

## Weighted mean patch size: a robust index for quantifying landscape structure

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Accepted 22 March 1997

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### Abstract

Variables such as number of patches and mean patch size have been widely used to describe landscape structure. However, these simple, independent measurements often fail to adequately represent or track offsetting or reinforcing changes that occur from interactions between patch number, size and shape. Here, we present a synthetic ‘weighted mean patch size’ (WMPS) index which combines information represented in patch size and number. The utility of the WMPS index, which was based on percolation theory, is demonstrated using two data sets. The first data set consisted of output from a cellular automata-based simulation of landscape response to disturbance that varied in intensity and scale. Unlike simple estimates of mean patch size, the WMPS index was highly sensitive to disturbance and varied in a consistent fashion with both intensity and scale of disturbance. The second application involved the use of historical aerial photography to compare the dynamics of tree/shrub clusters (= patches) in a subtropical savanna parkland during a period of drought (1941–1960) and a period of normal to above-normal annual rainfall (1960–1983). Contrary to expectations, mean cluster (= patch) size increased in both periods. In addition, greatest increases in mean patch size occurred during the drought period, apparently the result of higher mortality among small clusters relative to large clusters. In contrast, climate-induced vegetation dynamics indicated by the WMPS index (decrease during drought period; increase in subsequent pluvial period) tracked those of other structural measurements (cluster density, total cover, cluster growth rate) and appeared to reflect dynamic, rainfall-induced changes in patch structure associated with changes in tree and shrub canopy area and plant numbers. These examples suggest the WMPS index, by combining information on patch size and number, can preserve process-level ecological information and provide robust, functionally relevant numerical representations of landscape structure over time and in response to disturbance. © 1997 Elsevier Science B.V.

**Keywords:** Cellular automata; Patch size; Disturbance; Landscape response; Savanna; Spatial patterns; Vegetation dynamics

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## 1. Introduction

Landscapes are complex ecological systems that operate over broad spatio-temporal scales (O'Neill et al., 1989). Part of this complexity reflects climatic variability and topoedaphic heterogeneity; part of it is the result species with contrasting life histories (Huston and Smith, 1987) responding to multiple disturbances operating at different spatial and temporal scales (Collins, 1987). The result can be a shifting-mosaic of patches across the landscape over time (Remmert, 1991; Callaway and Davis, 1993). The response of heterogeneous landscapes to disturbance has received considerable attention (Turner, 1987; Turner et al., 1989; Li and Forsythe, 1992; Baker, 1993, 1995; Loehle and Li, 1996). However, the interpretation of landscape structure and its response to disturbance is often constrained by lack of long-term data (Baker, 1995) and by a lack of suitable methods for quantitatively monitoring and analyzing pattern and change in a functionally meaningful manner. Where long-term data are available, patch size and spatial scale are important attributes that can significantly influence data interpretation (Fuhlendorf and Smeins, 1996).

Several indices for measuring landscape pattern and change exist (c.f., O'Neill et al., 1988; Li et al., 1992; Hulshoff, 1995). These were developed from statistical measures of dispersion (Pielou, 1977), information theory (O'Neill et al., 1988), fractal geometry (Krummel et al., 1987; Milne, 1992; Plotnick et al., 1993; Li (in press) and percolation theory (Gardner and O'Neill, 1991; Gardner et al., 1993; Li et al., 1996). Such indices can be useful for evaluating spatial patterns and landscape heterogeneity, but cannot be used to quantify landscape response to different disturbances across scales. For example, Hulshoff (1995) compared five landscape indices (the proportion of land use types, patch number, mean patch size, and two indices of patch shape) for describing change on a Dutch landscape from 1845–1982. None of these explicitly tracked changes in geographical locations of patches. As a result, nothing could be induced with respect to real landscape dynamics. As shown in the simple

example in Table 1, mean patch size can be identical for landscapes with quite different patch structures. Thus, a landscape with many small patches may have a mean patch size identical to that of a landscape with fewer, larger patches. It is therefore desirable to develop a method which not only quantifies changes in landscape pattern but which also reflects scale-dependent processes producing changes in pattern.

