

MODELING PATCH DYNAMICS FROM INTEGRATION OF CELLULAR AUTOMATA SIMULATION AND HISTORICAL AIR-PHOTOGRAPHS ANALYSIS

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ABSTRACT:

Dynamics in nature are multi-faceted and difficult to follow. Computerized simulations offer new ways for investigating dynamic systems by incorporating their principle aspects . These simulations might be instrumental in discovering fundamental properties of dynamic systems such as duality between fragmentation and shape of changing patch patterns. Do fragmentation processes which occur over a range of scales, from planets to microecosystems, share a common geometrical evolution? Using remote sensing data and computerized simulation, we have formulated and assessed here the duality between geometrical properties of patch patterns. Fragmentation and shape, were found to be mutual and complementary in the way that they change, facilitating reconstruction of patch patterns from partial data over a wide range of natural phenomena.

1. INTRODUCTION

Fragmentation processes occur over a wide range of scales attracting attention in diverse fields of research: planets (Boss, 2000; Mayer et. Al., 2002) forests (Cochrane, 2003), microecosystems (Gonzalez et.al, 1998) and microscopic structures (Ilani et al., 2001). Quantitative measurements of the spatial attributes of fragmentation are mostly incomplete, allowing very limited discrete description of their course of action. While some of these processes are phenomenologically specific, others share common geometrical characteristics (i.e., self similarity (Mandelbrot, 1982)), which may facilitate closing the information gaps. Mutuality and complementarity between fragmentation and shape in patch patterns was observed in an earlier work (Shoshany, 2002).. Here we generalized, formulated and tested a fragmentation – shape duality hypothesis, using both real data and simulation. Its practical implications lie in reconstruction or prediction of spatial behaviour from partial data. The simulation emulates processes combining random patch generation with a non-random element (Hanski & Ovaskainen, 2000) represented by the adhesiveness of new patches to the existing ones.

2. PATTERN PARAMETERIZATION

Landscape ecology terminology was adopted here to allow intuitive interpretation within the context of issues of wide environmental concern, ranging from urbanization to species extinction.

Fragmentation represents (Forman, 1995) the “breakdown of objects into pieces”. It is parameterized mainly by characteristics of the relative size distribution of distinctive (unconnected) patches. Fragmentation is related to the level of connectivity between areas, which needs to be addressed in respect to modes of dispersion and migration of different species (Andren, 1994; Young & Jarvis, 2001) . Incorporating

connectivity within fragmentation analysis can be achieved by adding transition zones or buffers to the delineated patches. In ecological terms, increasing fragmentation represents intensification of disturbance, disconnection and decrease in habitat; while patch expansion and aggregation indicates recovery (Allan et al., 2003; Cochrane, 2003; Hanski & Ovaskainen, 2000) .

Here the parameterization of fragmentation is based on the well known Shannon and Weiner¹³ Information Index,

$$SW = - \sum S_i \ln S_i \quad (1)$$

where S_i represents the relative area of a patch i out of the total area of patches, and the summation is for all patches.

Shape is parameterized mainly according to relationships between perimeter length and area (Forman, 1995). Such parameterization facilitates differentiation in the elongation and convolution of patches, which in turn determine the flow of energy and matter in and out of patches. Increasing the relative boundary length may increase the variability of habitat conditions, which may in turn lead to an increase in species richness and vice versa. Within the context of a pattern of patches rather than an individual patch, the shape is measured using WAP1 and WAP2 weighted area-perimeter indices (Santiago & Javier, 2000) in the form:

