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Detecting fine-scale disturbance in forested ecosystems as measured by large-scale landscape patterns

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As GIS-based and satellite data have become increasingly accessible, it is possible to integrate empirical and simulation approaches to pattern analysis and to translate knowledge of ecosystem processes at the stand level to landscape and regional scales. As a result, there has become an increased reliance on pattern to provide insight into understanding ecological processes. Because different processes may produce similar patterns, there is a critical need to understand what information regarding ecosystem processes (e.g., disturbance) is retained and detectable from quantitative measures of spatial pattern. The relationship between statistical and ecological measures of pattern and process in the Pacific Northwest, USA, is explored using simulated landscapes generated by varying disturbance events. Simulation results indicate that statistical significance of pattern does not correspond systematically to ecological significance. A predictable correspondence between process (i.e., fine-scale disturbance) and pattern (i.e., large-scale landscape structure) only occurred consistently under the restricted conditions of intense or multiple-event disturbances.

Introduction

The past few years have been marked by an unprecedented burgeoning of geographic information systems (GIS) and remote sensing applications in natural resource sciences and ecology. These applications span physical scales ranging from the microscopic (e.g., soil structure profiles) to regional and global scales. Regionalized variable analysis (e.g., spatial statistics) is undergoing a similar revival in the environmental sciences (Ford and Renshaw, 1984; Bradshaw, 1991; Turner *et al.*, 1991). With a parallel growth in computer technology, an increased reliance on these techniques is anticipated (Stafford *et al.*, this volume).

The new directions in database quantity and quality have shifted the research focus from fine-scale sampling to landscape and higher order scales where the spatial and temporal patterns of data are considered explicitly. Ecosystem

scientists are working not only with multivariate data sets but also with multi-scale datasets, and hence the errors associated with each data layer. With increased usage of and reliance on raster- or vector-based databases such as satellite imagery and digital maps, it is essential to establish an understanding of the information content of landscape patterns in both a rigorous and quantitative manner. As a result of the growing technology, we are confronted with new problems that are both ecological and statistical in nature. One of these issues deals with pattern explicitly: what is the ecological and statistical significance of pattern?

A plethora of landscape metrics, statistics, time-series techniques and geostatistical methods are employed for the sole purpose of identifying pattern (e.g., Milne, 1988; Legendre and Fortin, 1989; Cohen *et al.*, 1990; Turner *et al.*, 1991; Bradshaw and Spies, 1992). Based on these methods, comparisons between landscapes and inferences relating to these statistical measures are drawn. Now that the initial excitement of the discovery of spatial pattern has passed, scientists are left with the less glamorous task of determining what the real significance of these numbers is relative to the ecosystem processes responsible for pattern generation; namely, determination of ecological and statistical significance of spatial pattern. Ecological significance does not necessarily imply statistical significance and vice versa.

For example, if a landscape has sustained two types of disturbance (e.g., fire and bark beetle outbreak) over a given time period, it is ecologically significant if one disturbance consistently occurs prior to the second disturbance event. In the case of a beetle outbreak, a consistent ordering of events may imply cause and effect, that is, the presence of fire may be required to precondition the susceptibility of the forest to beetle outbreak. However, measures of landscape pattern in the two distinct cases may not be distinct statistically. Subtle but important differences may fall below a statistically significant threshold. As a result, there may be limits to extracting process-related information solely from spatial and non-spatial patterns. This is particularly true if pattern is measured and evaluated using remote sensing techniques without field reconnaissance. Understanding the link between ecosystem processes and their related patterns as defined in a rigorous statistical and ecological sense will require the integration of both ecological and statistical analyses.

We provide an overview of the problems associated with inferring process from pattern and discuss concepts of the pattern-process duality leading to the relationship between ecological and statistical significance of landscape pattern. To illustrate some of these concepts for the Pacific Northwest (PNW), we designed a spatial simulation model to produce landscape patterns under varying sequences and intensities of natural disturbance. These simulations represent a pilot study to: (1) determine the statistical significance of landscape patterns, and (2) begin to unravel process attributes (e.g., type, intensity, sequence, size of disturbance) by examination of a given landscape pattern. Although the simulation study is directed at the landscape scale, it is amenable for application at larger scales as well.

