Linking metapopulation modelling and Information Theory for area-wide pest management

Uso congiunto di modelli di metapopolazione e Teoria dell'Informazione per la gestione a larga scala di parassiti.

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Abstract In [3], management strategies for threatened species conservation are evaluated by measuring the distance of a vector of presence/absence predicted by a metapopulation model from the vector representing some specified target state, like an extinction state, by the Kullback-Leibler divergence. In [4], it has been shown how this method supports the evaluation of short-term strategies for a pest, the Pine processionary moth metapopulation in Aspromonte (Italy). Here, we show by simulations that the method can deal with the management of pest organized in finite networks of discrete habitat patches with given areas and spatial locations.

Abstract *In* [3] *si è proposto di valutare strategie di gestione predefinite ai fini della conservazione di specie a rischio misurando, tramite la divergenza di Kullback-Leibler, la distanza tra un vettore di presenza predetto da un modello di metapopolazione ed un vettore rappresentante uno stato di riferimento, come l'estinzione. In* [4] *si è mostrato come questo metodo sia utile anche per la valutazione di strategie a breve termine per la gestione di una metapopolazione di processionaria del pino in Aspromonte. Qui si mostra tramite simulazioni come il metodo abbia validità più generale dell'applicazione precedentemente considerata.*

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Key words: Incidence Function Model, Kullback-Leibler divergence, simulated data set.

1 Introduction

Linking a metapopulation model to a divergence measure is the core of the method proposed in [3] and further developed in [4] for the evaluation of metapopulation management strategies in applied ecology. Metapopulation models are frequently used in a decision-making framework for conservation purposes mainly. However, only seldom the objectives of the management are explicitly stated in terms of metapopulation model variables, [7]. The approach proposed in [3] focuses on the evaluation of predefined control strategies by considering the consequent dynamics as described by a metapopulation model. Therefore, assessable strategies are defined in terms of the model elements only, and evaluated in terms of model outputs. As a spatially explicit metapopulation model, the Incidence Function Model (IFM) introduced in [5] has been considered due to the well documented relevance of fragmentation on population dynamics, [2].

In [3] the proposed method has been extensively discussed with respect to the pest control problems as well, and applied to a Pine processionary moth metapopulation in the National Park of Aspromonte (Italy). Here we discuss its performance from a more general point of view, by using simulated data sets with different habitat configurations.

In Sections 2 and 3 the main features of the IFM and of the use of the Kullback-Leibler for strategy evaluation are summarized. In Section 4, simulated data sets are presented and main results are briefly discussed in Section 5.

2 The IFM

In the IFM, the process of occupancy of patch i is described by a first-order Markov chain with two states, {0, 1}. Let A_i be the area of the patch i (km^2); A_0 the critical patch area for which the local population has a unit probability of extinction in one year; d_{ij} be the Euclidean centroid-to-centroid distance (km) between sites i and j. Moreover, let α be a positive constant setting the survival rate of migrants over the distance; x be a parameter reflecting the severity of environmental stochasticity and y a parameter describing the colonization ability of the species. Let be $\delta_i(t)$ the binary random variable of the occupation state at time t at site i, Then, the extinction probability of a population in patch i, E_i, is assumed to be constant in time: $E_i = \min[(A_0/A_i)^x, 1]$ while the colonization probability of patch i is assumed to vary in time: $C_i(t) = S^2_i(t)/(S^2_i(t) + y^2)$, where $S_i(t) = \sum[\delta_j(t) \exp(-\alpha d_{ij})A_j : j \neq i]$ is the connectivity of patch i.

3 Management strategies: definition and ranking

In the framework here considered, strategies of pest control are only defined in terms of spatial and temporal allocation of treatments, irrespective of the adopted control technique. The only requirements are that the patch area is the minimum spatial unit of intervention and control operations target the entire pest populations in a patch. Each strategy considers a set of occupied patches that are forced to be unoccupied at selected times.

At time T, the status of a metapopulation of n patches is evaluated by comparing the probability distribution P of the random n-vector of presence/absence ($\delta_1(T)$, ... , $\delta_n(T)$) predicted by the IFM, with the probability distribution P_0 indicating that populations in all patches are certainly unoccupied: $P_0(\delta_1(T) = 0, \ldots, \delta_n(T) = 0) = 1$. The distance of P from P_0 is measured by the Kullback–Leibler divergence, defined as $KL(P) = -\text{Log}\, P(\delta_1(T) = 0, \ldots, \delta_n(T) = 0)$. In the case of the multivariate IFM considered here, $KL(P)$ cannot be explicitly obtained, but it can be easily approximated by simulations. As each strategy is described in terms of the state of the local populations, the patches occupancy is simulated up to the evaluation time T according to the estimated model, and at the treatment times the state of the treating patches is forced to be 0 if they are occupied. Then, for each strategy the corresponding value $KL(P)$ is computed: the lower the value, the better the strategy.

