Environmental Metal Pollution Considered as Noise: Effects on the Spatial Distribution of Benthic Foraminifera in two Coastal Marine Areas of Sicily (Southern Italy)

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Abstract

We analyze the spatial distributions of two groups of benthic foraminifera (Adelosina spp. + Quinqueloculina spp. and Elphidium spp.), along Sicilian coast, and their correlation with six different heavy metals, responsible for the pollution. Samples were collected inside the Gulf of Palermo, which has a high level of pollution due to heavy metals, and along the coast of Lampedusa island (Sicily Channel, Southern Mediterranean), which is characterized by unpolluted sea waters. Because of the environmental pollution we find: (i) an anticorrelated spatial behaviour between the two groups of benthic foraminifera analyzed; (ii) an anticorrelated (correlated) spatial behaviour between the first (second) group of benthic foraminifera with metal concentrations; (iii) an almost uncorrelated spatial behaviour between low concentrations of metals and the first group of foraminifera in clean sea water sites. We introduce a two-species model based on the generalized Lotka-Volterra equations in the presence of a multiplicative noise, which models the interaction between species and environmental pollution due to the presence in top-soft sediments of heavy metals. The interaction coefficients between the two species are kept constant with values in the coexistence regime. Using proper values for the initial conditions and the model parameters, we find for the two species a theoretical spatial distribution behaviour in a good agreement with the data obtained from the 63 sites analyzed in our study.

Keywords: Heavy metals, Benthic foraminifera, Lotka-Volterra, Population dynamics, Multiplicative noise, Noise-induced phenomena

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I. INTRODUCTION

Natural ecosystems are open complex systems in which the intrinsic nonlinearity together with the environmental interaction gives rise to a rich variety of experimental phenomenologies. These can be explained through some recent counterintuitive noise-induced phenomena like stochastic resonance, noise enhanced stability and noise delayed extinction (Spagnolo et al., 2004). Random fluctuations and their role in natural systems have become an important topic of investigation in many different fields ranging from neuroscience to biological evolution and population dynamics (Goldenfeld and Kadanoff, 1999; Freund and Pöschel, 2000; Brown et al., 2001, Sugden and Stone, 2001; Turchin et al., 2002; Spagnolo et al., 2003; Spagnolo et al., 2004; Valenti et al., 2004a). Moreover noise-induced effects in biological systems appear in bio-informatics (Blake et al., 2003; Ozbudak et al., 2002), virus dynamics, epidemics (Tuckwell and Le Corfèc, 1998; Gielen, 2000; Chichigina et al., 2005) and population dynamics for zooplankton abundances (Caruso et al., 2005). Specifically the role of the noise in population dynamics has been intensively analyzed in theoretical investigations (Ciuchi et al., 1996; Vilar and Solé, 1998; Giardina et al., 2001; Rozenfeld et al., 2001; Scheffer et al., 2001; Staliunas, 2001; La Barbera and Spagnolo, 2002; Spagnolo and La Barbera, 2002a; Spagnolo et al., 2002b; Cirone et al., 2003).

Experimental data for population dynamics are often related to the spatial extension of the system considered. Understanding the dynamics which determines the spatial structures, that is the spatio-temporal patterns, is an important target in the analysis of the marine ecological time series in view of modelling their complex behaviour (Lourens et al., 1996; Sprovieri et al., 2003; Caruso, 2004 and references therein). In this context it is fundamental to understand the effects of noise in order to describe the spatio-temporal dynamics of real ecosystems (Zhonghuai et al., 1998; Blasius et al., 1999; King et al., 2001; Rozenfeld et al., 2001; Valenti et al., 2004b; Valenti et al., 2006).

In this paper we analyze abundances of two groups of benthic foraminifera and concentrations of six heavy metals. Data were obtained from 58 sites inside the Gulf of Palermo, containing high levels of pollutants (heavy metals), and from 5 sites along the coast of the Lampedusa island (Sicily Channel) characterized by unpolluted or very low polluted sea waters. In order to check whether the presence of heavy metals in the top-soft sediments affects the spatio-temporal dynamics of the two groups of benthic foraminifera, data were
analyzed calculating spatial correlations among species abundances and metal concentrations. Finally, to understand the spatial distributions of the two groups of foraminifera interacting with each other through the presence of the heavy metals in the environment, we consider a model of two generalized Lotka-Volterra equations in the presence of two peculiar multiplicative noises (Valenti et al., 2004a). The noise sources take into account for the interaction between the species and the heavy metal pollution. In the final section of the paper, the theoretical spatial behaviour obtained with this model are compared with the experimental ones obtained from samples of the considered sites.

II. MATERIALS AND METHODS

A. Sampling methods

We carried out the study on 63 samples taken from top soft-sediments, collected between autumn 2004 and summer 2006 using a Van Veen grab. Sampling site locations have been determined with Garmin 12 channels GPS (Global Position System). In the Gulf of Palermo (Sicily, Italy) a total of 58 samples sub-divided in 24 stations, far from the coastline, have been considered. Generally each station consists of three samples taken at different bathymetries. The 58 samples collected in the Gulf of Palermo are shown in Fig. 1. It is possible to distinguish three different "strips" formed by the sites (black dots) where the samples were collected. From the coast towards the shelf area one can recognize an internal strip (GP X-1), an intermediate one (GP X-2), and an external one (GP X-3), whose bathymetries are respectively $-10 \, m$, $-20 \, m$, $-30 \, m$. The sites of the Gulf of Palermo were named ”GP” followed by two numbers: the first one for the position inside the strip, the second one for the numeration of the strip (1, 2 or 3). For example, ”GP 9-1” means ”site 9 belonging to strip 1 in Gulf of Palermo”. Along the coast of Lampedusa Island we collected randomly 5 samples with different bathymetries ranging from $-3 \, m$ to $-30 \, m$.