Landscape Pattern-process Duality

During the past several years, the number of landscape- and regional-scale ecological studies has increased dramatically. In contrast to prior ecological analyses, the unit of study is now focused at the landscape level where the type, arrangement and function of its component parts are studied to understand the higher order spatial unit, the landscape. The exact dimensions of a landscape may vary according to a given ecosystem or biome. Obtaining a strict definition of a landscape is perhaps less important than understanding what the approach affords. Landscape ecology examines the interactions and relationships between individual biological and physical components which compose the system within the relevant temporal and spatial context (Forman and Godron, 1986). The underlying assumption is that these individual components (e.g., landscape subunits) are to varying degrees interdependent. Traditionally, the approach has been to view the system in terms of its pattern and processes. Implicit in this approach has been the underlying premise that pattern provides a window by which processes can be divined. While the pattern-process paradigm is well established, there is still a poor understanding of this relationship at the landscape scale, for several reasons.

A historical factor contributing to this pattern-process duality has its roots in the origin of landscape ecology itself. In Europe where many landscape ecology principles were first applied, the link between pattern and process is more obvious than in less developed landscapes of western North America. European landscapes have been organized in several iterations of human activities over the past centuries; Roman roads, Gaul settlements, and a further patchwork of private and state agricultural lands and forests. French farmland, English hedgerows, German farm and forest lands, and Dutch shelterbelts are landscape patterns as familiar as our own American lands (Forman and Godron, 1986). Even in the Alps, the signature of human activities is strongly etched in the landscape. The processes that are responsible for dominant structures forming these landscapes, namely, human activities, are readily observable within a lifetime. As a contrasting example, the conifer-dominated landscapes of the Pacific Northwest pose a different set of conditions. Here the sources and types of processes that form landscape patterns are less straightforward because of differences in the historical development of human activity in the landscape (Ripple *et al.*, 1991). Until only recently the signature of natural disturbance patterns has been masked by intense timber harvesting and road construction.

In addition, the accessibility of computer graphics technology, GIS, and spatial statistics has facilitated the first step in landscape analysis by allowing ecosystem scientists to identify and quantify landscape patterns. As a result, there is generally a better understanding of the range and types of landscape pattern in natural systems rather than the processes responsible for their generation. Thus, while we are much more cognizant of the types of patterns found in the Pacific Northwest forests (e.g., Ripple *et al.*, 1991, Spies *et al.*, in

press), the identification of landscape-level processes is only beginning. Few studies exist which translate knowledge of the ecosystem to an explicit spatio-temporal context. In general, among empirically based work, there is a tendency to find highly technical studies on landscape pattern and more qualitative studies describing landscape processes.

Sufficient quantitative information relating disturbance processes to resultant landscape patterns (i.e., stand structure, location and extent) is lacking. While certain processes might be related to an observed pattern (e.g., forest stand complexity and condition), there is insufficient understanding regarding the pattern-process relationship to allow for accurate prediction of a disturbance event and its resultant pattern. For example, fire is a known disturbance agent in sculpting PNW conifer landscapes (Morrison and Swanson, 1990). Although the mechanisms of fire spread and initiation are generally well accepted, we are still far from being able to predict resulting landscape patterns accurately (i.e., the size, location and intensity of events).

Ecological Versus Statistical Significance of Pattern

Confounding the issue is the realization that there is not always a 1:1 mapping of a given pattern to a given process, that is, two independent ecological processes may produce the same pattern (Moloney *et al.*, 1991). A second factor leading to a non-unique process-pattern relationship is the intrinsic stochasticity of the system (e.g., random location of fire initiation). This seeming inconsistency leads one to enquire: what makes one pattern differ from another?

Two landscape patterns may vary in terms of their composition, spatial arrangement of units and variability through time. Thus, it is often insufficient to classify a given landscape with a single statistic. In fact, the identification and definition of components composing landscape pattern in itself will determine what form the pattern will take and therefore distinguish it from other patterns. For example, an aerial photograph or satellite image provides a snapshot of the landscape at a single moment. The process of pattern analysis can involve complex steps requiring subjective interpretation. Image classification is a subjective process in many ways; developing objective, repeatable algorithms requires both time and conceptual effort. Once an image is classified, the researcher is faced with the question of translating ecological units (e.g., a forest stand) to an equivalent unit in spectral space. The definition of homogeneous units will depend on many factors. To illustrate, consider the problem of defining a forest stand as a coherent mappable unit. Obtaining a consistent definition of a forest stand will depend on several factors each relating to various sources of variability (e.g., image resolution relative to landscape variability (heterogeneity), within-class variability and interclass variability), which in turn is a function of data resolution relative to the spatial autocorrelation characterizing landscape structure. Stand definition will also vary according to the ecological context in which it is being considered; what may be a homogeneous