In this paper, we describe a 'weighted mean patch size' (WMPS) index based on percolation theory. We then evaluate the WMPS index performance using (a) output from a cellular automata-based simulation model of landscape response to disturbance at various intensities and scales; and (b) historical aerial photographs which document changes in savanna parkland vegetation patches in response to annual rainfall.

## 2. A new index

Percolation theory (Kesten, 1982; Stauffer, 1985) has been used to generate simple, random maps as neutral models in landscape ecology (Gardner and O'Neill, 1991), to model the spread of disturbance (Turner et al., 1989), and to model

Table 1  
Comparison of mean patch size (MPS) and weighted mean patch size (WMPS; Eq. (1)) on three hypothetical landscapes, each with  $n =$  ten patches

Patch ( $n_s$ )	Patch size ( $s$ )		
	Example no. 1	Example no. 2	Example no. 3
1	10	5	10
2	10	5	2
3	1	5	2
4	1	5	2
5	1	1	2
6	1	1	2
7	1	1	1
8	1	1	1
9	1	1	1
10	1	1	1
MPS	2.8	2.8	2.8
WMPS	7.4	4.1	5.2

forest spread and spatial phase transitions at forest-prairie ecotones (Loehle et al., 1996). Percolation-based simulation and associated analytical methods have provided a means of evaluating the significance of landscape patterns. For example, mean squared radius has been used as a measure of habitat dispersion and correlation length as the average distance between two suitable habitat sites in ecosystem fragmentation studies (Gardner et al., 1993). Li et al. (1996) used a percolation model to test size dependence of microbial particle diffusion and to estimate complexity of microbial transport in fractal space. Here, we use percolation theory to characterize multi-scale landscape response to disturbance.

Consider a landscape where the number of patches,  $n$ , of size,  $s$ , is  $n_s$ . On the basis of percolation theory, there is probability  $n_s/s$  that an arbitrary site (occupied or not) belongs to a given patch size class and a probability  $\sum n_s/s$  that a given patch size class occurs at a finite set of locations on the landscape (see Stauffer, 1985 for derivation and elaboration). Thus,  $w_s = n_s/s / \sum n_s/s$  is the probability that a given patch type size class, when randomly assigned landscape locations, will occupy exactly  $s$  sites. The weighted mean patch size (WMPS) index, which we are measuring in this process of randomly disturbing patches across the landscape, is

$$\text{WMPS} = \sum w_s s = \frac{\sum n_s s^2}{\sum n_s s} \quad (1)$$

where  $n_s$  is the number of patches of size  $s$  per site and  $w_s$  is the weighting factor.

The WMPS index, when applied to the hypothetical data in Table 1, changed as the proportionate distribution of patch sizes changed. Mean patch size (MPS) was static, despite differences in patch structure on the three landscapes. Taken at face value, MPS gave no indication that these landscapes differed in ways that were ecologically significant. In contrast, WMPS captured and conveyed information of potential functional significance.

### 3. Applications

The utility of the WMPS index for assessing spatio-temporal variation in landscape structure will be further demonstrated on two data sets. The first application involves output from cellular automata (CA)-based simulation of a multi-patch landscape subjected to different disturbances (Li and Forsythe, 1992). The second application was used in conjunction with historical aerial photography to assess the dynamics of woody plant clusters in a south Texas savanna over a 50 year period encompassing contrasting annual rainfall regimes (Archer, 1995a; Li, 1995).

