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SIMULATING THE SPATIAL PATTERNS OF CHANGE THROUGH THE USE OF THE DINAMICA MODEL

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Abstract. The DINAMICA model has been developed as a new tool to investigate trajectory of landscapes and dynamics of spatial phenomena. In this paper, we explore the capability of DINAMICA to reproduce a wide range of spatial patterns of change. First, we provide a short description of the DINAMICA architecture, and then we present and discuss the results of a series of simulations using simplified synthetic maps and varying the parameters of DINAMICA's transition functions. The simulation results are assessed by using selected landscape structure metrics, such as fractal dimension, patch cohesion index, and nearest neighbor distance. These simulation examples are used to show how DINAMICA can be calibrated, as well as its potential to replicate the evolving spatial patterns of a variety of dynamic phenomena.

Keywords: spatially explicit simulation model, DINAMICA, Landscape dynamics.

1. Introduction

Simulation models can be envisaged as a heuristic device useful for testing hypotheses, such as alternative scenarios, which can be translated as different regional socioeconomic, political, and environmental frameworks (e.g. Dale et. al.,1994; White et al. 2000a; Constanza et al. 2002). By mimicking, through a computer environment, the way a spatial system evolves, one can learn about the system dynamics and thereby project the spatial patterns of its change to evaluate possible environmental consequences. In light of the outcome of the model, a better conservation strategy or a management plan can be selected. We therefore have developed a spatially explicit simulation model of landscape dynamics – DINAMICA, as a new tool to investigate trajectory of landscapes and dynamics of spatial phenomena (Soares-Filho et al. 2002a, Soares-Filho et al. 2002b). As DINAMICA was designed to be a general purpose dynamic modeling software, it has been applied to simulate a variety of spatial phenomena, such as land-use change and urban growth (Soares-Filho et al. 2002a; Soares-Filho et al. 2002c; Almeida et al. 2002a; Almeida et al. 2002b).

In this paper, we explore the capability of the DINAMICA model to reproduce a wide range of spatial patterns of change. First, we provide a short description of the DINAMICA architecture, and then we present and discuss the results of a series of simulation using simplified synthetic maps and varying the parameters of DINAMICA's transition functions. The simulation results are assessed by using selected landscape structure metrics. These simulation examples are used to show how DINAMICA can be calibrated, as well as its potential to replicate the evolving spatial patterns of a variety of dynamic phenomena.

2. The DINAMICA Model Architecture

Considered as a cellular automata type model (Cf. White et al., 2000b), DINAMICA can be thought of as a dynamic spatial system in which the state of each cell in an array depends on the previous state of the cells within a cell neighborhood according to a set of transition rules.

Among other functions, DINAMICA incorporates multi-scale vicinity-based transition functions, stochastic multi-step simulation, a diffusion module, spatial feedback approach through the calculation of dynamic variables – including a road constructor module that projects new roads from an exiting road network -, and the application of either logistic regression (Soares-Filho et. al., 2001; Soares-Filho et al. 2002a) or weights of evidence (Almeida et. al., 2002a) to calculate the transition probability maps using information stored in a GIS (Geographical Information System). DINAMICA can be also linked to other models through a multi-level architecture consisting of intervening sub-models, *i.e.* a scenario generator that controls the transition rates or the inclusion of probability surfaces output by external models (**Figure 1**).

As input, DINAMICA receives a raster dataset encompassing the initial landscape map, the static spatial variables, and the sojourn time map. A subset of spatial variables in the model are dynamic, which means that they need to be calculated before each iteration. These variables are represented by maps showing the distances from a cell of a particular class to the nearest cell of a different class. Distances to roads are also considered dynamic; DINAMICA projects new roads by executing the road constructor module (Soares-Filho et al. 2002b). After each iteration, the model outputs the simulated landscape map, an updated sojourn time map, the dynamic distance and road network maps, and the transition probability maps.

DINAMICA can use a fixed transition matrix within each phase, or can be coupled with an external model, which calculates dynamic transition rates and passes on to the transition model by using the DINAMICA-VENSIM link. The external model must be written by using VENSIM - a system thinking software (Ventana, 2002). The transition matrix describes a system that changes over discrete time increments, in which the quantity of any variable in a given time is the sum of fixed percentages of quantities of variables at the previous time. For DINAMICA, time step can comprise any span of time, since the time unit is only a reference parameter externally set.

