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Using asymmetrical designs for environmental impact assessment of unplanned disturbances

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Abstract

Environmental impact assessment of unplanned disturbances is often difficult to accomplish due to the absence of 'before' data for the impacted sites. In an attempt to overcome this problem, a beyond BACI model is used in order to detect possible changes in the temporal patterns of variation when no previous data are available. The model attempted to detect changes in the abundance of macroinvertebrate species inhabiting the intertidal mussel matrix after an oil spill which occurred in northern Portugal. The detection of a significant impact failed, most probably due to low temporal replication. An extension of the analysis, including the hierarchical arrangement of temporal variability in periods, suggests that increasing the number of sampling times may result in a higher efficiency of the model.

Introduction

The unambiguous detection of environmental impacts in natural ecosystems requires the statistical comparison of differences in temporal changes of a certain variable (for example, the mean abundance of a species) from before to after the disturbance, between the putatively impacted site and several control locations. Beyond BACI analysis (Underwood, 1991, 1992, 1993, 1994) was specifically developed to address this problem, and is still the most logically robust method available to date.

Monitoring studies aiming to assess the effect of unexpected anthropogenic activities on natural populations require careful planning, especially in the selection of the number and location of sampling sites. In the case of oil spills, a reasonable procedure consists in the identification of 'risk areas', like the vicinity of harbours and oil refineries, where sampling should be focused. Unfortunately, the logistic constraints common to the vast majority of medium and long-term monitoring programmes make it almost impossible to survey more than a few control locations.

Such difficulty was felt after a small scale oil spill which occurred in northern Portugal in December 2000. A monitoring programme had been underway on northern Portuguese rocky shores since 1997. Its main goal was to acquire data on macrobenthic assemblages from a number of sites within a stretch of 90 km of coastline for before/after impact assessment. Although intensively studied, the only rocky shore affected by the oil spill had not been regularly monitored. Hence, no comparable data were available before the spill for that particular site. In this work, a beyond BACI model was used in order to detect environmental impacts when no 'before' data are available for the impacted site. Given the fact that there were many sampled sites (eight) which could serve as controls, these were divided into two sets. One of them provided 'after' data, as in usual ACI analysis, and the other was used to estimate 'before' variability as suggested by Underwood (1994).

Material and methods

Data acquisition

The study was carried out at eight locations in northern Portugal between August 1999 and June 2002. Sampling was conducted on randomly assigned dates and during low-tide by scraping over 20 × 20 cm replicate areas in the mussel matrix. The collected material was preserved in formalin (4%). Macroinvertebrate species found in the samples were identified and counted. Only species consistently present across sampling times were used in the analyses: *Brachystomia rissoides* (Hanley), *Littorina neritoides* (L.), *Gibbula umbilicallis* (da Costa), *Nucella lapillus* (Röding), *Rissoa parva* (da Costa), *Lasaea rubra* (Montagu), *Hyale* Rathke spp., *Idotea pelagica* Leach and *Jaera albifrons* Leach.

Statistical analysis

The model adopted in this work (Table 1) is a modified beyond BACI, since the factor Locations (L) is nested in Before-After (B). From the available set of sampled locations, four were randomly assigned to provide an estimate of natural variability before the incident. These were contrasted with 'after' data from a different set of three controls and the putatively impacted location. By explicitly including 'before' data for control locations, changes unrelated to the putative impact can be specifically tested.

The analysis is based on two assumptions. First, the patterns of temporal change within controls must not be different from before to after the disturbance, which means that the interactions T (Aft) × C (Aft) and T (Bef) × C (Bef) should not be significant. Second, if they are, their magnitude should not be different (two tailed test T (Aft) × C (Aft) vs. T (Bef) × C (Bef) not significant). Denominators for the *F*-ratios were identified following the logic of beyond-BACI designs (Underwood, 1992, 1993).