### 4. Simulated disturbance effects

Initial conditions consisted of distributing seven to ten vegetation patch types randomly among  $64 \times 64$  non-overlapping grid cells of equal size and allowing expansion into neighboring cells as described by Inghe, 1989. This initial simulation represented the structural development of a non-disturbed landscape. The steady-state landscape was then subjected to disturbance regimes of contrasting grain and extent. The disturbance regimes imposed at every time step in the model were of grain  $G = 1$  to  $G = 20$  ( $G =$  the side length of a single disturbance cell) and extent  $E = 400, 800, 1200, 1600$  or  $2000$  ( $E =$  the total number of cells disturbed). Disturbed cells were emptied or cleared of vegetation. Following clearing, cells were then re-occupied according to cellular automata rules described by Inghe, 1989 and Li and Forsythe, 1992. We computed MPS and weighted mean patch size (WMPS; Eq. (1)) for each time step in these simulations and for the landscape developing under non-disturbed conditions.

Under conditions of no disturbance, the WMPS index generated a smooth, saturating curve of vegetation patch dynamics of a shape and behavior similar to that produced by mean patch size (MPS) (Fig. 1). The larger values for WMPS reflected the greater influence of large patches on landscape structure. This feature preserved more patch size information than the simple MPS index and may therefore make the WMPS index more

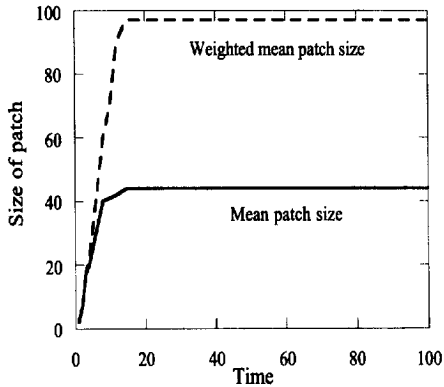


Fig. 1. Comparison of weighted mean patch size (WMPS) and mean patch sizes (MPS) for a landscape assigned patch types at randomly selected cell locations at time,  $t=0$  and allowed to expand according to rules described in Inghe, 1989 and Li and Forsythe, 1992.

ecologically meaningful when describing landscape structure.

Landscapes experiencing disturbances at different scales or intensities will produce patches of different sizes. However, simple computation of mean patch size did not convey the relative importance of patch size versus number of patches on the landscape (Table 1). Fig. 2 shows changes in landscape structure resulting from a disturbance regime of  $G=1$ ,  $E=2000$  and  $G=10$ ,  $E=400$  after 100 time steps. The computed WMPS index for each of these landscapes and for landscapes experiencing a range of disturbance grain and extent was very responsive and changed in a consistent fashion (Fig. 3). When disturbances were fine-grained ( $G=1$ ), WMPS increased steadily with decreasing disturbance extent (Fig. 3a). When disturbance grain was increased ( $G=10$ ), different behaviors were evident (Fig. 3b). WMPS was similar at disturbance intensities ranging from  $E=400$  to 1200. Increasing disturbance intensity to  $E=1600$  significantly decreased WMPS and, somewhere between  $E=1600$  and 2000, a critical threshold was reached where recolonization of vacated cells ceased. When the scale of disturbance was increased to  $G=20$ , WMPS was comparable at lower intensities ( $E=400-800$ ) but colonization of vacated cells ceased at  $E>1200$  (Fig. 3c). The importance

of grain or scale of disturbance and its interaction with disturbance intensity to affect patch size at greater than 150 time-steps is summarized in Fig. 4. Where the intensity ( $E$ ) of disturbance was relatively low, WMPS increases with increasing scale of disturbance ( $G$ ). At the other extreme, where intensity of disturbance was high, changes in WMPS with increasing scale of disturbance was of little consequence. At intermediate intensities of disturbance, WMPS increased with increasing scale of disturbance to some critical threshold, then sharply decreased.