The spatial transition probability maps depict the probability of a cell at position (x,y) to change from state i to state j . The spatial transition probabilities are calculated for each cell in the landscape raster map and for each specified transition. DINAMICA can employ two methods for calculating the spatial transition probabilities: weights of evidence (Goodacre et al., 1993; Bonham-Carter, 1994) and logistic regression (Hosmer and Lemeshow, 1989). Both methods use a general polytomous logit equation to select the areas most favorable for each type of transition and the calculations are made using spatial variables stored in the GIS.

The sojourn time is used to restrict a transition only after a cell has remained in a given state for a specified period of time. Hence, a minimum sojourn time must be specified for each type of transition.

Saturation can be computed globally, considering the entire landscape, or for local areas. In this case, a local area extend must be defined. The diffusion module works with a parameter called *Local Saturation Value*, which forces the stopping of a transition i to j, when the number of cells in state i reaches a minimum value within a geographical subregion. This module is used to replicate a diffusion process.

DINAMICA uses as local Cellular Automata rule a transition engine composed of two complementary transition functions, the *Expander* and the *Patcher*. DINAMICA splits the cell selection mechanism into these processes. The *Expander* function is dedicated only to the expansion or contraction of previous patches of a certain class. The *Patcher* function is designed to generate or form new patches through a seedling mechanism. For each transition, the percentage of transitions executed by the *Expander* in relation to *Patcher* must be defined. The Patch Isometry is a number varying from 0 to 2. The patches assume a more isometric form as a function of this number. The size of new patches and expansion fringes are set according to a lognormal probability distribution. Therefore, it is necessary to specify the parameters of this distribution represented by the mean size and patch size variance of each type of patch to be formed

DINAMICA can be run as a stand-alone console program, like those executed in DOS prompt. For graphical interface option the DINAMICA code was compiled as a Windows DLL. The graphical interface provides the means to set up a simulation, to execute it and to visualize its map outputs.

3. DINAMICA's Collection of Spatial Patterns of Change

In order to evaluate the possibilities of DINAMICA, we present a collection of spatial patterns produced by various combinations of its transition functions. A series of simulations, which one representing a different hypothesis, was run using simplified synthetic maps. Their results are presented as follows:

H0 to H5 are run, for a sole time step, by using a transition matrix 2x2 that models only one transition – from class 2 to 1 – with a rate of 0.01. The landscape map encompasses a matrix of 132 by 132 cells and all cells have equivalent spatial transition probability, which means that ancillary variables are not used to influence the cell allocation process (**Figure 2**).

H0: There is no spatial arrangement and no patch aggregation. The allocation process takes place randomly and does not interact with the neighborhood. The dynamics is only controlled by the transition matrix.

H1: The allocation process is set to form patches with a patch mean size of five cells, patch size variance is set to zero. Only the *Patcher* function is used. The *Patcher* isometry factor is set to zero, which means that the patches tend to be most linear as possible.

H2: The allocation process is set to form patches with a patch mean size of five cells, patch size variance is set to zero. Only the *Patcher* function is used. The *Patcher* isometry factor is set to 1, the patches still take linear form, although shorter.

H3: The allocation process is set to form patches with a patch mean size of five cells, patch size variance is set to zero. Only the *Patcher* function is used. The *Patcher* isometry factor is set to 1.5. Now the patches assume a more isometric form.

H4**:** Only the *Expander* function is used with patch mean size of 1742 cells, which is tantamount to the expected number of transitions. Patch variance is set to 0. The *Expander* isometry factor is set to 1.5. Notice the single patch produced around a cell of class 1 located at the center of the map.

H5**:** The transition functions are used in a combination of 0.8 of *Expander* and 0.2 of *Patcher*. Patch mean size is set to 600 with patch size variance of 0. The isometry factor is set to 1.5. Two more patches are produced around the expanded central cell.

To demonstrate how DINAMICA's transition functions can be calibrated to replicate a particular landscape structure, we ran a series of H3, varying the patch mean size from 1 to 20 cells. Patch size variance was set to zero. Each test was run 10 times and its results were assessed by using the landscape structure metrics: fractal dimension, patch cohesion index, and nearest neighbor distance (McGarical and Marks, 1995).

