# Population Dynamics Models Based on Cellular Automata that includes Habitat Quality Indices defined through Remote Sensing

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Abstract –The spatial distribution of different populations has a deep effect on their dynamics as well as on the landscape. Spatially explicit models are becoming very important tools in Ecology.

Patch occupancy models include two different spatial scales: the local neighborhood and the global landscape. Among these are Cellular Automata, which permit to visualize the evolution of the spatial dynamics of populations and analyze the strategies of the species in regard to environmental changes. In particular, they permit not only to estimate the percentage of occupation of the landscape when a species reaches its stable equilibrium level but also to observe the patterns of occupation. One interesting feature of Cellular Automata is the possibility of including spatial heterogeneity in a simple manner.

A standard tool for linking spatial heterogeneity to population dynamics is the definition of Habitat Quality Indices. These Habitat Quality Indices can be defined by respecting the philosophy of HEP procedures (Habitat Evaluation Procedures).

Here we present a methodology for the utilization of remote sensing information for the production of dynamic maps for landscape classification. The corresponding habitat quality indices are then defined and used to feed the discrete mathematical population models that run within the framework of Cellular Automata.

Models with these characteristics permit, as a first approach, to monitor the impact of environmental changes on the dynamics of the population under study as well as on the landscape, thanks to the availability of satellite images through time. Moreover, these models are appropriate for the analysis of different strategies that could be helpful in improving the habitat conditions of species that suffer the stress of negative environmental changes, the use of projections to simulate the space-time dynamics helping to evaluate "a priori" the results of any given strategy.

## I. INTRODUCTION

Spatially Explicit Models are creating great expectations in Ecology due to their ability to include the spatial distribution of species. Here, we present a Spatially Explicit Model based a Cellular Automata approach. The Cellular Automata Model CAM is based on a previously developed Mean-field Metapopulation Model (MMM). The MMM describes the dynamics of a modeled species by showing the proportion of occupancy of a homogeneous landscape, but not its spatial distribution.

In order to study the spatial distribution of the species, we developed a CAM analogous to the MMM. The CAM allows to verify the occupancy rate at equilibrium in homogeneous habitat conditions, and to study the strategy of species under different initial spatial distribution and minimum thresholds of occupancy so as to identify those that guarantee the persistence of the species in the landscape.

Once the behavior of the CAM was validated against that of the MMM, we introduced spatial heterogeneity in the CAM in order to analyze the effects of the different qualities of terrain on the species dynamics.

#### II. THE MODELS

A - MEAN-FIELD METAPOPULATION MODEL

We model an ecosystem occupied by one species and divided in an infinite number of identical patches, each of which can be either inhabited (by a subpopulation) or empty. The processes under study are the colonization of void patches, the persistence of species in occupied patches and the disturbances affecting both processes. The colonization process is assumed to be proportional to the number of occupied patches in the previous time step, and independent of neighborhood effects, hence it is given by the Poisson distribution

$$\boldsymbol{C}(\boldsymbol{y}_1) = 1 - \exp(-\boldsymbol{d}\boldsymbol{y}_1) \tag{1}$$

where  $d \ge 0$  denotes the dispersal coefficient of the species.

Disturbances affecting the colonization process are assumed to occur with probability f(y), and those affecting persistence with probability g(y). These represent process of different types, like predation induced by high levels of occupancy, fires induced by the abundance of flammable material in forest and pastures, etc., all of which are density dependent.

Under these same hypotheses, Barradas & Cohen (1994) considered the probabilities of disturbances to be constant, while Barradas & Canziani (1997)

considered a constant function f(y) and densitydependent functions g(y) for the probability of disturbance affecting persistence. Finally, Federico & Canziani (2000) considered the probability of disturbance to persistence to be constant and the probability of disturbance to colonization to be density-dependent functions. In all the cases stable and unstable steady states were found while under the last two hypotheses, periodic solutions are also possible.

### B – CELLULAR AUTOMATA MODEL

A CAM analogous to the MMM, that is considering the same hypotheses and rules, was first developed. Later, we extended it by including some modification of the hypotheses, thus allowing to model several other situations.