B. Benthic foraminifera

For the analytical studies only the uppermost part of soft-bottom sediments (3-4 cm) was utilized. One hundred grams of wet sediment of each sample were oven-dried at 80 $^\circ\text{C}$ for 48 hours; the dried sediment was weighted and washed through a 63 $\mu\text{m}$ sieve.
Quantitative analysis on benthic foraminifera was carried out on dead assemblage fraction > 63 µm, focusing on thanatocoenosis, using an Otto microsplitter to obtain a smaller, but statistically representative, amount of the total sediment. The total number of benthic foraminifera, contained in this fraction, has been counted. The accuracy in the counting of each species is less than 10%. The taxonomy of benthic foraminifera was essentially based on the classifications by Loeblich and Tappan (1964, 1988), and Sgarrella and Montcharmont Zei (1993). For this study we focused our attention on the percentages of some genera of miliolids (Adelosina spp. and Quinqueloculina spp.) and the genus Elphidium. Typically these genera are abundant in the top sediments of the upper shelf zone, but in the marine ecosystem the dominance of one of this group depends on chemical parameters as oxygen, salinity and nutrient concentrations. In particular miliolids generally prefer high oxygen concentration in the shelf area waters while Elphidium spp. are more tolerant to stressed environmental conditions for changes in salinity and high levels of nutrients (Sen Gupta, 2003).

C. Metal measurements

The heavy metals considered are zinc (Zn), copper (Cu), chrome (Cr), iron (Fe), lead (Pb), mercury (Hg). For Flame Atomic Absorption Spectrophotometry ”pseudo-total metal contents” analysis, a quantity of 1000 mg was digested in an open cavity microwave system (C.E.M. Star system 2) using the following procedure: 20 mL of HNO₃ 65% and 10 mL of H₂SO₄ 96% were first added to the 1000 mg sample aliquot and heated for five minutes at 75 °C. Temperature was then raised up to 85 °C and kept for ten minutes. Afterward temperature was raised to 95 C for ten minutes, then kept at 106 °C for seven minutes, at 115 °C for fifteen minutes, at 120 °C for ten minutes and at the boiling point for fifteen minutes (Man et al., 2004). Afterward, 15 mL of H₂O₂ 30% were added and the last above described four temperature steps were repeated. All reagent were of Merck Suprapure grade. The term ”pseudo-total” (Manta et al., 2002) accounts for the used digestion procedure not completely destroying silicates (Cook et al., 1997). Digested samples were cooled, filtered through 0.45 µm pores, and diluted to 100 mL with water (resistivity 18 M cm Smeg WP4100/A10). Cr, Cu, Fe, Pb and Zn concentrations were measured by a Varian SpectraAA 220 FS. The spectrophotometer was equipped with a deuterium background corrector. Cr, Cu and
Pb were measured using the standard addition methods, Zn was measured after that a calibration curve was performed and diluting samples 1 to 11. Hg was measured using the Varian SpectrAA 220 FS coupled with the continuous flow vapor generator (Varian VGA-77) and a SnCl$_2$ solution as reducing agent for Hg vapor release from sample solutions. Working standard solutions of metals were prepared using standard solution of each metal 1000 mg L$^{-1}$ (Merck). All samples were analyzed in duplicate. All glassware were previously soaked overnight with 10% HNO$_3$ solution and then rinsed with distilled and deionized water. The National Research Council Canada PACS-2 (Marine sediment) was used as certified reference material to test the repeatability of the measurements and to evaluate recovery (Table 1). For some metals (Cr and Pb) recovery was not complete because digestion methods used do not destroy silicates. The measurements are expressed in weight of metal per weight of dry sediment. The accuracy is about 7%.

|                  | Cr(µg g$^{-1}$) | Cu(µg g$^{-1}$) | Hg(µg g$^{-1}$) | Pb(µg g$^{-1}$) | Zn(µg g$^{-1}$) |
|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Measured         | 80.1±3          | 298±8           | 3.02±0.20       | 150±6           | 355±15          |
| Certified        | 90.7±4.6        | 310±12          | 3.04±0.20       | 183±8           | 364±23          |
| Recovery %       | 88.3            | 96.1            | 99.3            | 82.0            | 97.5            |

**TABLE I:** Results expressed as mean ± standard deviation of 10 measures obtained by measurements of certified reference material.

### III. EXPERIMENTAL DATA

#### A. Data from Gulf of Palermo

In these studies we consider only the percentage of abundances of *Adelosina* and *Quinqueloculina* (1$^{st}$ group), *Elphidium* (2$^{nd}$ group) and the concentrations of heavy metals, reported in Fig.2. We note that the two groups of foraminifera show an anticorrelated behaviour each other. Moreover the spatial behaviour of 1$^{st}$ and 2$^{nd}$ groups appears respectively anticorrelated and correlated with the metals, except two of them, namely *Cr* and *Fe*. In order to get a quantitative evaluation of this correlated/anticorrelated behaviour we consider the
FIG. 1: Gulf of Palermo. The black dots indicates the sites where the samples were collected. The sites "draw" three different "strips" formed by the sites (black dots) where the samples were taken. From the coast towards the shelf area one can recognize an internal strip (GP X-1), an intermediate one (GP X-2), and an external one (GP X-3), whose bathymetries are respectively 10 m, 20 m, 30 m. At Lampedusia island samples were randomly collected along the south-eastern part.

Spatial correlation coefficient given by

$$C = \frac{COV_{xy}}{s_x s_y}$$  \hspace{1cm} (1)

where

$$COV_{xy} = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{N}$$  \hspace{1cm} (2)$$

is the covariance with i running over the number of sites, N, of each strip. Here $\bar{x}$, $s_x$, $\bar{y}$, $s_y$ are mean value and root mean square, respectively of group 1 and group 2 of foraminifera, obtained over each of the three strips.

We calculated the values of $C$ (a) between the two groups of foraminifera and (b) between
FIG. 2: Spatial behaviour for the abundances of the two groups of foraminifera: (a) “strip 1”, (c) “strip 2”, (e) “strip 3”. The abundances of the two biological groups are expressed in percentage on the total number of the foraminifera counted in each sample. The accuracy is about 10%. Spatial behaviour of the concentrations of the six heavy metals: (b) “strip 1”, (d) “strip 2”, (f) “strip 3”. The metal concentration values are measured in µgram per gram of sediment for Zn, Cr, Cu and Pb, in mgram per gram of sediment for Fe, and in nanogram per gram of sediment for Hg. The accuracy is about 7%.

foraminifera and heavy metals. The results are reported in Table 2. To come to conclusion about correlations and anticorrelations we chose a threshold parameter, $C_0$, whose values are also given in Table 2. $C_0$ was determined by a randomization test based on some permutations of the original series (“shuffling”). For example, by using Eq. (1), we calculated
$C_r$ for a group of foraminifera, considered in the original order of sites, and a metal in random order. By iterating this procedure we can define the root mean squared value

$$C_0 = \sqrt{\frac{\sum_k C_r^2}{n_{exp}}}$$

(3)

with $k$ running over $n_{exp}$ different experiments (numerical realizations). For each set of data we fix the threshold at $C_0$ for correlated behaviour (meaningful correlation for $C > C_0$), and at $-C_0$ for anticorrelated behaviour (meaningful anticorrelation for $C < -C_0$). We performed this shuffling procedure setting $n_{exp} = 10000$. As expected, the values of $C_0$ depend on the number of point (sites) considered, so that we obtained, within a given strip, a threshold value $C_0$ common for all $C'$s.