The fractal dimension reveals the patch complexity. It is as a function of inner area in relation to the patch edge and varies from 1 to 2. Therefore, the fractal dimension is affected by the patch shape and size (Forman and Godron, 1986). According to McGarical and Marks (1995), the patch cohesion index gives an indication of the level of fragmentation of a landscape and thereby the habitat connectivity, thus large cohesion index indicates less fragmentation. In turn, the nearest neighbor distance shows the dispersion of patches in a landscape. **Figure 3** shows how these indices vary as a function of the patch mean size set in DINAMICA *patcher* function. The results of the landscape indices show a predictable behavior, indicating that DINAMICA can be set to replicate the structure of a reference landscape by fine-tuning the parameters of its transition functions.

H6: Transitions occur as a function of the spatial probability. DINAMICA sets up a spatial transition probability map for each transition, based on the weights of evidence chosen for specific ranges of each spatial variable stored in the static cube raster dataset. Simulation was run in 15 steps, with a rate of 0.005 per step. Only the *Patcher* function is used with patch mean size of 20 and patch size variance of 0. Patch isometry is equal to 2. **Figure 4** depicts the static variable map, the calculated spatial transition probability map, and the simulated landscape. Notice the concentration of changed cells in the higher probability areas at the center of the map.

DINAMICA can perform multiple transitions, up to 255 classes and 64770 transitions ($255^2 - 255$). To test its ability in simulating multiple transitions, simulations from H7 to H9 are run for a transition matrix 6 by 6 with 5 transitions.

H7: There is no spatial arrangement and no patch aggregation. *Expander* percentage is 0, patch mean size is 1, and patch size variance is 0. Transitions take place randomly only obeying the amounts of change set by the transition matrix. Simulations are run for 10 time steps.

H8: There is no spatial arrangement but patch aggregation. Patch mean size is set to 5, and simulation is run for 10 time steps. **Figure 5** depicts the original landscape map, and the simulated landscapes for H7 and H8.

H9: There is no patch aggregation, but now each transition is influenced by its spatial probability map computed over maps stored in the static raster cube. *Expander* percentage is 0, patch mean size is 1, and patch size variance is 0. Simulations are run for 10 time steps.

The B&W maps in **Figure 6** represent the weights of evidence functions, respectively, for transitions 1-2, 1-3, 1-4, 1-5, 1-6. The color map (7) represents the transition probability map for 1-2 computed by integrating the single weights of evidence functions. The last two color maps (8, 9) depict the simulated landscape after 1 and 10 iterations. Notice again the concentration of changed cells in the higher transition probability areas.

As shown in the previous simulations, the calibration of the DINAMICA model is divided into two steps. First, the spatial arrangement of the simulated landscape needs to be approximated to the one of the reference landscape by defining the weights of evidence for the modeled transitions and thereby their transition probabilities maps. Second, the reference landscape structure can be replicated by fine-tuning the parameters of the DINAMICA's transition functions.

These results presented are only a small set of possibilities; they aimed to show how DINAMICA can be adapted to replicate various dynamic phenomena.

4. Concluding Remarks

The combination of DINAMICA's transition function presents numerous possibilities with respect to the generation and evolvement of spatial patterns of change. As a result, DINAMICA can be considered as a potential tool for the replication of dynamic landscape structures. The calibration of a simulated landscape can be achieved by a series of simulation using varying parameters. An approximated solution can be attained comparing landscape metrics, such as fractal index, patch cohesion index, nearest neighbor distance, and mean patch size, of the simulated maps with the ones of the reference landscape. To facilitate this process, we plan to incorporate in the next version of DINAMICA an automatic calibration procedure aiming at the match of spatial patterns.