#### 4.1. Climate influence on shrub patch dynamics

The vegetation in southern Texas has been undergoing a phase change from grassland to thorn woodland over the past 100 years (Archer, 1995a). The driving force for this transformation appears to reflect alterations of grazing and fire regimes since settlement (Archer, 1995b; Archer et al., 1995). Upland portions of the present landscape consist of discrete shrub clusters embedded within a grassy matrix (Fig. 5). It is hypothesized that this two-phase vegetation pattern is an intermediate stage in the conversion of a monophasic grassland to monophasic closed-canopy woodland (Archer et al., 1988; Scanlan and Archer, 1991). This occurs as new clusters are initiated and existing clusters enlarge and coalesce. Small clusters enlarge at a greater rate than large clusters (Archer et al., 1988). In addition, as clusters develop, herbaceous production decreases, carrying capacity for wildlife and livestock changes and woody plant and soil C and N accumulate. Changes in cluster (= patch) number and size are thus an important feature of vegetation dynamics on this landscape and directly influence the functional ecology of this system.

The size-class distribution, density and total woody cover of clusters on upland portions of the landscape have been quantified on historical aerial photographs from 1941, 1960 and 1983 (Archer et al., 1988). We used this cluster size data to compute the WMPS index for upland portions of the landscape. The WMPS index (Fig. 6d) closely tracked other independent measures of landscape structure (total woody cover and cluster density

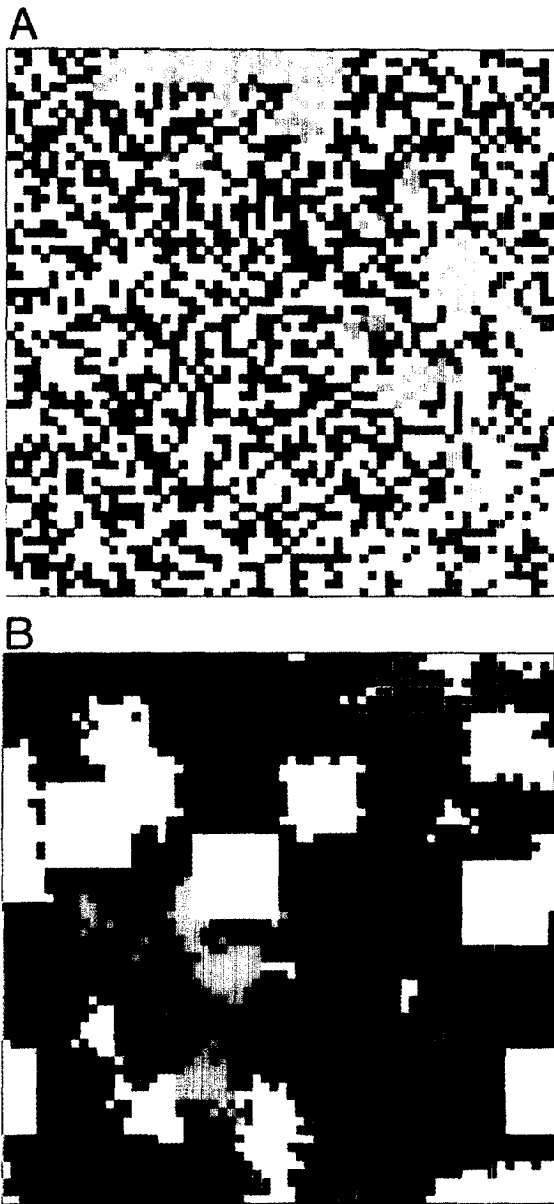


Fig. 2. Changes in landscape structure resulting from disturbance at two scales and intensities after 100 time steps. (A) Disturbance grain ( $G$ ) = 1 = side length of cells disturbed and extent ( $E$ ) = 2000 = total number of cells disturbed; and (B)  $G$  = 10 and  $E$  = 400. Colors represent different types of vegetation patches.