Metal concentrations measured in Posidonia oceanica meadow (Tranchina et al., 2004; Tranchina et al., 2005) and in sediments from the Gulf of Palermo are generally higher than those measured in sediments collected in clean sites along the Sicilian coast, and increase considerably in the sites just near the Palermo harbour, due to the increasing pollution (see GP 9-1, GP 9-2 and GP 9-3 in Figs.1,2). In Fig.2 the values of $Cr$, $Cu$, $Pb$, $Zn$ are reported in $\mu g \cdot g^{-1}$, Hg in $ng \cdot g^{-1}$, and Fe $mg \cdot g^{-1}$.

By comparing the values of $C'$s with the corresponding $C'_0$s (see Table 2) we observe that the abundances of Elphidium are correlated with the concentrations of $Cu$, Hg, Pb, Zn in strips 1 and 2, and uncorrelated in strip 3. Otherwise the group formed by Adelosina and Quinqueloculina is (i) uncorrelated with the same metals in strip 1, and anticorrelated in strip 3, (ii) anticorrelated with $Cu$ and Hg in strip 2. Moreover, we note between the 1st group of foraminifera and the concentrations of Cr and Fe (i) a correlated behaviour in strips 1 and 2; (ii) an anticorrelated behaviour in strip 3. We observe that Fe and Cr, with the concentrations we measured in our samples, contribute to produce favourable conditions of life for benthic foraminifera. In particular Fe represents an essential nutrient for zooplankton. Cr$^{III}$ is not a toxic agent for the biological species considered, since it is present in the cellular structure of benthic foraminifera (Frausto da Silva and Williams, 2001).

The anticorrelation observed in strip 3 could be ascribed to the contemporaneous presence of higher concentrations for the six metals considered. In particular, comparing panels b, d, and f Fig.2, we note the total metal concentration increases going from strip 1 to strip 3 when we consider the transects from GP9 to GP23. This behaviour produces a progressive
enhancement of the overall pollution that causes a greater toxicity for biospecies. It is therefore more interesting to focus on the global pollution produced by the presence of all metals. In order to emphasize the fluctuating behaviour both of the two species and six metals as a function of the different positions (sites), for each series of data (foraminifera and metals) we calculate the normalized abundances and concentrations. These are obtained for each series by calculating the mean value and normalizing the whole series respect to this value. For the heavy metals we performed, then, in each site the summation of all the normalized values, which we name total normalized concentration (TNC), obtaining one series for the spatial behaviour of the overall concentration of $\text{Zn}$, $\text{Cu}$, $\text{Cr}$, $\text{Fe}$, $\text{Pb}$, $\text{Hg}$. The results are reported in Fig.3. Here the graphs show more clearly the anticorrelated behaviour of the two groups of foraminifera. Moreover some correlated or anticorrelated behaviour between the normalized metal concentration and the two groups of foraminifera is more visible. In order to get a quantitative evaluation of this behaviour we calculated and reported in Table 3 $C'$s and $C'_0s$ between foraminifera and metals. The values of Table 3 confirm the presence of an anticorrelated (correlated) behaviour between the 1$^{st}$ group (2$^{nd}$ group) of foraminifera and the total pollution for which the heavy metals are responsible. The different responses of the two biological groups to metal pollution can be explained by considering that some species are able to adapt themselves to conditions that are prohibitive for other species. In this sense, the species belonging to $\text{Elphidium}$ show an opportunist behaviour, taking advantage from stressed environmental conditions. Conversely, the species belonging to $\text{Adelosina}$ and $\text{Quinqueloculina}$ are more sensitive to environment adverse conditions, so that in the presence of increasing pollution their abundance decreases.

B. Data from Lampedusa island

In this paragraph we discuss experimental data obtained from 5 samples, labeled LAMP-6, LAMP-12, LAMP-13, LAMP-18, LAMP-19, that have been collected along the coast of Lampedusa island. In view of an analysis based on a two-species competing model (see Section IV), we selected the same two groups of benthic foraminifera, already analyzed. In Fig.4 we report the abundances of the two biological groups and the concentrations of the six heavy metals measured in these 5 sites. From the inspection of the figure we note an anticorrelated behaviour between the 1$^{st}$ and 2$^{nd}$ groups of foraminifera. Moreover, they
appear spatially uncorrelated and correlated with metal concentrations, respectively. In order to get a quantitative evaluation of this behaviour we calculated $C'$s and $C'_0$s and reported them in Table 4. Because of the small number of sampled points the threshold value is 0.50. This high value of $C_0$ makes statistically meaningless the values of $C$ obtained between: (i) group 1 and group 2; (ii) group 1 and metals. However, group 2 shows a statistically significant correlation with metals.

This last result strengthens the trend observed in Gulf of Palermo. This uncorrelated/correlated behaviour between foraminifera and metals becomes more evident by calculating the normalized concentrations with the same technique of the previous section. The results are shown in Fig.5. In Table 5 we report $C'$s and $C'_0$s between the species and between each species and total normalized metal pollution. An inspection of Fig.5 together with the values of Table 5 shows: (i) an almost uncorrelated behaviour between the total normalized concentration (TNC) of metals and the 1st group of foraminifera, (ii) a strong correlation between the 2nd group of foraminifera and TNC. The absence of an anticorrelation between the 1st biological group and the metal pollution can be explained by considering

| Strip 1 ($C_{0.26}$) | Adelosina - Quinqueloculina | Epiphanes | Zn | Cu | Cr | Fe | Pb | Hg |
|------------------------|-----------------------------|-----------|----|----|----|----|----|----|
| Adelosina - Quinqueloculina | -0.01 | -0.03 | 0.37 | 0.53 | -0.12 | -0.10 | -0.16 |
| Epiphanes | 0.58 | 0.44 | 0.21 | -0.12 | 0.44 | 0.62 |

| Strip 2 ($C_{0.25}$) | Adelosina - Quinqueloculina | Epiphanes | Zn | Cu | Cr | Fe | Pb | Hg |
|------------------------|-----------------------------|-----------|----|----|----|----|----|----|
| Adelosina - Quinqueloculina | 0.06 | -0.33 | 0.41 | 0.14 | -0.06 | -0.38 |
| Epiphanes | 0.67 | 0.75 | 0.01 | -0.28 | 0.73 | 0.85 |

| Strip 3 ($C_{0.20}$) | Adelosina - Quinqueloculina | Epiphanes | Zn | Cu | Cr | Fe | Pb | Hg |
|------------------------|-----------------------------|-----------|----|----|----|----|----|----|
| Adelosina - Quinqueloculina | -0.55 | -0.47 | -0.22 | -0.22 | -0.30 | -0.39 |
| Epiphanes | 0.16 | 0.63 | -0.12 | -0.19 | 0.98 | 0.12 |