4 Simulated data sets

To analyze the performances of the proposed method we considered 100 patches in an area of 50×50 Km^2, arranged in four different habitat configurations, shown in Figure 1, varying from an almost uniformly spatial distribution to more fragmented and spatially structured distributions. Patches areas were simulated from a uniform distribution between 0.1 and 10 Km^2. Occupancies were simulated by running an IFM for 500 yr to reach quasi-equilibrium, as in [6]. The parameters choice was inspired by [4], however the original values were modified to guarantee strictly positive colonization probabilities and safe from too low extinction probabilities. The adopted values are: $A_0 = 0.0004$ Km^2, $\alpha = 1$, $x = 0.15$ and $y = 0.001$.

In typical empirical situations only a few snapshots of data are usually available. Accordingly, for each habitat configuration we first considered the case of one only snapshot (see Figure 1) and then the case of three sequential years of data, sampled from the above mentioned IFM model by considering as first snapshot the one shown in Figure 1.

For each habitat configuration, several strategies have been defined as described in Section 3. In other words, a strategy consists of a list of patches to be treated and of the corresponding treatment times.

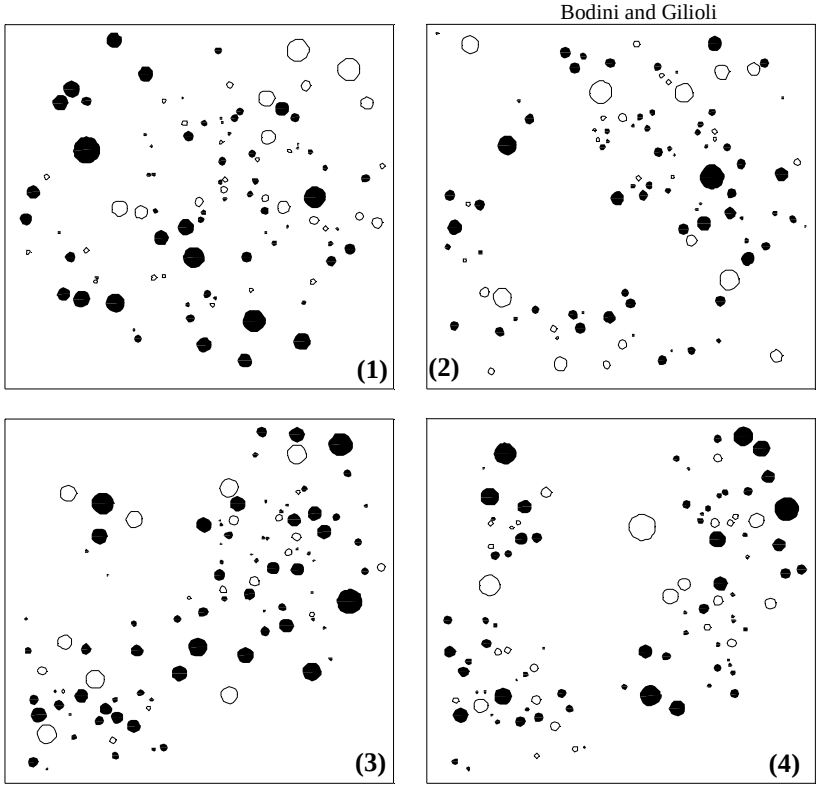


Figure 1 - The four simulated data sets, over an area of 50 × 50 Km^2. Filled circles indicate occupied patches. The circle area is proportional to the patch area. Each scenario consists of 100 patches. The number of occupied patches is, from scenario 1 to 4: 67, 69, 78 and 72 respectively.

The main aim of the analysis we summarize here was to better understand how modifying connectivity contributes to pest control, according to the Kullback-Leibler divergence criterion, as argued in [4]. Then, we focused on the spatial allocation of treatments. We suppose that we are dealing with species with no overlapping generations. A single treatment is applied after the last observed generation and strategies outcomes are evaluated two generation later. This means that in the previous formulas, generation replaces time.