Homogeneity of variances was tested using Cochran's test (Winer et al., 1991) and when necessary, data were transformed to log $(x+1)$. Missing values were compensated by averaging the remaining replicates and reducing the degrees of freedom of the Residual term (Underwood, 1997; Quinn & Keough, 2002).

Results

The beyond BACI analyses failed to detect a significant impact of the oil spill on the studied species. As an example, Table 2 depicts the results for *Lasaea rubra, Hyale* spp. and *Idotea pelagica*. For *Brachystomia rissoides*, *Nucella lapillus*, *Rissoa parva* and *Lasaea rubra* the

Table 1. General beyond BACI model used in the present study

Source of variation	DF	Estimates
B	1	Before vs. After impact
L (B)	$2(l-1)$	Differences between locations
L (Bef)	$l-1$	Differences between locations sampled before the impact
L(Aft)	$l-1$	Differences between locations sampled after the impact
C (Aft)	$l-2$	Differences between controls sampled after the impact
I	1	Differences between impacted and control locations after the impact
T (B)	$2(t-1)$	Differences between sampling times
T (Bef) × L (Bef)	$(t-1)(l-1)$	Variability patterns of locations sampled before the impact
T (Aft) × L (Aft)	$(t-1)(l-1)$	Variability patterns of locations sampled after the impact
T (Aft) × C (Aft)	$(t-1)(l-2)$	Variability patterns of control locations sampled after the impact
T (Aft) × I	$t-1$	Variability patterns of the impacted site vs. controls sampled after the impact
Residual	$2tl(n-1)$	–
Total	$2tln-1$	–

Table 2. Selected examples of the beyond BACI results

Source of variation	df	*Lasaea rubra*			*Hyale* spp.			*Idotea pelagica*		
		SS	MS	*F*	SS	MS	*F*	SS	MS	*F*
B	1	1.645	1.645		1.127	1.127		19.130	19.130	
L (B)	6	43.677	7.279		2.864	0.477		15.000	2.500	
L (Bef)	3	26.082	8.694		1.221	0.407		11.417	3.806	
L (Aft)	3	17.595	5.865		1.643	0.548		3.584	1.195	
C (Aft)	2	4.655	2.327		0.424	0.212		2.426	1.213	
I	1	12.940	12.940		1.219	1.219		1.157	1.157	
T (B)	4	2.933	0.733		2.826	0.707		4.057	1.014	
T (Bef) × L (Bef)	6	10.752	1.792		2.622	0.437		1.383	0.231	
T (Aft) × L (Aft)	6	7.896	1.316		1.382	0.230		3.936	0.656	
T (Aft) × C (Aft)	4	2.616	0.654	1.453	1.096	0.274	2.192	3.066	0.766	3.563*
T (Aft) × I	2	5.279	2.640	5.867*	0.287	0.143	1.144	0.870	0.435	
Residual	93	41.888	0.450		11.63	0.125		20.009	0.215	
Total	116	108.791			22.453			63.515		

Data sets were homoscedastic after log $(x+1)$ transformation. Missing values were compensated by averaging the remaining replicates and reducing the degrees of freedom. B = Before vs. After; L = locations; I = impacted; C = control; T = sampling times. *Significant ($p < 0.05$).

analyses ended up in non-significant T (Aft) × I vs. T (Bef) × C (Bef), meaning that the patterns of variability in the impacted site were not different from those measured at the controls before the impact. In the case of *Hyale* spp. and *Rissoa parva* the interaction T (Aft) × I was not significant. For *Idotea pelagica*, the patterns of variability in the impacted site were not different from those measured at the control sites after the impact (T (Aft) × I vs. T (Aft) × C (Aft) not significant). It is noteworthy that in all eight analyses the test T (Aft) × C (Aft) vs. T (Bef) × C (Bef) was non-significant.

