of *Mytilus edulis*, Oligochaetes and Nematodes were most important in defining CA results. Figure 2 shows density ellipses for CA axes 1 and 2 for the upper intertidal zone. The density ellipses shown will contain 90% of all scores for each year. If community structure is similar in two or more years the density ellipses will be coincident. Density ellipses for 1990, 1991 and 1999 are very nearly coincident in the diagram. Visual inspection shows that 1998 ellipse is rotated counter clockwise to other years.

MANOVA results (Table 1) show that mean CA results differed significantly among years. Site specific variables, degree of oiling, and the interaction between year and degree of oiling were not significant. MANOVA results did not show which years differed. ANOVA was performed on axes 1 and 2 results with year as a grouping variable.

Figures 3 and 4 show means, 95% confidence intervals and multiple comparisons for CA scores among years. For both axes 1 and 2 for the upper intertidal zone 1998 significantly differed from all other years.

Similar analyses were performed for the middle and lower intertidal zone. No significant differences were found. There results will not be further considered.

Table 1. MANOVA results for effects concomitant environmental variables, degree of oiling, and year on scores for axes 1 and 2 at the upper intertidal zone. The denominator degrees of freedom was 75 for all effects. Only the effect for year was significant at $\alpha = 0.05$.

Effect	Value	F-statistic	Num d.f	P-value
Wave energy	0.0036	0.2706	1	0.6045
TOC	0.0009	0.0670	1	0.7965
% Sand	0.0095	0.7162	1	0.4001
% Silt	0.0230	1.7260	1	0.1929
Year	0.4790	11.9742	3	<0.0001
Oil Degree	0.0002	0.0185	1	0.8992
Year * Oil Degree	0.0293	0.7331	3	0.5355

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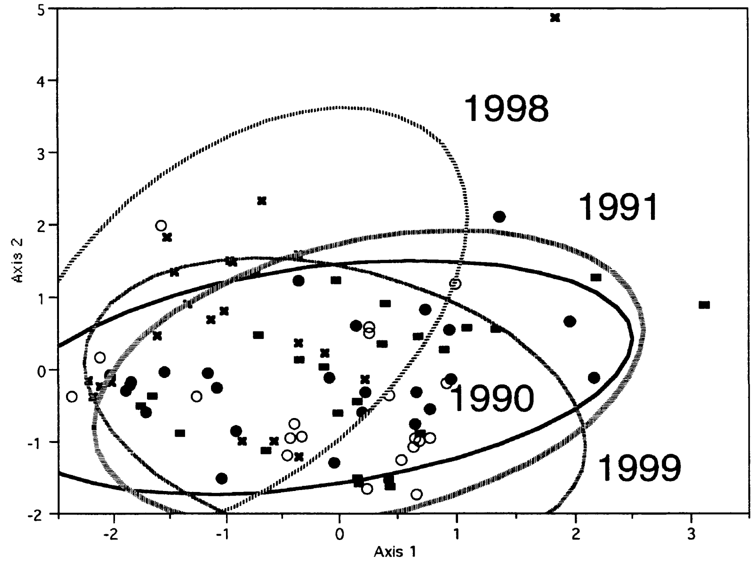

Figure 2. CA results for the upper intertidal zone community. Sample scores for axes 1 and 2 are plotted. 90% density ellipses are calculated for each year. Symbols differentiate data for different years: solid circles (1990), solid rectangles (1991), X (1998) and open circles (1999).

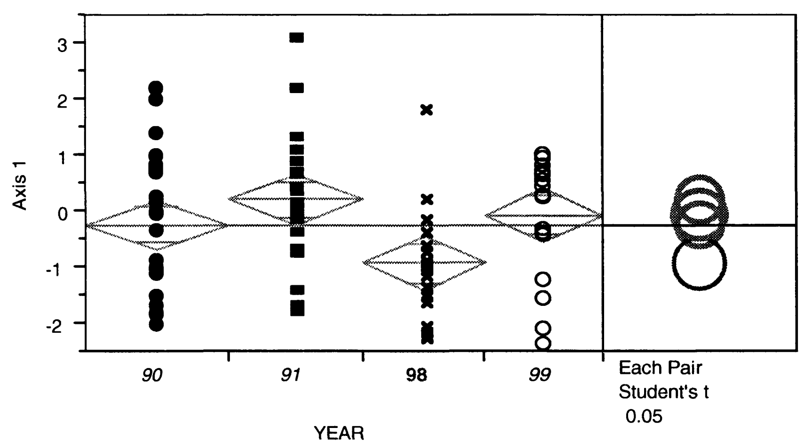

Figure 3. Scatter plot of annual means and 95% confidence limits for scores on CA axis 1. Right panel shows results of multiple comparisons among means. Scores for 1998 are significantly different from other years.

