



# The effect of colored noise on spatiotemporal dynamics of biological invasion in a diffusive predator–prey system

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## ARTICLE INFO

### Article history:

Received 8 November 2010

Received in revised form

21 December 2010

Accepted 25 December 2010

Biological invasion

Colored noise

Predator–prey

Spatiotemporal dynamics

## ABSTRACT

Spatiotemporal dynamics of a predator–prey system is considered under the assumption that the predator is sensitive to colored noise. Mathematically, the model consists of two coupled diffusion–reactions. By means of extensive numerical simulations, the complex invasion pattern formations of the system are identified. The results show that a geographical invasion emerges without regional persistence when the intensity of colored noise is small. Remarkably, as the noise intensity increases, the species spreads via a patchy invasion only when the system is affected by red noise. Meanwhile, the relationship between local stability and global invasion is also considered. The predator, which becomes extinct in the system without diffusion, could invade locally when the system is affected by white noise. However, the local invasion is not followed by geographical spread.

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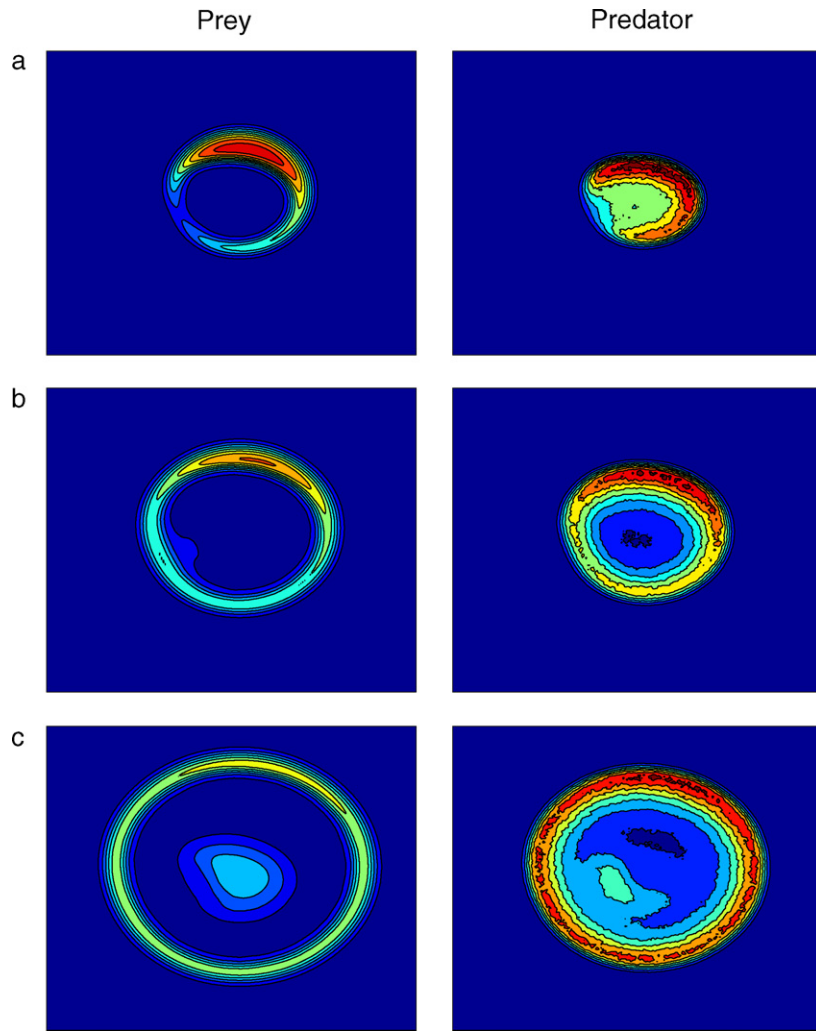
## 1. Introduction

Invasion by alien species has increasingly been recognized as one of the important problems in contemporary ecology and attracts considerable attention both from theoretical and field ecologists (Hengeveld, 1989; Hastings, 1996; Shigesada and Kawasaki, 1997; Frantzen and van den Bosch, 2000; Keitt et al., 2001; Petrovskii et al., 2005b). Among many issues related to biological invasion, the patterns and mechanisms of species spatial dispersal are of significant interest. Although the patterns of spread observed in nature are rather complicated, one can distinguish roughly between the two following scenarios (Hengeveld, 1989; Shigesada and Kawasaki, 1997; Lewis and Pacala, 2000; Morozov et al., 2008): (1) propagation of continuous travelling population fronts of high species density and (2) spread via formation and movement of patches of high density separated by areas with density close to zero. In the following, we will call the second scenario a patchy invasion. Identification of factors enhancing or hampering species spreading via propagation of a continuous population front or patchy invasion are problems of significant practical and theoretical importance. Especially in the case of patchy invasion the spatiotemporal dynamics should be more complicated and its origin has not been fully understood.