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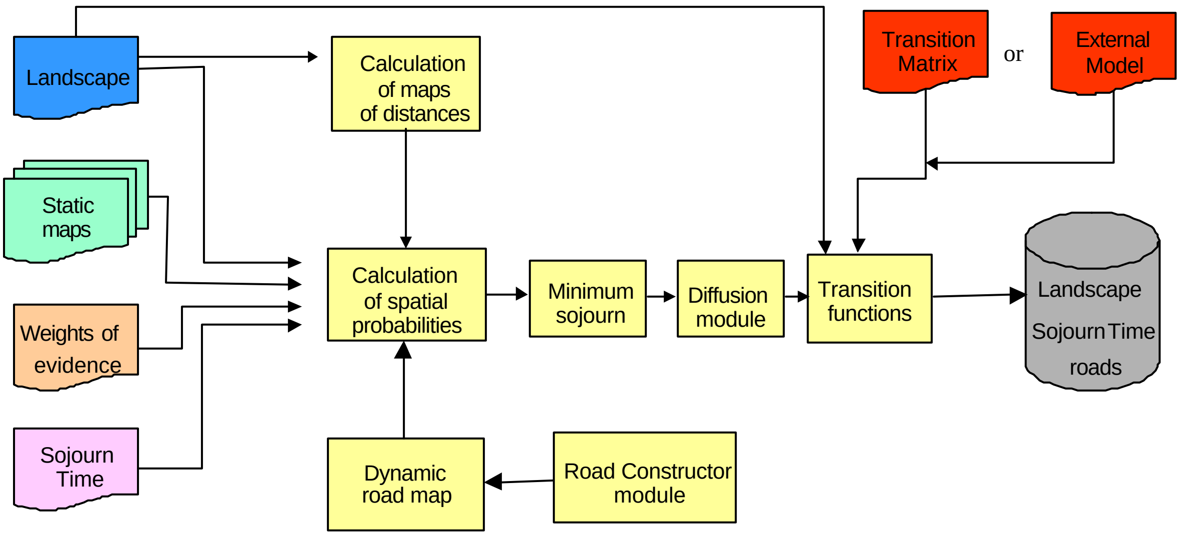

Figure 1. The DINAMICA model architecture.