unit for a silviculturist may be interpreted differently by a wildlife biologist where considerations of landscape connectivity may play a role. To develop a consistent stand classification algorithm, meaningful definitions of ecological units and process must be established. Once ecological significance of pattern and its corresponding processes are established, we must relate statistical significance to its occurrence.

Statistical Detection of Ecological Patterns

The spatial patterns recorded by GIS and imagery represent the summation of a multitude of processes and patterns sustained by the landscape over time (i.e., a snapshot or a single pattern sample from a population of possible patterns). From this perspective it is perhaps suitable to view spatial pattern and temporal variability in a fashion analogous to the statistical mean and variance. Until recently, ecologists were chiefly concerned about the mean value of a phenomenon. With the advent of ecological concepts of heterogeneity, spatial correlation and patch dynamics, the variance has instead become the statistic of interest. Spatial pattern, like the mean, gives an average picture of the landscape; a sample averaging over time. However, similar to the mean, spatial pattern can mask the sets of processes and other patterns that have created it.

In determining statistical significance, it is important to stress that landscape pattern may be spatial or non-spatial in nature. Two landscapes may differ in pattern based simply on a non-spatial summary statistic like the mean or variance of total mean basal area (Ripple *et al.*, 1991). On the other hand, landscape pattern may comprise a difference in one or more elements composing spatial pattern (e.g., patch size, patch distribution, anisotropy, nested structure; Bradshaw, 1991). The existence of statistical significance is therefore a function of what aspect of pattern is being measured and compared. The pattern element of interest is most often designated by its ecological significance, bringing us full circle to the importance of establishing meaningful definitions of ecological patterns.

Pattern Generating Processes in the Western Cascades, Oregon

Simplistically, the state of the forest ecosystems can be described as two opposing forces: regeneration and growth, and disturbance and mortality. These processes are not decoupled but interact over space and time. Forest composition and structure reflect a number of different factors, including endemic genetics, site conditions, and the type, frequency and magnitude of disturbance events. A given region will be characterized by its own set of landscape patterns.

The Western Cascade forests of Oregon are patterned by an array of disturbance events such as drought, insect predation, fire, blowdown and root

rot (Bradshaw and Spies, 1992). Each agent of disturbance can be characterized by a specific range in space and time. The nature of the disturbance will influence the type of landscape pattern observed. For example, drought may be regarded as a regional or even global-scale phenomenon resulting from a shift in the large-scale precipitation regime (e.g., ENSO events). Temporally, average precipitation may vary from annual to decadal or longer periods. Note that, while the domain over which drought varies is regional, the observable effects of the drought (i.e., pattern) follow the landscape (e.g., south-facing slopes may experience higher seedling mortality as opposed to north-facing slopes).

In contrast to drought, root-rot (*Phellinus*) is an individual-based disturbance agent attacking a single tree at a single point in time. The pathogen spreads radially from the source and may subsequently create patches of mortality within the stand. The difference in the two disturbance processes create parallel differences in the resultant landscape pattern; *Phellinus* pockets punctuate a stand while drought effects are pronounced both on the individual level and at the larger landscape or regional scales.

Two disturbance processes and hence their patterns may not always be mutually distinct and independent. *Phellinus* has been documented to attack both healthy and stressed trees by spreading along tree roots below ground. The rate and direction of spread depend on factors influenced by below-ground processes. In contrast, the Douglas fir bark beetle (*Dendroctonus pseudotsugae*) prefers downed logs and live but stressed large Douglas fir (*Pseudotsuga menziesii*) trees (Atkins and McMullen, 1958). Large concentrations of suitable host material, occurring from disturbances such as windthrow or high intensity wildfire, can cause epidemic outbreaks, resulting in infestation and subsequent death of live and healthy Douglas fir trees (Bedard, 1950). Bark beetle outbreaks have also been linked to areas that have sustained high moisture stress (i.e., loci where the effects of drought are pronounced). Thus, mortality patterns related to bark beetle infestation reflect an imprint of drought effects and pattern as well.