TABLE II: *Spatial correlation coefficients (i) between the two groups of foraminifera and (ii) between foraminifera and heavy metals.*
### Gulf of Palermo

**Correlation coefficients with total normalized metal pollution**

| Strip 1 ($C_t = 0.26$) | Elphidium (normalized) |
|-------------------------|------------------------|
| *Adelosina* + *Quinqueloculina* (normalized) | -0.25 |

| Strip 2 ($C_t = 0.25$) | Elphidium (normalized) |
|-------------------------|------------------------|
| *Adelosina* + *Quinqueloculina* (normalized) | -0.36 |

| Strip 3 ($C_t = 0.20$) | Elphidium (normalized) |
|-------------------------|------------------------|
| *Adelosina* + *Quinqueloculina* (normalized) | -0.43 |

**Summation of all normalized metal concentrations**

| *Adelosina* + *Quinqueloculina* (normalized) | 0.09 |
| *Elphidium* (normalized) | 0.49 |

| *Adelosina* + *Quinqueloculina* (normalized) | -0.14 |
| *Elphidium* (normalized) | 0.77 |

| *Adelosina* + *Quinqueloculina* (normalized) | -0.45 |
| *Elphidium* (normalized) | 0.64 |

### Lampedusa ($C_r = 0.50$)

**Correlation coefficients for the normalized concentrations**

| *Adelosina* + *Quinqueloculina* | Elphidium |
|-------------------------------|-----------|
| *Adelosina* + *Quinqueloculina* | -0.24 |

| Zn | Cu | Cr | Fe | Pb | Hg |
|----|----|----|----|----|----|
| 0.02 | 0.14 | -0.14 | 0.04 | 0.06 | 0.10 |
| 0.77 | 0.57 | 0.74 | 0.70 | 0.68 | 0.56 |

### Table III

**Spatial correlation coefficients**

(i) between the two groups of foraminifera, (ii) between each group of foraminifera and total normalized concentration of heavy metals.

### Table IV

**Spatial correlation coefficients**

(i) between the two groups of foraminifera and (ii) between foraminifera and heavy metals for data collected along the coast of Lampedusa.
FIG. 3: Spatial behaviour for the normalized abundances (NA) of the two groups of foraminifera: (a) "strip 1", (c) "strip 2", (e) "strip 3". Spatial behaviour of total normalized concentration (TNC) of heavy metals: (b) "strip 1", (d) "strip 2", (f) "strip 3".

that the global level of pollution over all the 5 sites is quite low. Because of this data from Lampedusa can be a good reference point for calibration in our investigation. In fact, all the sampled sites, except Lamp-6, which corresponds to the harbour of Lampedusa, present low levels of metal concentrations. We note also that even low concentrations of metals produce a correlated behaviour of the 2\textsuperscript{nd} group of foraminifera, which show an extreme sensitivity to the presence of metals in their habitat. The global uncorrelated behaviour between the total normalized metal concentration and all 1\textsuperscript{st} group of foraminifera can be considered as a signature of clean sea waters. This can help for a better evaluation of data coming from
FIG. 4: (a) Spatial behaviour for the abundances of the two groups of foraminifera in Lampedusa island; (b) Spatial behaviour of the concentrations of the six heavy metals. Units of measurements and accuracies are the same used in Fig.2.

FIG. 5: (a) Spatial behaviour for the normalized abundances (NA) of the two groups of foraminifera in Lampedusa island; (b) Spatial behaviour of total normalized concentration (TNC) of heavy metals in Lampedusa island.

highly polluted waters, where a clear anticorrelation exists between the so-called "clean" species (1st group) and the metal pollution which, conversely, is well correlated with the abundances of "opportunist" species (2nd group).
TABLE V: Spatial correlation coefficients (i) between the two groups of foraminifera, (ii) between each group of foraminifera and total normalized concentration of heavy metals for data collected along the coast of Lampedusa.

IV. THE MODEL

In this section we present a model based on Lotka-Volterra equations to describe the time evolution of two competing species according to the spatial experimental data obtained for the two groups of foraminifera. A similar model was applied to describe the time evolution of two competing species of planktonic foraminifera (Caruso et al., 2005).