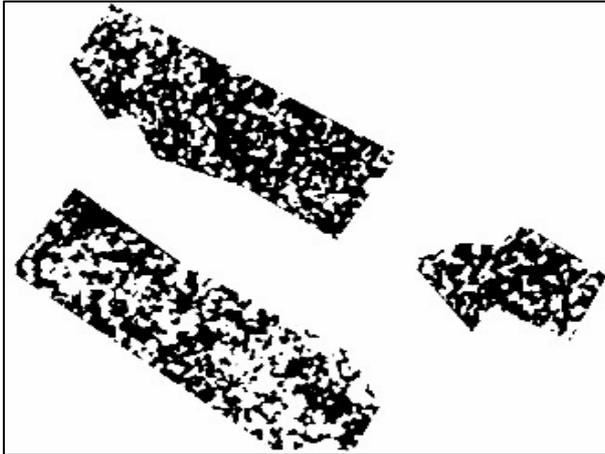
$$WAP_m = \sum S_i * A_i / P_i^m, \quad (2)$$

where A_i and P_i are the area and perimeter of a patch indexed i ; WAP1 and WAP2 are closely related, with the first representing the area per unit boundary length, and the second a dimensionless index .

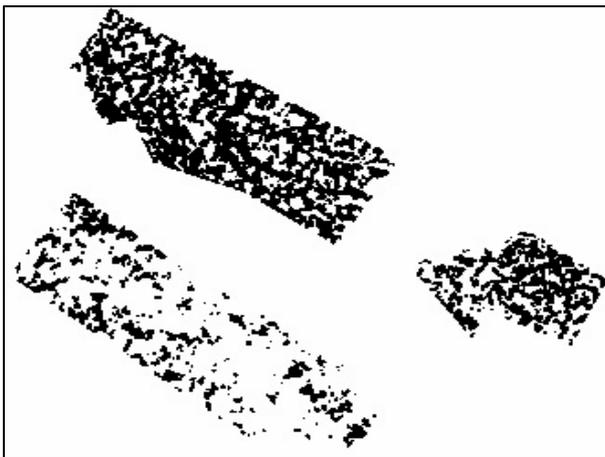
3. DUALITY : FORMULATION AND ASSESSMENT

Duality hypothesis states that there is mutuality and complementarity in the way SW and WAP of patch patterns change and that relationships between SW and WAP represent characteristics of the spatial processes. Relationships between fragmentation and shape were first assessed by us with real patch pattern data derived from processing historical air photographs (Shoshany, 2002) made on three dates between 1956 and 1990 (Figure 1).

1956



1976



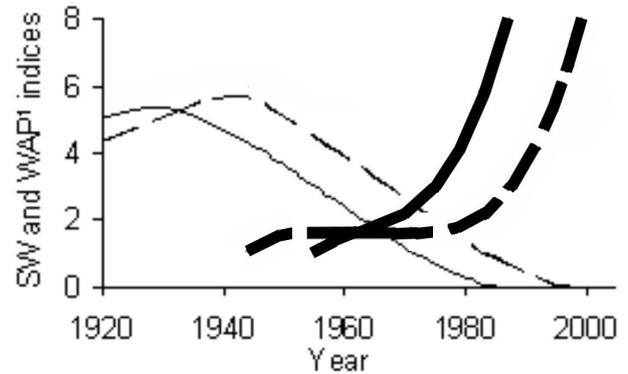
1990



Figure 1. Soil (in black) and Vegetation (in white) patches as mapped from historical air-photographs.

Broadening the information basis was achieved by looking both at soil and vegetation patch characteristics and by utilizing the phase difference in the process between north and south facing slopes (approximately 12 years). A hypothetical continuum of 90 years was thus formed representing the recovery process, from almost bare terrain in 1920 (realistic assumption due to the extensive use of wood for fuel during the Ottoman rule in Palestine) to almost total shrub cover, which could be achieved in 2010.

A



B

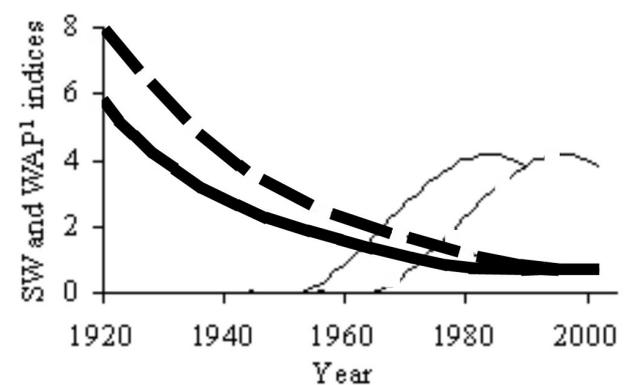


Figure 2. Graphically generalized curves of Shannon and Weiner Information Index (SW) with thin lines and Weighted Area-Perimeter Index (WAP1) with bold lines: vegetation (a) and soil (b) on south facing (broken lines) and north facing slopes (solid lines). Represent extrapolation of data derived from air photographs interpretation for dates between 1956 and 1990.