Until the last 100 years and in particular the last 30 years, the signature of natural disturbance in Northwest forests has been the predominant pattern. During the past century, the Northwest landscape has become dominated by timber harvesting and road construction; the range of cutting styles of private and public holdings has created a patchwork of young, even-aged stands with patches of older, intact stands, which has resulted in a gradual masking of the imprint of natural disturbance.

Pattern and Process Simulation of Forested Landscapes in the Western Cascades, Oregon

We developed a spatial simulation system capable of simulating fine-scale stand dynamics and multiscale disturbances to evaluate the relationship between

pattern and process in the coniferous-dominant forests of the PNW region. The model was developed specifically for stand and disturbance conditions characterizing the H. J. Andrews Experimental Forest Long-Term Ecological Research (LTER) site, located in the central Western Cascades of Oregon.

The vegetation-dynamics model component of the system is an adaptation of the individual process-based stand-level gap model ZELIG.PNW.2.2 (Urban, 1993), which has been successfully parametrized and tested for the H. J. Andrews Experimental Forest (Garman *et al.*, 1992). Similar to the stand-level gap model, the present version uses a stochastic approach to simulate demographics of individual live trees, and snag and log dynamics in 0.1-ha cells. To accommodate simulation of stand dynamics across large spatial scales, computational speed of the stand model was substantially increased by replacing some of the detailed computation of tree growth with non-linear functions derived from simulation experiments using ZELIG.PNW.2.2. Despite this simplification, model output compares favourably between the two models. The state space of each cell in our version includes diameter at breast height (dbh) of live stems by species, and mass of slow (= Douglas fir) and fast (= all other species) decaying snags and logs. Each cell on the landscape can be initiated with specific composition and structure information or initiated from bare ground.

Of the numerous disturbances agents found in the Western Cascades, three types were considered for the simulation: Douglas fir bark beetle, drought and fire. Bark beetle infestation is simply modelled as a function of the amount of log mass of Douglas fir and the occurrence of live Douglas fir >60 cm dbh. A specified number of initial points of beetle outbreak are determined prior to a simulation. The initial location for each outbreak is randomly selected. For a cell to be infected, both it and at least three adjacent or diagonal neighbours must meet the log mass and tree size threshold. This neighbourhood approach was motivated by field observations of the tendency for bark beetle infestations to be locally aggregated. All cells satisfying the infestation criteria become infected. All neighbours of the initial location and of all newly infected cells are evaluated in a similar manner. Infestation will spread from the initial location across a landscape in a contiguous manner until all surrounding cells are below the criteria threshold. When infected, all Douglas fir >60 cm dbh within the cell are killed and transferred to the snag and log pool.

Drought is manifested as a lowering of the threshold requirements for the spread of bark beetle, that is, the amount of log mass required for beetle infestation decreases under increasing drought. This representation of drought was used to examine the effects of imposing a landscape-level disturbance on detection of pattern by globally altering the susceptibility threshold of the landscape to beetle outbreak. This simplistic approach was deemed adequate within the study context to represent the relative response of beetle outbreak to drought. Through sensitivity analysis, threshold values based on the mean and standard deviation of log mass of Douglas fir on the simulated landscape were derived to represent a range of drought conditions; ranging from no drought (= normal conditions) to severe drought. The mean minus 0.1 times the standard

deviation was used to represent no drought; severe drought equalled the mean minus 0.5 times the standard deviation.

A modified version of a detailed wind-driven spatial fire model was used to emulate spread and intensity of wildfire (Garman, 1992). Frequency and size of each fire are specified prior to a simulation. The point of initiation and direction of maximum spread of each fire are randomly selected. The rate at which a fire spreads to neighbouring cells increases with log mass. In general, fires tend to be elliptical in shape, but deviation from this general form results where dead and downed fuels (= log mass) are much greater than that of neighbouring cells. The intensity of a fire in each cell was modelled as a linear function of log mass. Fire intensity increases with increasing log mass, resulting in the death of a greater proportion of the live basal area in a cell. In this version of the model, trees are stored in an array by decreasing dbh. Killing of trees begins at the bottom of this array and continues until the required basal area has been removed. Thus, a lower intensity fire kills the relatively smaller trees; larger trees are only killed in a high-intensity fire. Fire intensity was scaled so that 50 per cent of the basal area would be killed when the log mass of a cell was equal to the mean of the simulated landscape. Killed trees are divided equally between the snag and log pool.