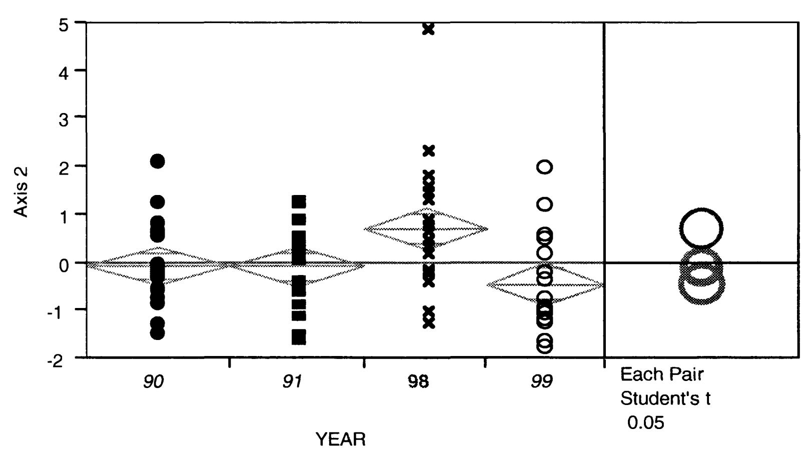

Figure 4. Scatter plot of annual means and 95% confidence limits for scores on CA axis 2. Right panel shows results of multiple comparisons among means. Scores for 1998 are significantly different from other years.

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Discussion

Previous papers relying on univariate statistical tests on species' abundances and community structure parameters, e.g., total abundance, showed evidence for oil spill effects in the 1990-1991 time frame. When natural variability is recognized and taken into account, the oil spill signal is small and at times, equivocal (Page *et al.* 1999, Gilfillan *et al.* 2000). These univariate analyses showed that the most consistent effect was due to interannual variability (Gilfillan et al., 2001). Similar results have been reported by Hoff and Shigenaka, (1999).

Applying multivariate analyses (CA and MANOVA) to the same data analyzed with univariate analysis (Gilfillan et al. 2001) also reveals a large amount of interannual variability in community structure. This interannual variability is equally evident at formerly oiled sites and never oiled sites. The multivariate approaches are particularly effective since they assess all members of the community in a single analysis. Hence, the sum total of the information about the communities is expressed in the sample scores, as represented in CA axes 1 and 2 (Figure 2). Results of MANOVA (Table 1) showed that neither site specific variables nor degree of oiling affected CA scores. Only the effect of years was found to be important. Results from ANOVA showed scores for 1998 significantly differed from other years (Figures 3 & 4). Since changes in the site specific variables were excluded from affecting CA scores in the MANOVA, some other source of environmental effect must be sought. The large interannual changes in temperature and salinity are obvious candidates.

Examination of the time trends in sea surface temperature and sea surface salinity for the period 1985 to 1999 shows that there were major fluctuations in both oceanographic properties during this period.(Mann, 1993; Muter *et al.*, 1994; Parker *et al.*, 1995). These are both properties important to the composition of animal communities.

The only intertidal zone where interannual, or other, effects were observed was in the upper intertidal zone. This is probably because the upper intertidal zone is most exposed to environmental stress and can be expected to respond more to environmental change. It is also the location where most of the remaining oil exists.

Conclusions

- CA is a useful tool for assessing community structure because it summarizes information on the distribution and abundance of many taxa into vectors of scores which can be graphed and statistical analyzed to assess anthropogenic and natural factors.
- In the present study, large interannual differences in the benthic infaunal communities on B/C beaches in Prince William Sound may associated with cyclical changes in sea surface temperature and salinity.
- Effects of the oil spill were restricted to the two years after the spill. Spill effects were small in comparison those resulting from oceanographic change.

Biography

Edward Gilfillan has a BA degree from Yale University (1963) and MS and PhD degrees from the University of British Columbia (1967; 1970) He taught at Bowdoin College for 24 years. He has authored more than 70 publications dealing with ecological effects of oil spills.

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