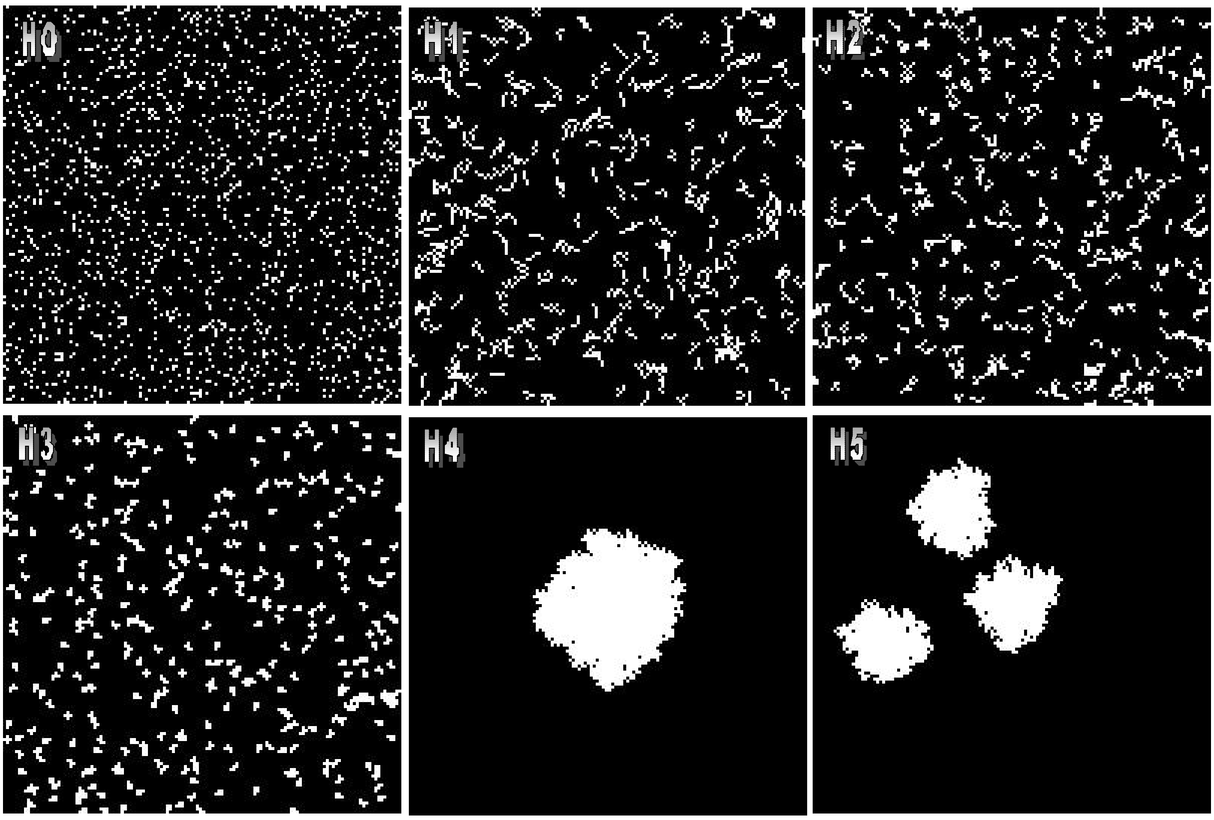

Figure 2. Maps output by hypotheses H0 to H5.

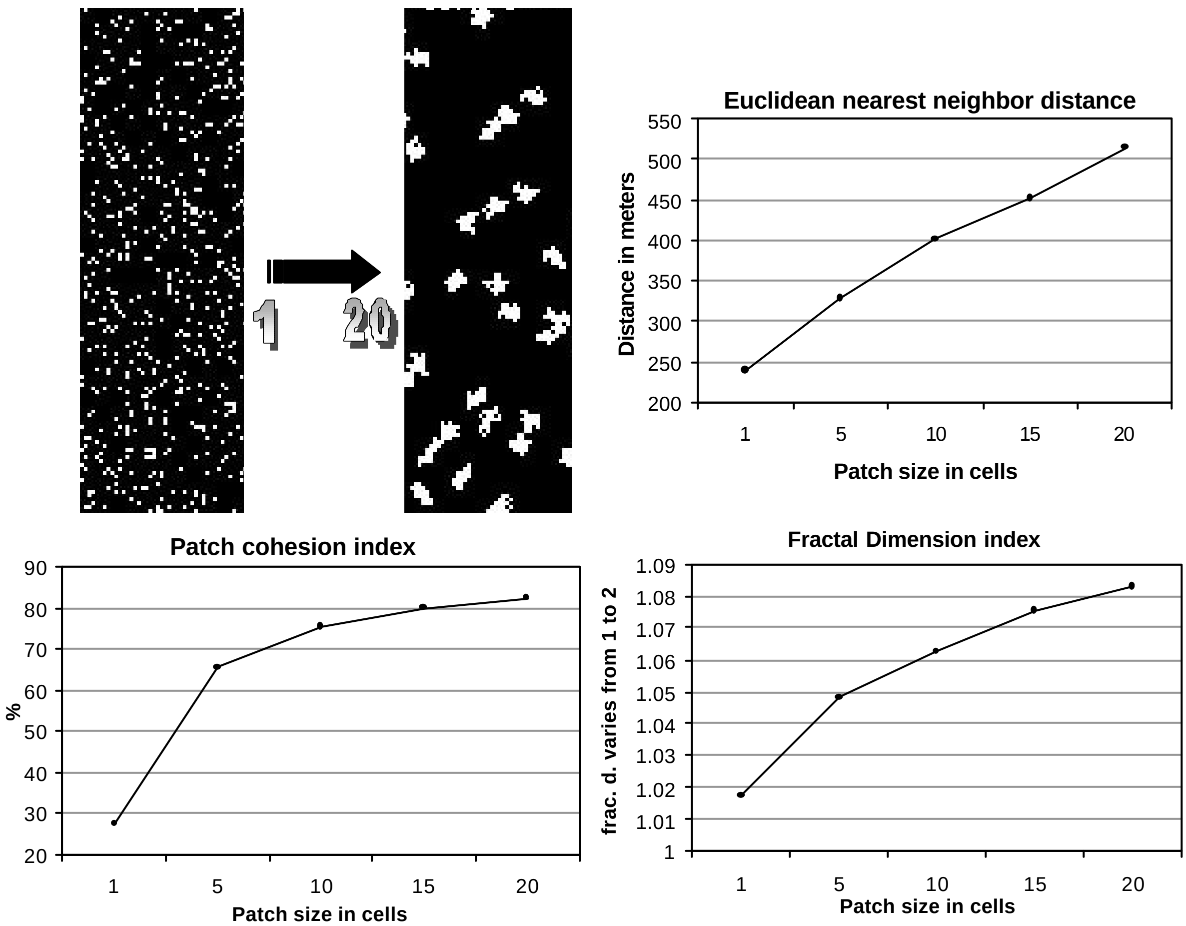

Figure 3. Landscape metrics obtained for the simulation results, varying patch size of H3, from 1 to 20 cells.