Simulation Experiments

For all simulation experiments, we used a simulated 200-year-old landscape 100 × 100 cells in size (1000 ha), which was generated from bare ground using the vegetation dynamics model. Although the landscape was relatively even-aged, the stochasticity of the vegetation dynamics model ensured that log mass and overstorey composition and structure of each cell varied in a manner similar to that expected on a real-world landscape recovering from a large disturbance such as catastrophic wildfire.

Using a variety of values for intensity and frequency, simulations were initially performed to evaluate the effects of beetle outbreak and wildfire separately (e.g., Figures 31.1a–d). For the purpose of illustration, we chose those conditions that would provide an adequate contrast. Two levels of initiation frequency for bark beetle outbreak (1 and 5), two levels of drought (severe and no drought) and two intensities of wildfire (one fire 1000 ha in size, and three fires each 3000 ha in size) were used. Temporal sequencing of the two levels of wildfire and beetle outbreak under the two levels of drought were varied. Initial locations of disturbances were held constant between paired simulation runs (i.e., runs differing only in the temporal order of disturbance). This ensured that any observed differences in temporal sequencing were not confounded by different locations of initiations. Disturbances were generated on the simulated 200-year-old landscape in selected order, and total basal area of each cell and the corresponding spatial co-ordinates (= row and column) were recorded. In this exercise, we did not vary the temporal dynamics of the landscape but merely