For the sake of exemplification, Figure 2 shows an instance of the three kinds of strategies we considered: a scattered allocation; an *organized* allocation where contiguous occupied sites are treated; and an *organized-peripheral* allocation, where an organized allocation defines a clump at the edge of the metapopulation. In all but a few cases, the treatment effort varies from 15% to 30% of the total area. All the considered treatment allocations are presented in [1], an extended version of this work. All the proposed strategies have been compared to the do-nothing strategy. For each treatment allocation, the Kullback-Leibler value (i.e., the probability $P(\delta_1(T) = 0,\ldots, \delta_n(T) = 0)$ has been estimated by 100,000 simulations of the

dynamics obtained by the IFM with the above mentioned parameters, the occupancy as in Figure 1 and by forcing sites to be treated to be empty.

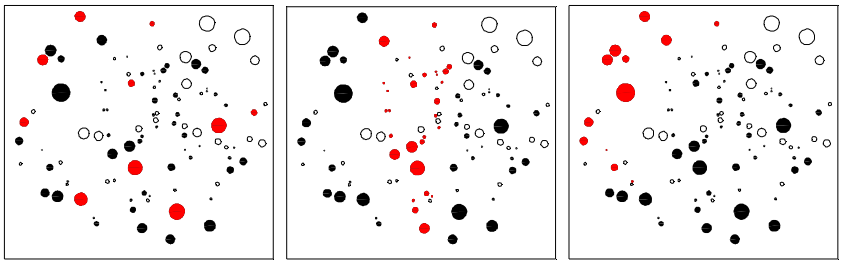
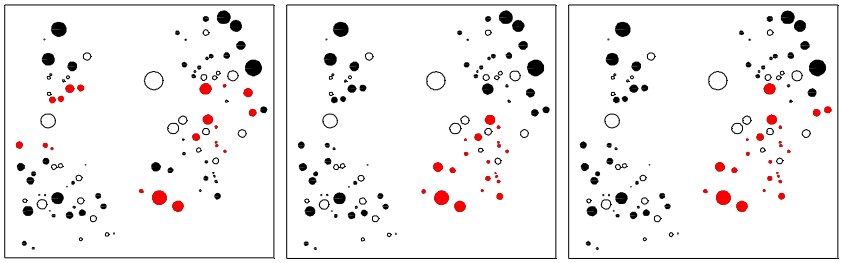


Figure 2 – Habitat configuration 1. Filled circles indicate occupied patches: the red ones indicate those to be treated. From the left to the right: a scattered strategy, an organized strategy and an organized-peripheral strategy

5 Results and discussion

One of the major issues of the Kullback-Leibler criterion for ranking management strategies is computation. As the explicit expression of *KL*(*P*) can not be written down, simulations should be carried out. By several attempts we can guess that a relatively small number of simulations (i.e., 10,000) provide a good approximation for "useless" strategies. However, to better approximate the *KL* value of more effective strategies the number of simulations should be largely increased. For this reason we used 100,000 simulations, but we need some criterion for uncertainty evaluation.



KL = 162.5; T.A. : 22.1% *KL* = 170.4; T.A. : 16.2% *KL* = 177.4; T.A. : 20.8 %

Figure 3 – Habitat configuration 4. Filled circles indicate occupied patches: the red ones indicate the treated ones. From the left to the right, the three best strategies. *KL* values and treated area (T.A., in percentage) are indicated below the each picture. The *KL* value of the do-nothing strategy is 207.6.

Based on 100,000 simulations, the do-nothing strategy has the highest *KL* value in all the four cases, as expected. In general, scattered strategies have *KL* values higher than the other strategies, while organized strategies reach the lowest

KL values. The results obtained by using these simulated data sets seem to confirm that good strategies are the ones reducing habitat connectivity. This will be further investigated in future work.

Organized strategies perform better than organized-peripheral in the case of the simulated scenario number 4 as well. Here, the habitat structure allowed the consideration of several organized-peripheral strategies, even nested each other. This allowed us to gain further insight into the effects of the treatment effort, i.e. the amount of treated area. Treating increasing areas does not yield, in general, lower *KL* values. This is shown in Figure 3, where the best strategy (on the left) is compared to two best organized-peripheral strategies with increasing treated area.

Further results can be found in [1], where both different data sets and parameter sets have been considered, as well as temporal treatment allocations.

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