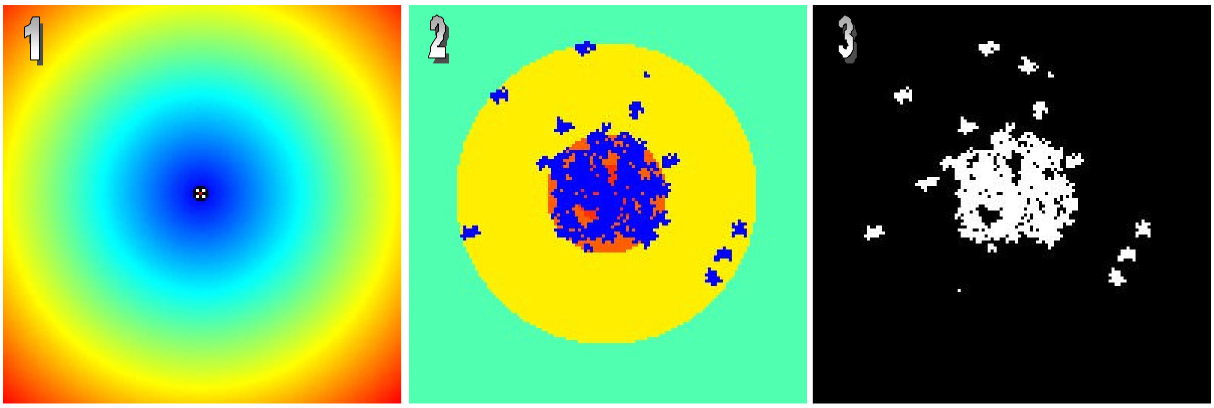

Figure 4. The H6 dataset comprising the static variable map (1), the calculated spatial transition probability map (2), and the simulated landscape (3).

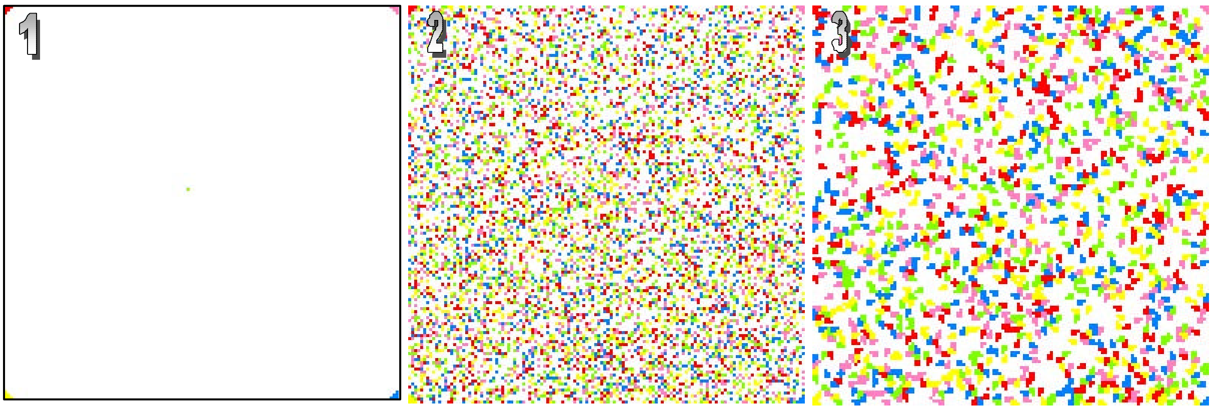

Figure 5. The initial landscape (1), H7 simulated landscape (2), H8 simulated landscape (3).