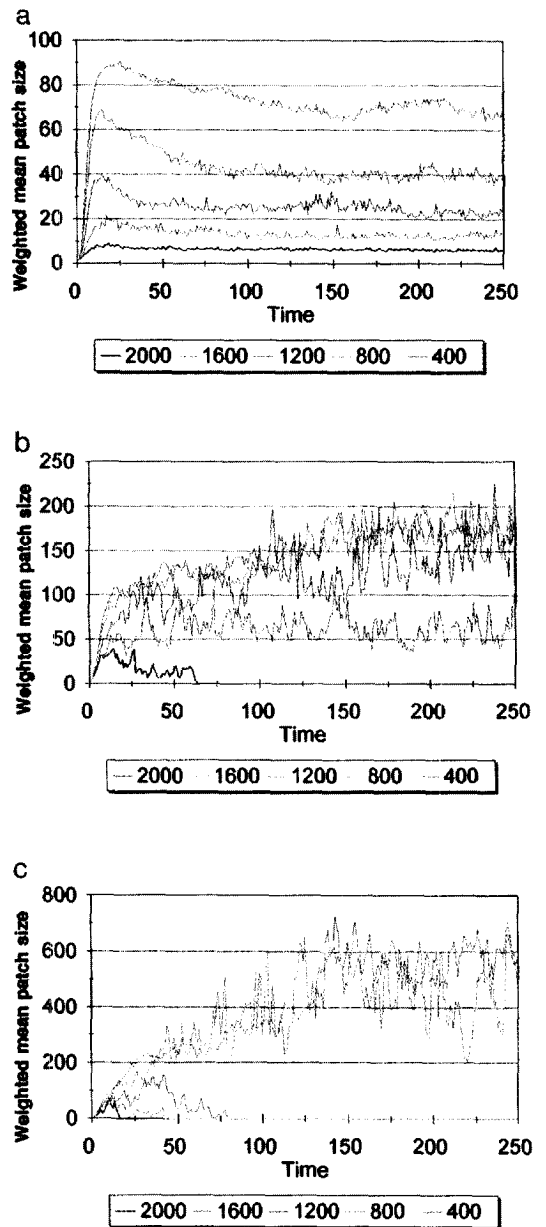


Fig. 3. Weighted mean patch size (WMPS) of a simulated vegetation on a landscape receiving disturbances ranging in extent ( $E$ ) from 400 cells to 2000 cells at different scales ( $G$  = side length of grid cells) fixed at (a)  $G$  = 1 (b)  $G$  = 10 and (c)  $G$  = 20.

[Fig. 6a and 6b]) and growth rates of individual clusters (lowest in 1941–1960; highest in 1960–1983). Each of these measures indicated the adverse effect of the severe drought of the 1950s on woody vegetation and a period of woody plant recruitment and canopy expansion in the post-drought, pluvial period from 1960 to 1983. In contrast, mean cluster (= patch) size increased throughout the 42 year period, with greatest increases occurring during the drought period. This counter-intuitive result partially reflects an inflation of the mean size because of high mortality among small (young) clusters. As such, it misrepresents significant functional changes in patch structure associated with reductions in leaf area, woody plant growth rate and increases in individual plant mortality known to occur during periods of low rainfall and the reversal of these trends during years of higher rainfall. This example indicates the pitfalls of interpreting mean patch size data and the advantages of using WMPS. In this case study application, the WMPS index has preserved process-level ecological information reflecting dynamic, rainfall-induced changes in patch structure associated with changes in tree and shrub canopy area and plant numbers. As a result, the functional consequences of changes in patch structure were consistent with expectations and were more readily apparent.

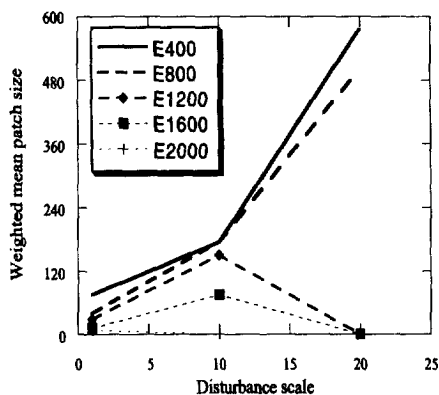


Fig. 4. Comparison of changes in weighted mean patch size (WMPS) across a range of disturbance scales (grain), as influenced by extent ( $E$ ) or intensity of disturbance.