Figures 2a and 2b provide a graphic generalization of the change in fragmentation and shape within this hypothetical time frame. The WAP1 and SW indices are generally inversely related: while low WAP1 and high SW characterized the initial spread of vegetation or the end of soil fragmentation; high WAP1 and low SW were inferred when vegetation clumped into large patches and when the large soil clumps began to disaggregate. In addition to representing the stages of patch dynamics, these graphs exhibit differences in the rate of change between slope aspects, indicating sensitivity to differences in the types of process occurring respectively on south and north facing slopes. Based on this data, it may be suggested that soil-vegetation patch dynamics is embedded within the generalized graphic description and it furthermore provides empirically based support for the duality hypothesis. Further verification and generalization of the validity of these fragmentation-shape relationships was obtained by simulating patch pattern dynamics.

The patch dynamic simulation here is based on cellular automata with probability transition rules. A 500X500 blank grid is initiated, and N=100 single pixels are colonized at each iteration of an iterative process representing cycles of patch growth. At each iteration, a candidate pixel is selected at random, with its colonization probability dependent on the pixel's neighbourhood. An isolated pixel with no occupied pixels within its 8 neighbour configuration will colonize with probability p_e . An adjacent pixel with at least one occupied pixel within its 8 neighbour configuration will be occupied with the probability p_n . The ratio (Pratio) between p_n and p_e , represents the adhesiveness or contagion of the process: the higher probability of a patch to survive when it joins an existing patch. Following each iteration, when all N pixels were colonized, analysis was conducted of the contiguous pixels forming patches. Area and perimeter were calculated for each patch. SW and WAP2 were then calculated following each iteration. The process was repeated 10 times to allow assessment of variations due randomness.

Time and density are mutually related here, as disturbance and recovery will result in loss or regeneration of patches, while rate of density change will vary between environmental/spatial systems according to their resilience or carrying capacity. Modelling relationships between fragmentation and shape changes with density as an independent variable facilitates generalization and applicability of these relationships to a wide range of phenomena without becoming tied to a specific time scale. Figure 3 plots SW and WAP2 against density as obtained for typical random processes. The patterns of change in fragmentation and shape closely resemble the graphic generalizations of Figure 2. While there are also some differences resulting from the explicit determination of both parameters for the full density range during simulation, the graphic generalizations were most implicit and based on crude assumptions.

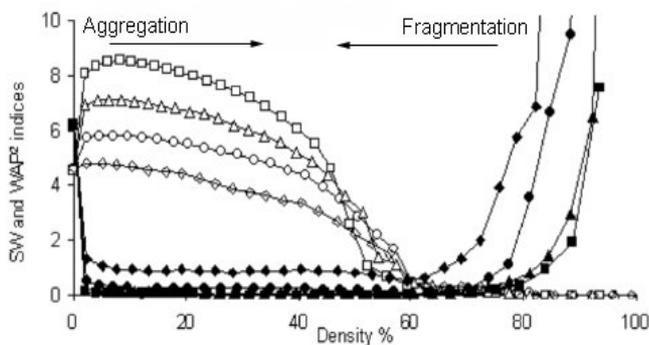


Figure 3. Shannon and Weiner Information Index (SW) with empty symbols and Weighted Area-Perimeter Index (WAP2) with filled symbols for four adhesiveness levels: Pratio=5 (squares), Pratio=50 (triangles), Pratio=500 (circles) and Pratio=5,000 (rhombuses). WAP2 indices are multiplied by $k=10,000$ for demonstrating them on the same graph with SW indices.