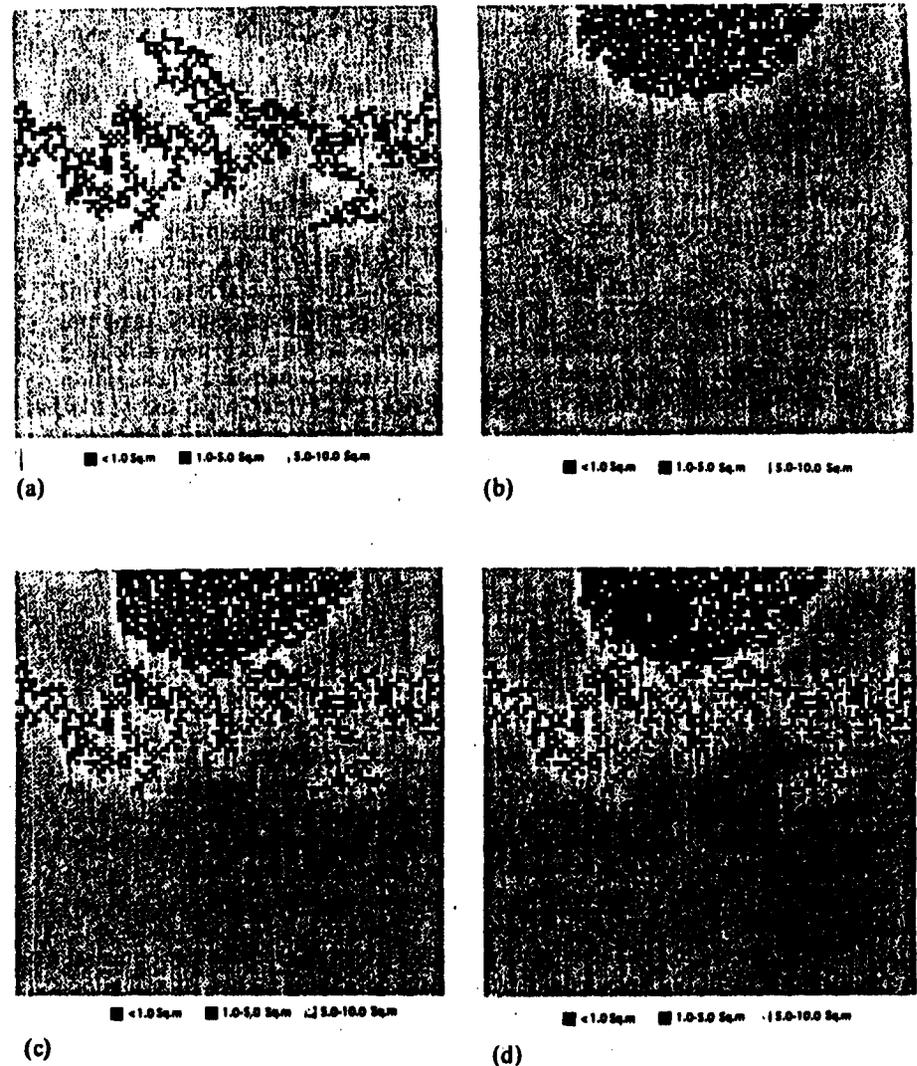


Figure 31.1 Examples of simulated patterning of total basal area resulting from different combinations of bark beetle infestation and wildfire.

Note: Initiation points for wildfire and for beetle outbreak were held constant among all runs: (a) bark beetle under the no drought condition and with one initiation point, (b) a 1000 ha wildfire, (c) bark beetle outbreak followed by wildfire, (d) wildfire followed by bark beetle outbreak.

imposed disturbances on the initial simulated landscape. Five replications of each scenario were performed, each initiated with a different random number seed to vary initial locations for each disturbance.

Spatial and non-spatial statistics were calculated for each simulation run and used to compare the response of landscape pattern to the temporal sequence of disturbances. Mean total basal area was used as the non-spatial metric. The continuous values of basal area were translated into three discrete classes (aggregation criteria of $<1 \text{ m}^2$, $1-5 \text{ m}^2$ and $>5 \text{ m}^2$) before calculating spatial metrics. These intervals were selected because they emphasized the effects of each disturbance. Because of the potential for biasing results, we varied our intervals by ± 30 per cent and compared results among several scenarios. This sensitivity analysis indicated little change in relative differences among temporal order of disturbance and among the different levels of disturbance, indicating that our initial interval values provided a relatively unbiased classification scheme. The landscape metrics program FRAGSTATS (McGarigal and Marks, 1993) was used to calculate a wide range of spatial metrics for each classified map. Mean nearest neighbour (summation of minimum distance between patches of similar type/total number of patches in the landscape) and total patch edge (summation of the amount of edge of each patch) metrics best represented the pattern of the classified maps, and were used for statistical comparisons.

Results

Visual examination of individual landscapes shows considerable variability of both spatial and non-spatial pattern. Three landscapes are included to illustrate a representative spectrum of pattern variability observed in the numerous simulation runs (Figures 31.1c, 31.3a and 31.3c). These landscapes were generated using the same parameters (low drought, and a single fire event following a single beetle outbreak); the sole factor that differed among the three was the random initiation point of disturbance. In contrast with significant differences in visual assessment of pattern, the variability within a given disturbance scenario as measured by the variance is relatively low (Figure 31.2a-c).

General trends in the three metrics used to analyse pattern under temporal sequencing of disturbance events were fairly consistent across all scenarios. When wildfire was implemented first, the landscape had lower total mean basal area (Figure 31.2a), higher mean nearest neighbour distances (Figure 31.2b), and lower total edge length (Figure 31.2c). Statistical comparison of metrics indicates a significant interaction between disturbance severity and temporal order. Under the single fire scenario, spatial and non-spatial metrics distinguished temporal order under severe drought regardless of the number of bark beetle initiations. This was also evident under the multiple fire-no drought scenario. Under the most severe level of disturbance simulated (multiple fires, severe drought), spatial metrics were significantly different ($p < 0.05$) between disturbance sequences, but mean total basal area was similar ($p > 0.05$). In