0 100 200 m

Fig. 5. Aerial view of a savanna parkland landscape in southern Texas, USA (scale is approximate). Discrete *Prosopis* mixed species shrub clusters and groves (dark, circular patches) are embedded in a continuous matrix of grasses (grey areas) to produce a two-phase vegetation pattern in uplands. These uplands grade (1–3% slope) into lowlands are dominated by closed-canopy *Prosopis* woodlands. Changes in size of upland clusters (= patches) from 1941 to 1983 (Archer et al., 1988) are used to illustrate the utility of the weighted mean patch size index described in this paper.

## 5. Discussion and conclusions

Patch size can affect response to disturbance (Turner, 1987; Li and Forsythe, 1992; Yates et al., 1994; Loehle and Li, 1996). Conversely, disturbance at different scales and intensities can influence patch size and shape across a landscape (Pickett and White, 1985; Baker, 1993, 1995). It is therefore useful to quantify and track changes in the type, size and number of patch types on landscapes (Turner et al., 1989). Descriptions of landscape structure based simply on the number of patches or mean patch size often do not adequately capture functionally important aspects of patch size-number interactions or patch dynamics over time (Table 1, Fig. 6c). With this in mind, we propose a 'weighted mean patch size' (WMPS) index. The examples presented illustrate that while both indices can describe the structure of