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The origin of patchy invasion is often seen either in the case of environmental heterogeneity (Murray, 1989) or environmental stochasticity (Lewis, 2000; Lewis and Pacala, 2000). Indeed, the whole dynamics of ecological communities appears as a result of the interplay between numerous deterministic and stochastic factors. Holling (1973) emphasized the influence of noise in ecological dynamics and resilience. The noise may arise from stochastic disturbance of the external environment. Under the disturbance of noise, the species dynamics are always stochastic or seemingly stochastic. Petrovskii et al. (2005a) found that the patchy invasion can take place in a system of virally infected phytoplankton and zooplankton as a result of strong environmental noise. Sun et al. (2009) also argued that the noise can make patchy invasion possible in a predator–prey system with Allee effect. Recently, the potential importance of another characteristic of environmental noise has been recognized: the variance spectral, or the noise color (Kaitala et al., 1997; Xu and Li, 2003). White noise (or noise with a white variance spectrum) contains no temporal autocorrelation and is essentially a series of independent random numbers. For example, if a series of daily temperatures were white, tomorrow's temperature would be independent of today's temperature. Red noise, however, contains positive temporal autocorrelation: tomorrow's temperature is likely to be similar to today's. Recent theoretical investigations have suggested that population dynamics are sensitive to the noise color (Foley, 1994; Caswell and Cohen, 1995). Although several studies have referred to the effect of noise on the dispersal pattern formations (Lewis and Pacala, 2000; Malchow et al., 2002; Petrovskii et al., 2005b; Sun et al., 2009), there is



**Fig. 1.** Snapshots of the invasion regimes of the prey and predator at different moments for the system ((8)–(9)) affected by white noise. Parameter values:  $\gamma = 0.3$ ,  $\delta = 0.1$ ,  $\alpha = 0.5$ ,  $\beta = 0.2$ ,  $c = 0$  and initial conditions ((12)–(13)) with  $\delta_{11} = 30$ ,  $\delta_{12} = 28$ ,  $\delta_{21} = 15$ ,  $\delta_{22} = 22$ ,  $x_1 = 108$ ,  $y_1 = 105$ ,  $x_2 = 100$ ,  $y_2 = 99$ ,  $u_0 = 1$  and  $v_0 = 0.4$ . (a)  $t = 150$ , (b)  $t = 300$ , (c)  $t = 500$ .

no research on the spatiotemporal dynamics of species invasion responding to the noise of different colors.

Motivated by that, in this study, we focus on the influence of colored noise on the spatiotemporal pattern formation of a predator–prey system in a uniform environment. By means of extensive computer simulations, we make a thorough study of this system in connection to biological invasion and give a detailed classification of possible patterns of species spread. We show that the system spatiotemporal patterns are remarkably rich and complicated when disturbed by the noise of different colors. In particular, for a moderate noise intensity, there is a parameter range where the spread of invasive species occurs via patchy invasion. We also show that, as a result of the local interaction and colored noise, successful establishment of an exotic species does not necessarily lead to its geographical spread and also does not guarantee species regional persistence.

## 2. The model and method

We consider a two-dimensional model of predator–prey interaction in a homogeneous environment. According to a widely accepted approach (Murray, 1989; Malchow, 1993; Holmes et al., 1994; Shigesada and Kawasaki, 1997; Sherratt, 2001), the func-

tioning of a predator–prey community can be described by a reaction-diffusion system of the form:

$$\frac{\partial N(X, Y, T)}{\partial T} = D \left( \frac{\partial^2 N}{\partial X^2} + \frac{\partial^2 N}{\partial Y^2} \right) + F(N) - f(N, P), \quad (1)$$

$$\frac{\partial P(X, Y, T)}{\partial T} = D \left( \frac{\partial^2 P}{\partial X^2} + \frac{\partial^2 P}{\partial Y^2} \right) + \kappa f(N, P) - EP. \quad (2)$$

where,  $N(X, Y, T)$  and  $P(X, Y, T)$  are the abundance of prey and predator, respectively, at moment  $T$  and position  $(X, Y)$ .  $D$  is the diffusion coefficient. We assume that the diffusivities are equal for both species, which is the usual case in natural plankton communities where the mixing is mainly caused by marine turbulence. The function  $F(N)$  describes the intrinsic growth of the prey, and  $f(N, P)$  describes trophic interaction between the species, i.e., predation. The parameter  $E$  is the mortality rate of the predator, and  $\kappa$  is the coefficient of food utilization.

We assume that the local growth of the prey is logistic and the predator response is of Holling type II, which are usually parameterized as follows:

$$F(N) = rN \left( 1 - \frac{N}{K} \right), \quad (3)$$

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