Discussion

The failure to detect differences in the patterns of variability of the selected species may indicate that these were not significantly affected by the oil spill. On the other hand, it could be a consequence of the low overall efficiency of the analyses which, in turn, may result from high spatial and temporal variability of the data (Underwood, 1994). The main challenge in environmental impact assessment studies is to isolate the effect of interest from natural variability. In highly variable systems, this is seldom achievable with low spatial and/or temporal replication.

Small-scale oil spills like the present one are classified as pulse events (Bender et al., 1984), which normally cause short-term disturbances. According to Underwood & Chapman (2003), beyond BACI designs which use nested sampling times within periods are more powerful in the detection of such disturbances. It was not possible to include periods in the model employed in this study due to insufficient temporal replication prior to the disturbance. However, 'after' data were not limited by such constraint. A new approach was attempted, using an after control/impact (ACI) design, which allowed the inclusion of one more control location and another sampling time. Increasing replication in time enabled the hierarchical arrangement of temporal variability, by nesting sampling times within an extra factor (periods).

Results revealed significant differences in the patterns of temporal variation in abundance between impacted and control shores for three of the nine studied taxa (Table 3). Those were detected at different spatial scales – T (P) × L or P × L depending on the species. It is very likely that the increase of small-scale temporal variability

Table 3. Results of the asymmetrical ANOVAs to test for differences in temporal patterns of variation after the spill, between the impacted location and several controls

Source of variation	df	*Lasaea rubra*			*Hyale* spp.			*Jaera albifrons*		
		SS	MS	*F*	SS	MS	*F*	SS	MS	*F*
L	4	30.029	7.507		798.548	199.637		5.205	8.801	
P	1	7.205	7.205		937.996	937.996		0.786	0.786	
T(P)	2	7.249	3.624		154.548	77.274		1.693	0.846	
P × L	4	6.558	1.640		824.820	206.205		2.596	0.649	
P × I	1	2.243	2.243		520.596	520.596	10.635*	0.697	0.697	
P × C	3	4.315	1.438		304.224	101.408	2.074	1.899	0.633	
T (P) × L	8	7.876	0.985		495.420	61.927		9.125	1.141	
T (P) × I	2	3.066	1.533	3.992*	162.299	81.149	1.660	0.173	0.087	†
T (P) × C	6	4.810	0.802	2.089	333.121	55.520	1.135	8.952	1.492	2.908*
Residual	80	30.697	0.384		3911.567	48.895		41.073	0.513	
Total	99	89.614			117.258			90.478		

†2-tailed test: T (P) × I vs. T(P) × C (F = 17.149*). Data sets were homoscedastic after square root transformation for *Hyale* spp. and *log* $(x+1)$ transformation for the remaining species. L = locations; I = impacted; C = control; P = periods; T = sampling times. *Significant ($p < 0.05$).

detected at the impacted site was related to the effects of the spill and also to distinct rates of recovery of the different species, after the oil was removed or washed away.

ACI models have been used by several authors (e.g. Chapman et al., 1995; Roberts, 1996; Glasby, 1997; Lardicci et al., 1999; Bishop et al., 2002; Underwood et al., 2003). By excluding 'before' data from the model a relationship between the human activity in question and observed effects can only be presumed. However, the beyond BACI model used in this study showed no significant differences between patterns of variation among controls from before to after the putative impact. Therefore, it is safe to assume that eventual differences in patterns of variation detected by the ACI analyses between the impacted and control shores are likely to have been caused by the oil spill.

The present work demonstrated the applicability of asymmetrical designs in the detection of unplanned anthropogenic disturbances. As demonstrated by this study, sampling as many sites as possible at the expense of temporal replication should be avoided, especially if it can be anticipated that the disturbance is of small scale type and thus unlikely to affect any of the selected sites. The inclusion of factor 'periods' seems to be mandatory to detect small scale temporal effects, particularly when organisms that exhibit seasonal variation in abundance are monitored. The apparent complexity of the analysis does not imply a sophisticated sampling strategy. Thus, monitoring programs targeted towards the detection of environmental disturbances should be easily set up according to beyond BACI models.

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