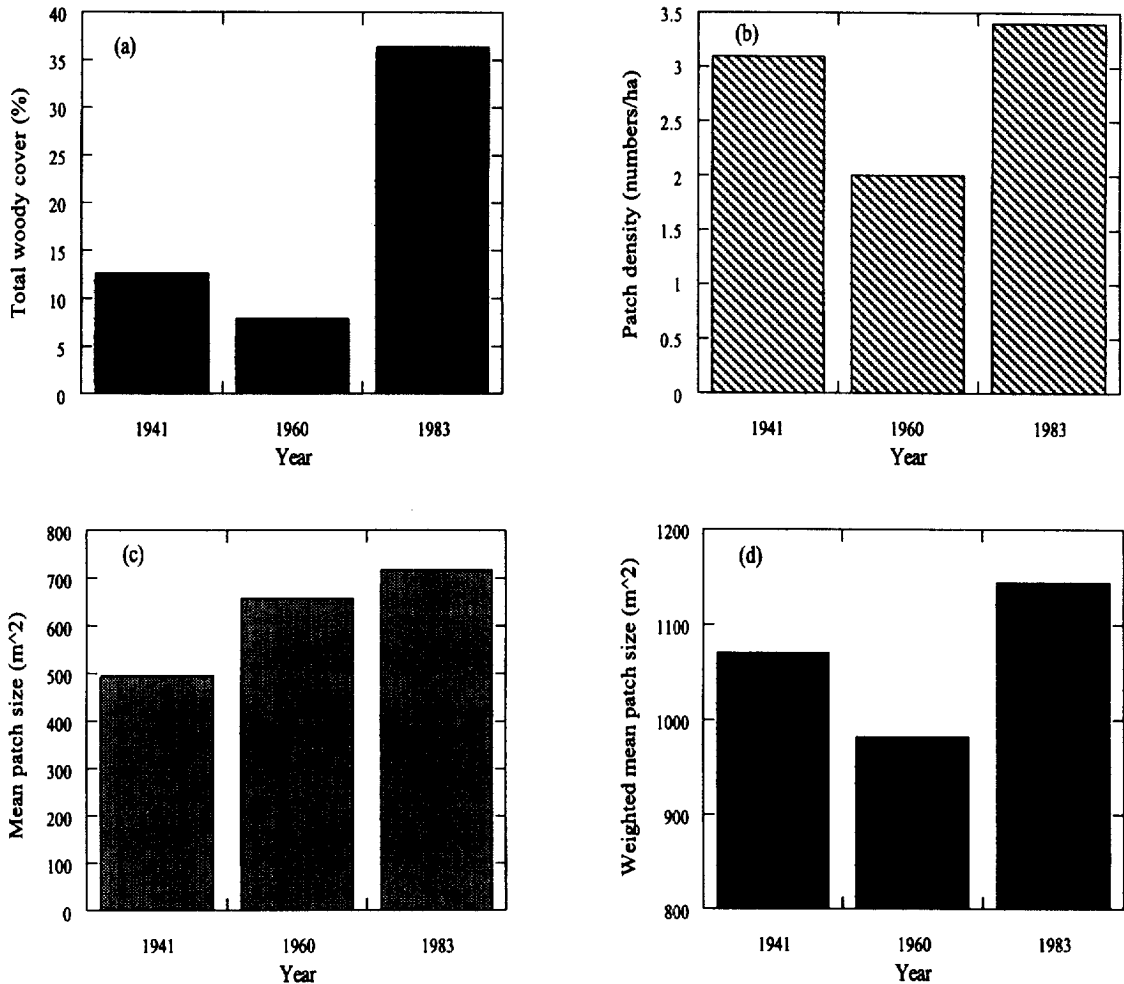


Fig. 6. Dynamics of woody vegetation in a southern Texas savanna from 1941 to 1983 as indicated by (a) total woody cover, (b) shrub cluster density, (c) mean cluster size and (e) weighted mean patch size (WMPS). The 1941–1960 period was characterized by severe drought in the 1950s, whereas the 1960–1983 period generally received normal to above-normal annual rainfall. Data in (a)–(c) from Archer et al., 1988; WMPS computed from data in (c).

landscapes (Fig. 1), the MPS index may be of limited utility in cases (a) where the size class distribution of patches changes without changes in mean size (Table 1); (b) where changes in mean size result from disproportionate mortality or recruitment of certain size classes (Fig. 6c); or (c) where disturbance causes changes in patch structure with time (Fig. 3 and Fig. 4). In contrast to mean patch size, the WMPS index was dynamic with respect to disturbance and environmental effects on landscape structure. As a result, the

WMPS index can be monitored and changes in its value with can serve as an indicator of functional changes in ecosystem or landscape organization (Fig. 4 and Fig. 6d).

From a linear perspective, changes (increases or decreases) in disturbance intensity and scale are often presumed to elicit proportionate, parallel changes in system behavior. While this may hold true for some specified range of disturbance scales or intensities, landscape structure may change dramatically and unexpectedly at certain scales or

intensities of disturbance or environmental change to produce non-linear behavior (Fig. 3 and Fig. 4). The WMPS index appeared to be capable of expressing threshold behavior and describing linear and non-linear landscape response to disturbance across a wide range of spatial and temporal scales. The WMPS index could be used directly for lattice (or grid-cell) raster data analysis (Fig. 2) of a satellite image or aerial photograph or easily extended for polygon-geometric data analysis (Fig. 6). In either case, one could use continuous patch size data, or, discrete patch size-class data to perform the WMPS calculation.

The WMPS index combined the information contained in separate measurements of patch number and mean patch size and provided a new and more explicit measure of patch structure on a landscape. Our examples suggest the WMPS index can provide robust, functionally relevant numerical representations of landscape structure over time and in response to disturbance.

### Acknowledgements

Special thanks to Bob Gardner, Craig Loehle and Ed Rykiel, for their valuable discussions regarding earlier drafts of this manuscript. Bill Forsythe provided computer program support. The research was partially supported by the National Science Foundation Ecosystems Studies Program under grant BSR 91–09240 and by NASA Earth Observation System grant NAG-2662.

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