Interaction between species and its environment is strictly connected with the spatial behaviour of populations. A huge amount of spatial models for ecological systems has been developed in the last two decades (Spagnolo et al., 2004; Jørgensen, 2007; Sumedha et al., 2007). In particular among these different approaches we mention: (i) Coupled Map Lattice (CML) model (Kaneko, 1992; Solé et al., 1992a; Solé et al., 1992b; Valenti et al., 2004b); generalized Lotka-Volterra equations with diffusive terms (Raychaudhuri et al., 1996; Jesse, 1999; Tsekouras et al., 2004; López-Sánchez, 2005; Valenti et al., 2006); (iii) migration-drift models based on space-time autoregressive moving average (STARMA) processes (Epper-son, 2000); (iv) simple size structured metapopulation models based on logistic equations in the presence of different types of dispersal among patches (Ezoea and Nakamura, 2006); (v) approaches neglecting an explicit time evolution, such as geostatistical models with Poisson distributions (Monestiez et al., 2006), generalized additive models (GAM) (Ferguson et al., 2006) and mixed regressive-spatial autoregressive models (Overmars et al., 2003); (vi)
probability transition models with random dispersal (Zhang et al., 2006); (vii) predictive vegetation models based on statistical methods (Miller et al., 2007). However, all these models account for spatial behaviour by considering spatial structures of data and fitting procedures and/or diffusive phenomena. Conversely, in our model we neglect the transport effects due to marine currents and water flows, since benthic foraminifers lie in seabed. In this context transport of biospecies could occur because some individuals move from a highly populated site towards another one, where life conditions are more favourable. However, foraminifers are not able to change their positions, so that they are confined inside a given site. Therefore we choose a time evolution model, without considering the spatial dynamics. Moreover, in order to take into account the effects of heavy metal pollution and its diffusion, we consider that the metal concentrations, affecting the foraminifera abundances, are not constant over time but undergo random fluctuations. This behaviour can be also connected with passive diffusive processes from the sediment to the water column and vice versa. Therefore, in view of devising a predictive dynamical model we consider metal pollution as a noise source, so that the biospecies are governed by a stochastic dynamics. As we saw in the previous section, from experimental data we found that, through the different sampling sites, the abundances of the two biological groups show a fluctuating behaviour in which we were able to recognize some peculiarities. In particular we note that the first group (Adelosina and Quinqueloculina) appears to be more sensitive to the environmental pollution (presence of heavy metals) with regards to their survival, playing a role of sentinel species (Jamil, 2001). The second one (Elphidium), differently, survives in the presence of environmental pollution due to the metal concentrations. We can consider, therefore, the pollution as an environmental disturbance, whose intensity is given by the value of its concentration. It is then reasonable to think of the two populations as two competing species in the presence of an environmental noisy pollution. It is important to note that the competitive behaviour of the two populations is mediated by several environmental parameters, as water dissolved oxygen, sediment grain-size composition, presence of seagrass in the soft-bottom, etc. The heavy metal pollution plays the role of an external perturbation of the normal life conditions, by modifying, for example, the growth rates of the two populations. Moreover we note that in a dynamical model of an ecological system it is reasonable to consider that the values of the environmental parameters vary during the time evolution. In particular the pollution represents a parameter subject to fluctuations whose behaviour is difficult to predict, so that
its concentration at a given time can be considered as a random variable, that is a noise. Therefore, to model the dynamics of the two groups of foraminifera we use the generalized Lotka-Volterra equation

\[
\begin{align*}
\frac{dx}{dt} &= x(\alpha_x - x - \beta_x y) + x \xi_x(t) \\
\frac{dy}{dt} &= y(\alpha_y - y - \beta_y x) + y \xi_y(t),
\end{align*}
\]

in the presence of a multiplicative noise, which mimics the random fluctuations of the total normalized metal concentration (TNC). In Eqs. (4) and (5), \( \alpha_x \) and \( \alpha_y \) are the growth rates of species \( x \) and species \( y \), \( \beta_x \) and \( \beta_y \) the coefficients of the interspecies competition. Here \( \xi_x(t) \) and \( \xi_y(t) \) are defined respectively as non-positive and non-negative white noises

\[
\begin{align*}
\xi_x(t) &= -|\xi(t)| \\
\xi_y(t) &= +|\xi(t)|,
\end{align*}
\]

where \( \xi(t) \) is a Gaussian white noise with the usual statistical properites

\[
\langle \xi(t) \rangle = 0, \quad \langle \xi(t)\xi(t') \rangle = \sigma \delta(t-t')
\]

and \( |\xi(t)| \) indicates the absolute value of \( \xi(t) \). The semi-Gaussian noise sources allow to take into account the different effects that the random fluctuations of heavy metal concentrations produce in the dynamics of the two foraminifera groups. TNC appears to be spatially anticorrelated with the 1st group of foraminifera and correlated with the 2nd one. In Eqs. (4), (5) \( \xi_x(t) \) and \( \xi_y(t) \) produce respectively a decrease and an enhancement in the species densities. Therefore the noise reduces the ”natural” growth of one population and helps that of the other one. Concerning the deterministic dynamics, that is in the absence of noise, the stationary states of the species concentrations in the coexistence regime are

\[
\begin{align*}
x_{st} &= \frac{\alpha_x - \beta_x \alpha_y}{1 - \beta_x \beta_y} \\
y_{st} &= \frac{\alpha_y - \beta_y \alpha_x}{1 - \beta_x \beta_y},
\end{align*}
\]

and the following conditions

\[
\begin{align*}
\alpha_x > \alpha_y \beta_x, \quad \alpha_y > \alpha_x \beta_y \\
\beta_x \beta_y < 1,
\end{align*}
\]
should be satisfied in such a way that both species survive. Otherwise an exclusion regime is established, that is one of the two species vanishes after a certain time. Coexistence and exclusion of one of the two species correspond to stable states of the Lotka-Volterra’s deterministic model (Bazykin, 1998).

A. Theoretical results

To describe the dynamics of our real system, where the two groups of foraminifera are contemporary present, we assume that the two populations are in coexistence regime, choosing the values of $\alpha_x$, $\beta_x$, $\alpha_y$, $\beta_y$ according to the inequalities (11) and (12). We obtain the time series of the two species for different levels of the noise intensity $\sigma_x$ and $\sigma_y$, whose values are obtained from TNC (see Fig.3b,d,f). For each value of TNC, that we indicate with the symbol $P$, we calculate the decimal logarithm of the quantity $(1 + P)$ to obtain positive values for the noise intensity, and multiply it by a scale factor ($f_x$ for species $x$ and $f_y$ for species $y$)

$$\sigma_x = f_x \log(1 + P)$$

$$\sigma_y = f_y \log(1 + P).$$

(13)

(14)

The use of the logarithm allows to reduce the fluctuations of experimental data. The scaling factor is used to calibrate the noise intensity with respect to the value chosen for the interaction parameter $\beta$. So that we control the effect of the environmental interaction and the interspecies competition. Here we consider the same value for $f_x$ and $f_y$

$$\sigma = \sigma_x = \sigma_y = f \log(1 + P),$$

(15)

obtaining for both species the same value of noise intensity $\sigma$ for each value of the TNC.