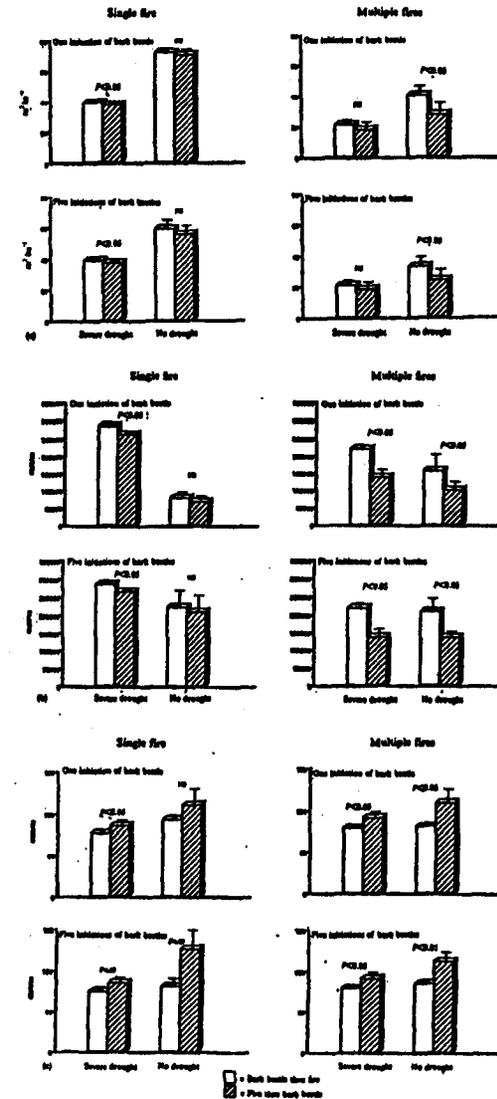


Figure 31.2 Non-spatial and spatial statistics of simulated landscapes under varying drought conditions and number of initiations of bark beetle and wildfire, and for different sequencing of disturbances.

Note: (a) mean total basal area, (b) mean minimum distance between patches of similar types, (c) mean total edge of patches. Means based on five replications. Error bar represents upper 95 per cent confidence interval. NS = not significantly different at the 0.05 level.