Findings from the simulation (Figure 3) allow characterization of forms of change in the following three density ranges:

Low density (< 45%): A clear hierarchy is formed where decrease in adhesiveness increases entropy/heterogeneity at the beginning of the process.

Analysis of patterns produced for 40% vegetation density (Figure 4) with Pratio of 5, 50, 500, and 5,000 respectively, indicates sensitivity of both parameterizations to the differences between patterns. While the SW index represents the distinctive

fragmentation levels obtained for scale differences in adhesiveness, WAP2 response is most expressive only between Pratio of 500 and 5,000. It is moreover interesting to note that WAP2 does not change much in the lower density range as also seen in Figure 2..

Medium Density (between approximately 45 and 65%):

The information content in both parameterizations seems to decrease and form a fuzzy situation where measurements of pattern properties might be confusing.

High density (> 65%):

WAP2 is most sensitive to clumping of small/medium patches into large patches at the end of the vegetation recovery process, or to early fragmentation (using soil/background/matrix terminology) while SW approaches 0. WAP2 exhibits both a high rate of change and a distinctive shift between adhesiveness levels, although this shift is relatively small between Pratio of 5 and 50.

Thus, relative variation in both parameterizations below 45% and above 65% density represents most markedly the duality of the patterns' fragmentation and shape.

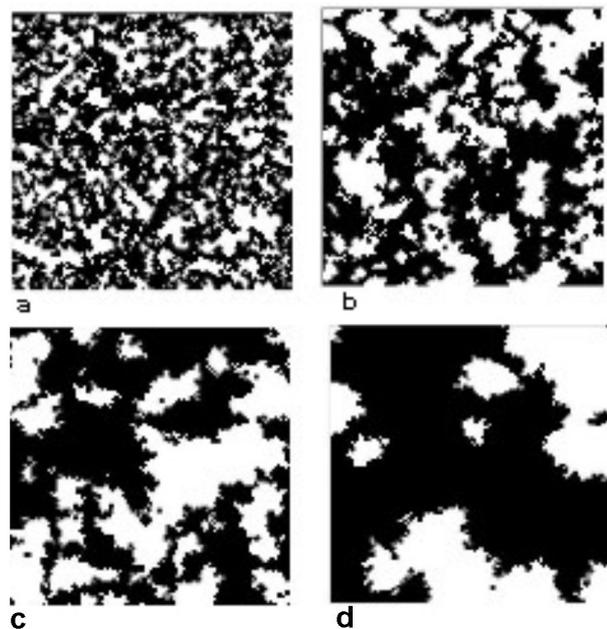


Figure 4. Patch patterns produced by the simulation with density 40% for four adhesiveness levels: a) Pratio=5, b) Pratio=50, c) Pratio=500, d) Pratio=5,000. Note: images represent only a small portion of the simulated patterns

This property allows to predict/reconstruct fragmentation properties attained at the end of the fragmentation process from the shape properties observed at their initial stages, and vice versa. This was exploited, for example, by assessing the correlation between WAP2 reached at several discrete densities between 90% and 80% and the SW levels reached at a density of 15% (Figure 5). High correlation levels were determined for all three linear prediction regression models. Sensitivity analysis of these prediction models, performed by calculating inaccuracies obtained by adding +/-10% to the WAP2 estimates, indicates that they are relatively low: yielding SW differences less than 0.03.

These results might be indicative, in a most general sense, of modeling inverse relationships: from SW to WAP2.

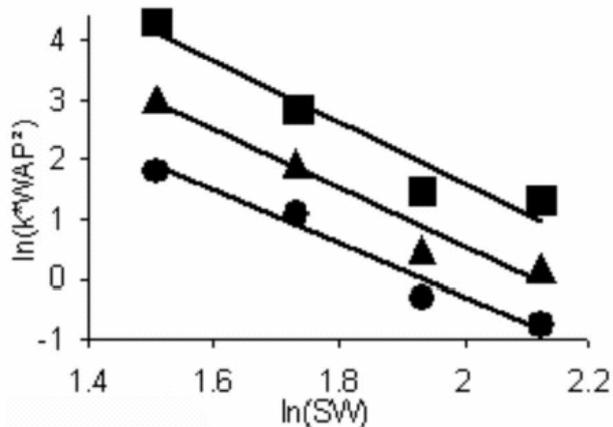


Figure 5. Prediction from duality relationships: Regression graphs (all $R^2 > 0.95$) between Shannon and Weiner Information Index (SW) for 15% density and four Weighted Area-Perimeter Index (WAP2) obtained at three densities: 90% (squares), 85% (triangles) and 80% (circles). Note: WAP2 indices are multiplied by $k=10,000$.