B. Time series and spatial distributions

First we investigate the effect of the noise on the time behaviour of the species. Since the dynamics of the species strongly depends on the value of the multiplicative noise intensity, we initially analyze the time evolution of $x(t)$ and $y(t)$ for different levels of the multiplicative noise. In order to obtain the densities of the two species at different points (sites) we
integrate Eqs. (4) and (5) by setting $\sigma = \sigma_x = \sigma_y$ at different values, which correspond to TNC’s measured in our samples. By following this procedure, and taking into account the scaling of Eqs. (13) and (14), we obtain the time series of the two species for different levels of the pollution. The time series for the two populations are obtained by setting $\alpha_x = 3.0$, $\alpha_y = 2.0$, $\beta_x = 7.5 \cdot 10^{-1}$, $\beta_y = 3.3 \cdot 10^{-1}$, $f = 5.5 \cdot 10^{-5}$. We applied a trial and error procedure to select the values of the parameters $\alpha_x$, $\alpha_y$, $\beta_x$, $\beta_y$, $f$, for which we obtain the best fitting between theoretical results and experimental data. The initial values for the two species densities are $x(0) = y(0) = 1$. In Fig.6 we report the time series for $\sigma = 0$, (TNC = 0, no pollution), $\sigma = 2.01 \cdot 10^{-6}$ (TNC = 1.32), which is the lowest level of pollution measured, in the site GP 19a-1, and $\sigma = 8.09 \cdot 10^{-6}$ (TNC = 28.60), which is the highest level of pollution, measured in the site GP 9-1. In Fig.6 we note that, after a short transient, which is not clearly visible because of the scale used for the horizontal axis, both species reach the stationary values that depend on the multiplicative noise intensity $\sigma$. In the deterministic regime these values are given by $x_{st}$, $y_{st}$ of Eqs. (9) and (10). In the presence of semi-Gaussian noise sources these values undergo variations, i.e. decrease for species $x$ (non-positive noise), and increase for species $y$ (non-negative noise). In the absence of noise (Fig.6a) species $x$ prevails, reaching a stationary value of density quite bigger than species $y$. For a low level of noise (Fig.6b) the stationary values for the densities of species $x$ and species $y$ decreases and increases respectively. For higher noise intensities (Fig.6c) an inversion of population densities occurs and the density of species $y$ exceeds that of species $x$.

In order to model the spatial distributions obtained from experimental data for the two groups of foraminifera, for each value of TNC we integrate numerically Eqs. (4), (5), averaging on 1000 simulative experiments. Then, for every noise intensity which corresponds to a given pollution level (according to Eq. (13)), we take the stationary values for both species. By this procedure, for each species we get 58 abundance values. The results are reported in Fig.7. In particular, in Fig.7b,d,f we report the values of $\sigma$ calculated from real data. We let the Lotka-Volterra system to evolve until the stationary regime is reached (see Fig.6). Afterwards, for the two species densities we consider the stationary values and we report them in Fig.7a,c,e. As a consequence of the model used the behaviour is (i) anticorrelated between the two species, (ii) anticorrelated between the species $x$ and the pollution noise intensity, (iii) correlated between the species $y$ and the pollution noise intensity (see Table
FIG. 6: Time evolution of the two species for different values of the total normalized metal concentration (TNC): (a) TNC = 0 (σ = 0); (b) TNC = 1.32 (σ = 2.01 \cdot 10^{-6}); (c) TNC = 28.60 (σ = 8.09 \cdot 10^{-6}). Both time and species densities are expressed in arbitrary units (a. u.). The values of the parameters are \( \alpha_x = 3.0, \alpha_y = 2.0, \beta_x = 7.5 \cdot 10^{-1}, \beta_y = 3.3 \cdot 10^{-1}, f = 5.5 \cdot 10^{-5} \). The initial conditions are \( x(0) = y(0) = 1 \).

3. However, the choice of the parameter values allows to obtain a good agreement between theoretical results and experimental data (compare Fig.7 with Fig.3). Finally, as we did for the data sampled in Gulf of Palermo, we applied the generalized Lotka-Volterra system of Eqs. (4), (5) to reproduce the spatial behaviour obtained for the two biological groups along the coast of Lampedusa island. For each species we get 5 abundance values and we report them in Fig.8a. Moreover we present in Fig.8b the behaviour of \( \sigma \) calculated from real data.
FIG. 7: Theoretical spatial behaviour for the densities of the two species in the Gulf of Palermo obtained by numerical integration of Eqs. (4), (5) and using, as pollution noise intensity, $\sigma = f \log(1 + P)$ where $P$ is the TNC: (a) strip 1, (c) strip 2, (e) strip 3. We set $f = 5.5 \cdot 10^{-5}$. Spatial behaviour for the pollution noise intensity $\sigma$: (b) strip 1, (d) strip 2, (f) strip 3. Both species densities and concentrations are expressed in arbitrary units (a. u.). Values of parameters and initial conditions are the same of Fig.6. The values of the species densities at each site are the stationary values obtained from Eqs. (4), (5).

The behaviour reported in Fig.8a shows a good qualitative agreement with the experimental data (compare Fig.5 with Fig.8a). In particular, from Fig.8a we note a spatial anticorrelation between the two theoretical species and a correlation between species $y$ (which mimics the 2$^{nd}$ group of foraminifera) and the noise intensity (see Table 5). We note that the values of $f$ used to obtain the theoretical results of Figs. 7, 8 are different, because of the different
FIG. 8: (a) Theoretical spatial behaviour for the densities of the two theoretical species obtained by numerical integration of Eqs. (4), (5) and using, as noise intensity, $\sigma = f \log(1 + P)$ where $P$ is the TNC in Lampedusa island. We set $f = 9.0 \cdot 10^{-5}$. (b) Spatial behaviour for the pollution noise intensity in Lampedusa island. Both species densities and concentrations are expressed in arbitrary units (a. u.). Values of parameters and initial conditions are the same of Fig.6. The values of the species densities at each site are the stationary values obtained from Eqs. (4), (5).

fluctuating spatial behaviour of TNC in the two Sicily areas.

V. CONCLUSIONS

In this paper we studied the spatial distributions of some species of zoobenthos and heavy metals, taking into account their correlations. In particular we focused on two groups of benthic foraminifera, the first one constituted of *Adelosina* spp. and *Quinqueloculina* spp., the second one formed by *Elphidium* spp. From the data analysis we found a spatial anticorrelation between the two biological groups. Moreover we observed an anticorrelated behaviour between the 1\textsuperscript{st} group of foraminifera and the overall metal pollution (TNC) in strip 3 where TNC values show marked fluctuations. Conversely, the 2\textsuperscript{nd} group shows an "opportunistic" behaviour, increasing its abundance in the presence of higher levels of TNC. We modeled the behaviour of these two foraminiferal groups, by introducing a generalized Lotka-Volterra (LV) system with multiplicative Gaussian noise which takes into account TNC effect. The theoretical spatial behaviour obtained by our model agrees qualitatively with that obtained from the experimental data, where the 1\textsuperscript{st} and 2\textsuperscript{nd} groups of foraminifera
show respectively anticorrelated and correlated behaviour with TNC. Benthic foraminifera abundances and metal concentrations from Lampedusa island show a behaviour similar to that found for the Gulf of Palermo, but with a peculiarity: the uncorrelated spatial behaviour between the 1st group of foraminifera and TNC. This specific spatial behaviour could be considered as a signature of clean sea water sites. The theoretical results, obtained with the same LV system, are in a good qualitative agreement with the experimental data. We note finally that the model proposed should be useful to explain the time evolution of ecological species, whose dynamics is strongly affected by fluctuations of environmental parameters (Zimmer, 1999; Bjornstad and Grenfell, 2001; Caruso et al., 2005), including temperature, food availability and, as in the above analyzed case, pollution.