The initial CAM represents the space through a bidimensional array of cells. In this CAM, we respect the hypothesis made about the colonization process: *new subpopulations are distributed randomly into the landscape following a Poisson process.* At time step t, from any occupied cell it is possible to occupy any other cell in the next time step with a probability C(y). This means that each cell is a neighbor of all the other cells in the array, its location having no importance.

The extension made to the CAM discards this hypothesis. In order to model a more realistic situation, we define a "neighborhood", the new model being called extended Cellular Automata Model with Neighborhood definition (CAMN). The neighborhood is defined as a sub-matrix V of the entire cellular automata matrix M. By overlapping V on M, the neighbors for the central cell of V are established. (Ruiz-Moreno et al, 2000).

Transition Rules for CAMN are defined from colonization and persistence processes and their disturbances.

In the MMM the occurrence probabilities of processes at time step t+1 are determined by the system's global state at time step t, while in the CAMN the occurrence probabilities of processes at time step t+1 are based only in the occupancy rate inside the neighborhood. Moreover, the colonization process (for CAMN) is assumed as a constant probability process,  $\mu$ , instead of a Poisson distribution (Ruiz-Moreno et al. 2000).

Once the probability of occurrence of any process is calculated for each cell, this value is compared against an uniformly distributed random number in the interval [0,1] corresponding to that cell, and the actual occurrence of a process (Colonization or Persistence) is determined.

#### III – HABITAT QUALITY

The CAMN represents a landscape conformed by **identical** patches or cells. But, in Nature, it is

very difficult to find a totally homogeneous environment relative to the interests of any given species although some scaling issues should be considered.

There is no doubt about the influence of landscape's structure on the dynamics of a species (*Durret & Levin, 1994; Tilman & Kareiva, 1997; Hill & Caswell, 1999*). Hence, the different environmental conditions of each patch can locally alter the behavior of the species under study by affecting colonization and persistence processes and disturbances to them.

In order to include the spatial heterogeneity we defined a **Habitat Quality** (HQ) Index that can modify those processes.

The philosophy of HEP, Habitat Evaluation Procedures (NERC, 1987), is based on fundamental ecological principles, including the hypothesis that habitat values can be described through a set of variables that are important for the species and that can be easily measured. One of the basic hypotheses for HEP is that the relationship between Habitat and potential population can be expressed through an index.

Hence, we develop and CAMN extension that includes HQ, now called CAMNH. The value of habitat quality will modify the colonization and persistence probabilities. One way to include this variation is by the introduction of a factor to alter the probabilities. Hence, we define the habitat quality value (*qual*) to be in the interval (-1,1).

## IV – SATELLITAL DATA

There are many methods to enhance the information contained in the satelital images. Some of these methods produce only one band as output, for example *NDVI*, but other methods yield more bands that can be combined in different ways to improve the knowledge of the region under study (Morisette, 1997; Cebecauert, 1997; CAST, 1999; Edwards, 2000; Jennings, 2000).

One of these methods is the **Tasseled Cap Transformation (TCT)**. The TCT relates the information present in different bands by building (at least) three new bands:

- Greenness: measuring vegetation
- Brightness: measuring soil exposition
- Wetness: measuring the interrelationship of soil and canopy moisture

These bands could also be directly related to characteristic of the physical environment. The transformation's emphasis is focused on the presence of water and vegetation, two fundamental components for ecological studies.

Multi-spectral Classification is the process of ordering the pixels into a finite number of individual classes or categories of data. Unsupervised Classification requires only minimal initial input to run. This method is usually used when previous knowledge of field data is scarce, but requires the appropriate interpretation of the resulting classes after classification. The **Iterative Self-Organizing Data Analysis Technique (ISODATA)** is the method used here for unsupervised classification. It uses spectral distance to classify the pixels, and iteratively classifies and redefines the criteria for each class, so that the spectral distance patters in the data gradually emerges.

The CAMNH is able to load a file containing classified satelital data together a file of habitat quality indices. In this way we can include the true pattern of heterogeneity in the specific landscape of the study site as background for the simulation of the chosen species dynamics.

V - CASE OF STUDY: "LOS ESTEROS DEL IBERÁ"

This work was developed in the framework of the *INCO-DC Project "The Sustainable Management of Wetland Resources in Mercosur"*. This project is part of the *SAC-C Mission* coordinated by CONAE, hence the satelital data of the region under study were available. Given that the spatial resolution of SAC-C images is 180m, square cells of this dimension were chosen for the CAMNH.