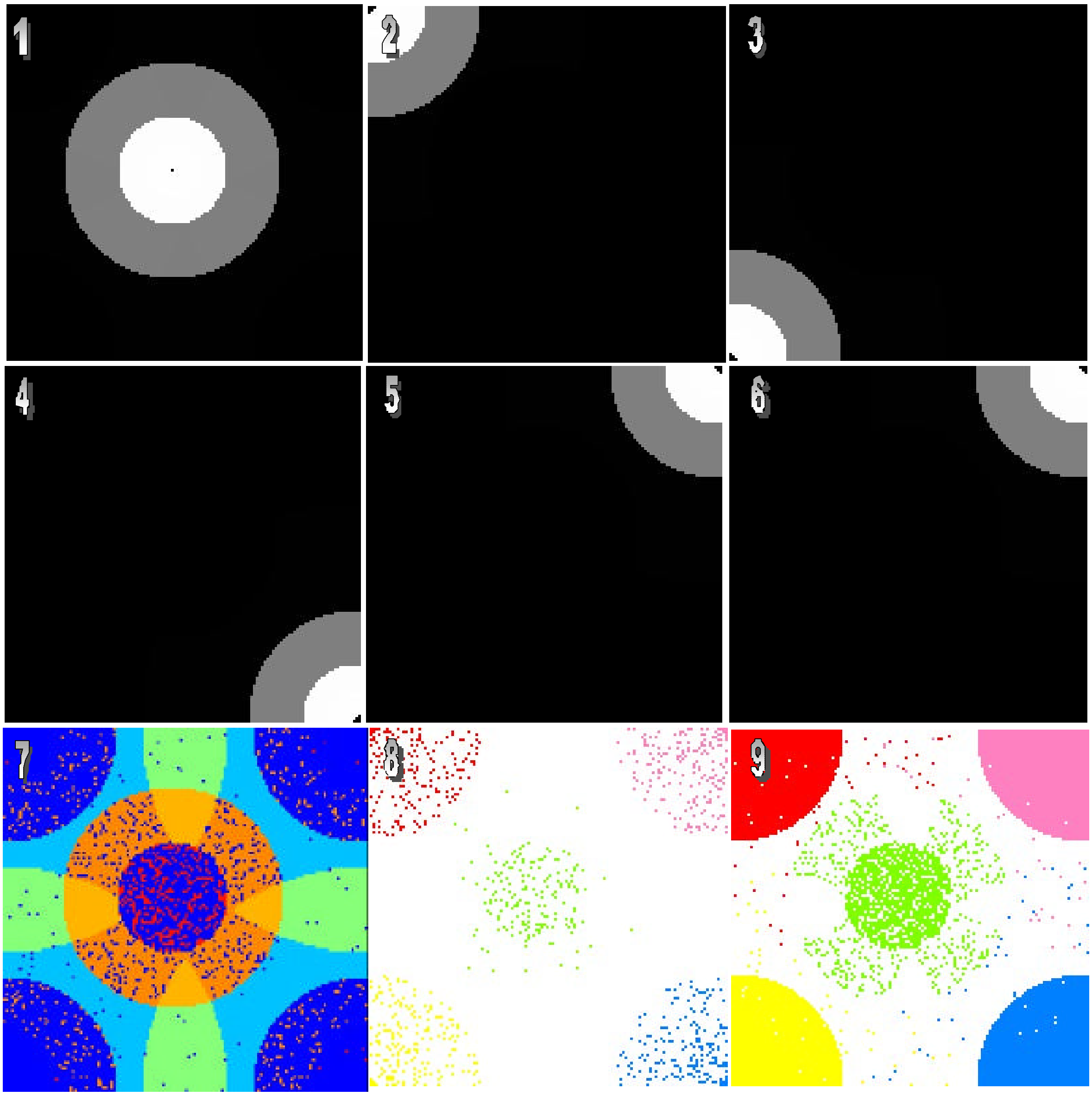

Figure 6. The B&W maps represent the weights of evidence functions, respectively, for transitions 1-2, 1-3, 1-4, 1-5, 1-6; (7) the transition probability map for 1-2 computed by integrating the single weights of evidence functions; 8 and 9 depict the simulated landscape after 1 and 10 iterations.