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References

Bazykin, A.D., 1998. Nonlinear dynamics of interacting populations, World Scientific Series on Nonlinear Science, Series A, Vol. 11, Singapore.

Bjørnstad, O. N., Grenfell, B. T., 2001. Noisy Clockwork: Time Series Analysis of Population Fluctuations in Animals. Science 293, 638-643.

Blake, W. J., Kaern, M., Cantor, C. R., Collins, J. J., 2003. Noise in eukaryotic gene expression. Nature 422, 633-637.

Blasius, B., Huppert, A., Stone, L., 1999. Complex dynamics and phase synchronization in spatially extended ecological systems. Nature 399, 354-359.

Brown J. H., Whitham, T. G., Ernest, S. K. M., Gehring, C. A., 2001. Complex Species Interactions and the Dynamics of Ecological Systems: Long-Term Experiments. Science 293, 643-650.
Caruso, A., 2004. Climatic Changes During Upper Pliocene/Lower Pleistocene at Capo Rossello (Sicily, Italy): Response from Planktonic Foraminifera Approach. In Coccioni et al. eds. Special Volume Grzybowski Foundation, University of London 9, 17-36.

Caruso, A., Gargano, M. E., Valenti, D., Fiasconaro, A., Spagnolo, B., 2005. Climatic Changes and Role of Noise in Planktonic Foraminifera in the Mediterranean Sea. Fluc. Noise Lett. 5, L349-L355.

Chichigina, O., Valenti, D. and Spagnolo, B., 2005. A Simple Noise Model with Memory for Biological Systems, Fluc. Noise Lett., 5, L243-L250.

Cirone, M. A., de Pasquale, F., Spagnolo, B., 2003. Nonlinear relaxation in population dynamics. Fractals 11, 217-226.

Ciuchi, S., de Pasquale, F., Spagnolo, B., 1996. Self-regulation mechanism of an ecosystem in a non-Gaussian fluctuation regime. Phys. Rev. E 54, 706-716; ibidem, 1993. Non linear Relaxation in the presence of an Absorbing Barrier. Phys. Rev. E 47, 3915-3926.

Cook, J. M., Gardner, M. J., Griffiths, A. H., Jessep, M. A., Ravenscroft, J. E., Yates, R., 1997. The comparability of sample digestion techniques for the determination of metals in sediment. Marine Pollution Bulletin 34, 637-644.

Epperson, B. K., 2000. Spatial and SpaceTime Correlations in Ecological Models. Ecol. Model. 132, 6376.

Ezoea, H., Nakamura, S., 2006. Size Distribution and Spatial Autocorrelation of Sub-populations in a Size Structured Metapopulation Model. Ecol. Model. 198, 293300.

Ferguson, M.C., Barlowa, J., Fiedler, P., Reilly, S.B., Gerrodette, T., 2006. Spatial models of delphinid (family Delphinidae) encounter rate and group size in the eastern tropical Pacific Ocean. Ecol. Model. 193, 645-662.

Frausto da Silva, J. J. R., Williams, R. J. P., 2001. The Biological Chemistry of the Elements: The Inorganic Chemistry of Life. Oxford University Press USA.
Freund, J. A., Pschel, T. (Eds.), 2000. Stochastic Processes in Physics, Chemistry, and Biology, Lecture Notes in Physics, vol. 557, Springer, Berlin

Giardina, I., Bouchaud, J. P., Mezard, M., 2001. Proliferation Assisted Transport in a Random Environment. J. Phys. A: Math. Gen 34, L245-L252.

Gielen, J. L. W., 2000. A Stochastic Model for Epidemics Based on the Renewal Equation. J. Biological Systems 8, 1-20.

Goldenfeld, N., Kadanoff, L.P., 1999. Simple Lessons from Complexity. Science 284, 87-89.

Jamil, K. 2001. Bioindicators and biomarkers of environmental pollution and risk assessment. Science Publishers, Enfield, New Hampshire, USA.

Jesse, K.J., 1999. Modelling of a diffusive Lotka-Volterra-System: the climate-induced shifting of tundra and forest realms in North-America. Ecol. Model. 123, 53-64.

Jørgensen, S.E., 2007. Two hundred volumes of Ecological Modelling. Ecol. Model. 200, 277-278.

Kaneko, K., 1992. Overview of Coupled Map Lattices. Chaos 2, 279-282.

King, A. A., Schaffer, W. M., 2001. The Geometry of a Population Cycle: A Mechanistic Model of the Snowshoe Hare Cycle. Ecology 82, 814-830.

La Barbera, A., Spagnolo, B., 2002. Spatio-temporal patterns in population dynamics. Phys. A 314, 120-124.

Loeblich, A. R., Tappan, Jr., 1964. H. Sarcodina, chiefly 'Thecamoebians' and Foraminifera. In: Moore, R. C. (Ed.), Treatise on Invertebrate Paleontology. University of Kansas Press, New York.

Loeblich, A. R., Tappan, Jr. H., 1988. Foraminiferal Genera and their Classification vol. 4. Van Nostrand Reinhold, New York, 970 pp.

López-Sánchez, J.F., Alhama, F., González-Fernández, C.F., 2005. Introduction and permanence of species in a diffusive Lotka-Volterra system with time-dependent coefficients. Ecol. Model. 183, 1-9.
Lourens, L. J., Antonarakou, A., Hilgen, F. J., Van Hoof, A. A. M., Vergnaud Grazzini, C., Zachariasse, W. J., 1996. Evaluation of the Pliocene to Early Pleistocene Astronomical Time Scale, Paleoceanography 11, 391-413.

Man, K. W., Zheng, J., Leung, A. P. K., Lam, P. K. S., Lam, M. H. W., Yen, Y. F., 2004. Distribution and behavior of trace metals in the sediment and porewater of a tropical coastal wetland. Science of the Total Environment 327, 295-314.