The simulation and the prediction/reconstruction of SW from WAP2 were based on the assumption that the adhesiveness would not change significantly during the process. Such an assumption would not hold in many instances: for example, where there would be species change or where habitat conditions (carrying capacity) would deteriorate. In these cases the fragmentation or shape evolution would not follow the trajectories predicted by the simulation as conducted here. However, the results presented here suggest that both at the beginning and end of the fragmentation process there is high sensitivity to the adhesiveness, which may allow detection of its change. Relating observed trajectories to simulated trajectories may then infer the change in adhesiveness, which could be related to structural changes in the ecosystem.

4. SUMMARY AND CONCLUSIONS

Both remote sensing data and patch pattern simulation presented here, suggest duality between fragmentation and shape changes in patch dynamics: the pattern changes seem to be mutually and informationally complementary. Furthermore, fragmentation and shape duality might indicate informational and functional duality in patch pattern dynamics: where fragmentation level characteristics affect the disturbance/recovery mechanisms and vice versa. These two levels of duality must be further assessed with real-world data and other forms of simulation to reveal their modes of mutual change. From a broad scientific perspective, the importance of research into dualities is enhanced by the exponential growth of the volume of information in diverse fields, calling for the identification of generalizations, which go beyond specific phenomenology.

5. REFERENCES

- Allan, B. F., Keesing, F. & Ostfeld, R.S., 2003. Effects of Forest fragmentation on Lyme Disease Risk. *Conserv. Biol.* **17**, 267-280.
- Andren, H., 1994. Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. *Oikos* **71**, 355-366.
- Boss, A.P., 2000. Star formation: Three's a crowd. *Nature* **405**, 405-407.
- Cochrane, M.A., 2003. Fire science for rainforests. *Nature* **421**, 913-919.
- Forman, R.T.T., 1995. *Land Mosaics. The ecology of landscapes and regions* (Cambridge University Press, Cambridge,
- Gonzalez, A., Lawton, J.H., Gilbert, F.S., Blackburn, T.M. & Evans-Freke, I., 1998. Metapopulation Dynamics, abundance and Distribution in Microecosystem. *Science* **281**, 2045-2047.
- Hanski, I. & Ovaskainen, O., 2000. The metapopulation capacity of a fragmented landscape. *Nature* **404**, 755-758
- Ilani, S., Yacoby, A., Mahalu, D. & Shtrikman, H., 2001. Microscopic structure of the Metal- Insulator Transition in Two Dimensions, *Science* **292**, 1354-1357.
- Mandelbrot, B., 1982. *The Fractal Geometry of Nature* (Freeman, San Francisco.
- Mayer, L., Quinn, T., Wadsley, J. & Stadel, J., 2002. Formation of Giant Planets by fragmentation of Protoplanetary Disks, *Science* **298**, 1756-1759.
- Shannon, C.E. & Wiener, W., 1949. *The Mathematical Theory of Communication* (University of Illinois Press, Urbana.
- Santiago, S. & Javier, M-M., 2000. Landscape patterns simulation with modified random clusters method. *Landscape Ecol.*, **15** 661-678.
- Shoshany, M., 2002. Landscape fragmentation and soil cover changes on south- and northfacing slopes during ecosystems recovery: an analysis from multi-date air photographs, *Geomorphology* **45**, 3-20.
- Young, C.H. & Jarvis, P.J., 2001. Measuring urban Habitat fragmentation: an example from the Black Country, UK. *Landscape Ecol.* **16**, 643-658.