The freshwater wetland ecosystem under study is the *Esteros del Ibera*, in the Province of Corrientes, in NE Argentina. The region is located between latitudes 27°30' and 29° S, and longitudes 56° 25' and 58° W.

This region has a high density of dammelands (*embalsados*). The dammedlands are formed by accumulation of interweaving aquatic vegetation that creates floating platforms strong enough as to allow the growth of other plants and trees over them. These floating islands can go up or down with the fluctuations of water level. They are the ideal habitat for birds and for large vertebrates, which have adapted to live on them, such as capybara (*Hydrochaeris hydrochaeris*), black caiman (*Caiman yacare*) and marsh deer (*Blastocerus dichotomus*). Dammedlands together with water transparency are the main factor of noise in the classical remote sensing approach.

So, in order to use the CAMNH for analysis of the population dynamics of one particular species in the selected region, it was necessary to do a preliminary work. First of all it was very important to determine the watershed boundaries. Combining data from several studies and cartographic maps we could obtain a set of level curves (see work done by Ferrati et all ). Level Curves were utilized to delimit the watershed, so that all the satelital data outside the watershed could be ignored and thus noise in the classification process was minimized.

To enhance the satelital information we decided to use the **TCT**, which can be used only with *TM* or *MSS* but is not appropriate for SAC-C data due to the absence of the equivalent to band *TM6* or band *MSS4*. It was then necessary to create a **Modified Tasseled Cap Transformation** to overcome this difficulty and make possible the development of a synthetic map for use it as input for the classification process. The MTCT was suggested by S.Loiselle & L.Bracchini, University of Siena (unpublished pers. com.).



Fig. I: A 10 Class Image near Parana Lagoon

Due to the fact that the interior of the Ibera wetlands is for the most part inaccessible, the available data describing the environmental components such as vegetal communities, or the location of population settlements, are few and scattered. This and the fact that the landscape exhibits a high degree of heterogeneity make the development of spectral signatures a very complex subject. Hence, unsupervised classification is the adequate tool for this case. Using the **ISODATA** option, we set the process to have an output map with **10 classes** (Fig. I).

Once the classification process is finished, it is necessary to assign to each class a descriptive label in order to set up HQ values.

Class	Color	HQ
Not Classified		Forbidden
Free Water		Forbidden
Water with Few		Forbidden
Vegetation		
Deep Puddle		Low
Puddle		Low
Prairies		Low
Grassland		Very Good
Similar-savanna		Very Good
Shrub		Good
Crops		Low
Urban		Bad

Table. I: Habitat Quality for the region

Using the sparse available data, it was possible to determine the interpretation of the class values as shown in the left column of Table I. Then, for each class and thinking in a hypothetical species we can assign adequate values for the HQ Index as shown in the right column of Table I.

The HQ Values are in all cases dependent of the modeled species. A terrestrial species can not settle in water habitat (this is given by choosing a *special value* that forbids the occupation of a cell). Hence, urban areas have a bad HQ value. Puddle and easily flooded areas have low values due to possible water accumulation. Crop areas have low value too, but due to human presence. However, graze and shrub areas have a good HQ.

With this configuration we simulate, 50 times during 500 time steps, the species dynamics beginning with a spatially random distribution of subpopulations occupying a 26% of the landscape. The average occupancy behavior is observed in Figure II.



Fig. II: Average Values of Species Dynamics Simulation with Habitat Quality . The graphic shows Ocuppancy Proportion Vs. Time for the region presented

The spatial distribution at steady state is concentrated around the high HQ areas, as can be observed in the Figure III.



Fig. III: Simulation of Species Presence (white points) in the landscape.

## VI - CONCLUSIONS

Spatial Habitat Distribution obtained from satellital images allows to simulate species dynamics within a real landscape structure. Habitat Quality represents the environmental physical pressure on the species. Moreover, with this Spatially Explicit Model it is possible to study the evolution of the spatial distribution and its strong and complex relationship with the species dynamics, which depends on environmental factors.

This kind of model can be used to develop the necessary experience to evaluate management species issues where the landscape structure and geometry are fundamental.

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