Manta, D. S., Angelone, M., Bellanca, A., Neri, R., Sprovieri, M., 2002. Heavy metals in urban soils: a case study from the city of Palermo (Sicily), Italy. The Science of the Total Environment 300, 229-243.

Miller, J., Franklin, J., Aspinall, J., 2007. Incorporating spatial dependence in predictive vegetation models. Ecol. Model. 202, 225242.

Monestieza, P., Dubrocab, L., Bonninc, E., Durbec, J.-P., Guinetb, C., 2006. Geostatistical modelling of spatial distribution of *Balaenoptera physalus* in the Northwestern Mediterranean Sea from sparse count data and heterogeneous observation efforts. Ecol. Model. 193, 615-628.

Overmars, K.P., de Koning, G.H.J., Veldkamp, A., 2003. Spatial autocorrelation in multi-scale land use models. Ecol. Model. 164, 257270.

Ozbudak, E. M., Thattai, M., Kurtser, I., Grossman, A. D., van Oudenaarden, A., 2002. Regulation of noise in the expression of a single gene. Nat. Genet. 1, 69-73.

Raychaudhuri, S., Sinha, D.K., Chattopadhyay, J., 1996. Effect of time-varying cross-diffusivity in a two-species Lotka-Volterra competitive system. Ecol. Model. 92, 55-64.

Rozenfeld, A. F., Tessone, C. J., Albano, E., Wio, H. S., 2001. On the influence of noise on the critical and oscillatory behavior of a predator-prey model: Coherent stochastic resonance at the proper frequency of the system. Phys. Lett. A 280, 45-52.

Sen Gupta, B. K., 2003. Foraminifera in Marginal Marine Environments. In: Sen Gupta, B. K. (Ed.), Modern Foraminifera. Kluwer Academic Publishers, New York, 141-159 pp.
Sgarrella, F., Montcharmont Zei, M., 1993. Benthic Foraminifera of the Gulf of Naples (Italy): systematics and autoecology. Bollettino della Società Paleontologica Italiana, 32, 2, 1145-264.

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., Walker, B., 2001. Catastrophic shifts in ecosystems. Nature 413, 591-596.

Solé, R.V., Bascompte, J., Valls, 1992a. Nonequilibrium Dynamics in Lattices Ecosystems: Chaotic stability and dissipative structures. Chaos 2, 387-395.

Solé, R.V., Bascompte, J., Valls, 1992b. Stability and Complexity of Spatially Extended Two-Species Competition. J. Theor. Biol., 159, 469-480.

Spagnolo, B., Cirone, M., La Barbera, A., de Pasquale, F., 2002a. Noise Induced Effects in Population Dynamics. J. Phys.: Cond. Matter 14, 2247-2255.

Spagnolo, B., La Barbera, A., 2002b. Role of the noise on the transient dynamics of an ecosystem of interacting species. Phys. A 315, 114-124.

Spagnolo B., Fiasconaro, A., Valenti, D., 2003. Noise Induced Phenomena in Lotka-Volterra Systems. Fluc. Noise Lett. 3, L177-L185.

Spagnolo, B., Valenti, D., Fiasconaro, A., 2004. Noise in Ecosystems: A Short Review. Mathematical Biosciences and Engineering 1, 185-211.

Sprovieri, R., Di Stefano, E., Incarbona, A., Gargano, M. E., 2003. A high-resolution record of the last deglaciation in the Sicily Channel based on foraminifera and calcareous nannofossil quantitative distribution. Palaeogeography, Palaeoclimatology, Palaeoecology 202, 119-142.

Staliumas, K., 2001. Spatial and temporal noise spectra of spatially extended systems with order-disorder phase transitions. Int. J. Bifurcation and Chaos 11, 2845-2852.

Sugden A., Stone, R. (Editors), 2001. Special issue, Ecology Through Time. Science 293, 623-657.

Sumedha, Martin, O.C., Peliti, L., 2007. Selection and population size effects in evolutionary dynamics, J. Stat. Mech. P05011.
Tranchina, L., Bellia, S., Brai, M., Hauser, B., Rizzo, S., Bartolotta, A., Basile, S., 2004. Chemistry, mineralogy and radioactivity in *Posidonia oceanica* meadows from north-western Sicily. Chemistry and Ecology 20, 203-214.

Tsekouras, G.A., Provata, A., Tsallis, C., 2004. Nonextensivity of the cyclic lattice Lotka-Volterra model. Phys. Rev. E 69, 016120(7).

Tranchina, L., Miccichè, S., Bartolotta, A., Brai, M., Mantegna, R. N., 2005. *Posidonia oceanica* as a historical monitor device of lead concentration in marine environment. Environmental Science and Technology 39, 3006-3012.

Tuckwell, H. C., Le Corfec, E., 1998. A stochastic model for early HIV-1 population dynamics. J. Theor. Biol. 195, 451-463.

Turchin, P., Oksanen, L., Ekerholm, P., Oksanen, T., Henttonen, H., 2002. Are lemmings prey or predators? Nature 405, 562-565.

Valenti, D., Fiasconaro, A., Spagnolo B., 2004a. Stochastic resonance and noise delayed extinction in a model of two competing species. Phys. A 331, 477-486.

Valenti, D., Fiasconaro, A., Spagnolo, B., 2004b. Pattern formation and spatial correlation induced by the noise in two competing species. Acta Phys. Pol. B 35, 1481-1489.

Valenti, D., Schimansky-Geier, L., Sailer, X., Spagnolo, B., 2006. Moment Equations for a Spatially Extended System of Two Competing Species. Eur. Phys. J. B 50, 199-203.

Vilar, J. M. G., Solé, R. V., 1998. Effects of Noise in Symmetric Two-Species Competition. Phys. Rev. Lett. 80, 4099-4102.

Zhang, F., Li, Z., Hui, C., 2006. Spatiotemporal dynamics and distribution patterns of cyclic competition in metapopulation. Ecol. Model. 193, 721-735.

Zhonghuai, H., Lingfa, Y., Zuo, X., Houwen, X., 1998. Noise Induced Pattern Transition and Spatiotemporal Stochastic Resonance. Phys. Rev. Lett. 81, 2854-2857.
Zimmer, C., 1999. Life After Chaos. In: R. Gallagher and T. Appenzeller (Editors), Complex Systems. Science 284, 83-86.