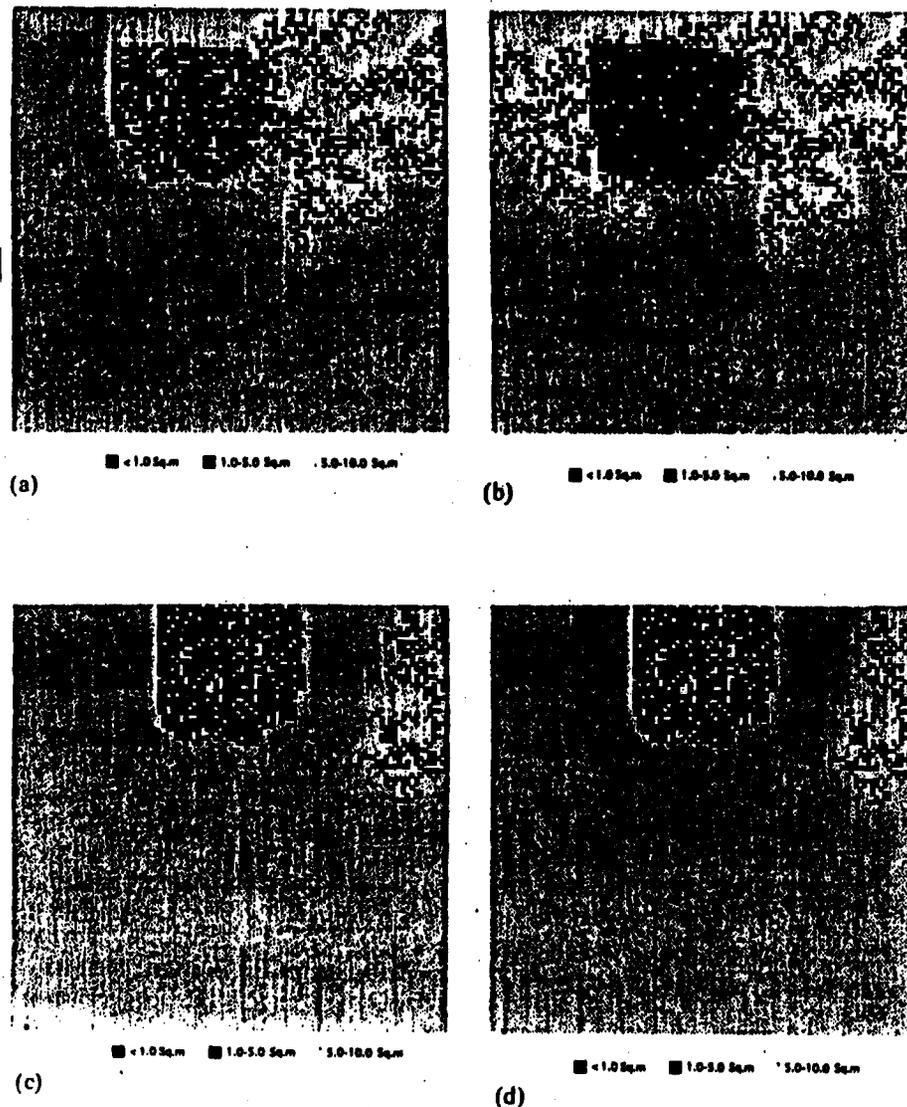


Figure 31.3 Examples of simulated patterning of total basal area under different sequences of a 1000 ha wildfire and bark beetle infestation under the no drought condition, showing importance of location of disturbance initiation.

Note: (a) bark beetle outbreak followed by wildfire, (b) reverse order of (a), (c) bark beetle outbreak followed by wildfire, (d) reverse order of (c).

contrast, metrics differed little between temporal order in the single fire no drought scenario, which represents the least severe set of conditions evaluated.

In general, there is a similar trend observed when the number of disturbance events increases (i.e., fire events or beetle outbreaks) as when drought conditions are changed to severe (Figures 31.2 a-c). More specifically, it is not possible to say that spatial and non-spatial metrics are systematically significant. On closer scrutiny, there are some interesting deviations from this trend. For example, under conditions of severe drought and multiple fires, increasing the number of beetle outbreaks from one to five does not increase statistical significance for total mean basal area though there is a change in significance in the case of landscape metrics (Figures 31.2 a-c).

The effects of increasing beetle outbreaks is not symmetric with increasing the number of fire events, demonstrating that the individual process mechanism acts as a regulating factor in determining the type and spread of disturbance in the landscape. Wildfire tended to form large elliptical shapes comprising a mosaic of patches. This mosaic resulted from the heterogeneous distribution of log mass as well as stand conditions of the initial landscape (e.g., Figure 31.1b). When wildfire was the first disturbance event, the increased levels and the contiguous pattern of log mass promoted the spread of beetles throughout the burn, thus further reducing standing basal area. The initial mosaic produced by wildfire was reduced to a single large patch of low basal area, thus decreasing the overall number of patches on the landscape. This in turn accounts for the greater mean distance between patches and the increase in total edge of patches on the landscape. When wildfire occurred after beetle outbreak, the intensity of the fire would be greater where it overlapped with trees killed by beetles, resulting in small patches of low basal area. A mosaic of patches would tend to be produced, however, where the two disturbances did not overlap. Thus, the number of patches on the landscape would increase, which in turn would increase the total amount of edge and decrease the distance between similar patch types.

Discussion

The simulations presented here lack the complexity of natural landscape dynamics observed in the forests of the Pacific Northwest. This observation is not surprising as the central objective of the study has been to reduce the problem's dimensionality to isolate a single component of the dynamics; namely, the temporal order of disturbance events. Nonetheless, the simulations have provided some insight into the original inquiry relating pattern to process.

At the beginning of our discussion, two landscapes were considered similar when the ecological functions shared by the two landscapes were alike. In the examples presented here, the 'same' ecological processes were defined as those examples where the same disturbance algorithms with identical parameters and the same initial landscape conditions were used. Two cases were examined: (1) ecologically identical processes (i.e., pattern variability resulting from a differ-

ence in random initiation points), and (2) ecologically distinct processes (i.e., pattern variability resulting from a reversal in disturbance order (e.g., fire-beetle versus beetle-fire). These landscape patterns generated by the same ecological processes but differing in the disturbance initiation locations comprise a set of visually very different and distinct patterns (Figures 31.1c, 31.3 a and 31.3 c). In light of our definition, although these landscapes do not differ in terms of the ecological processes that created them, they are spatially and visually distinct (see Pfaltz and French, this volume, for what constitutes 'change').

In the second case, where landscape patterns were generated from ecologically distinct processes (i.e., reversal of temporal order of disturbance events, see figures 31.1d and 31.3 d), pattern variability as measured by spatial and non-spatial metrics was generally significant only under the restricted conditions of severe disturbance (severe drought or multiple large disturbance events; Figures 31.2 a-c). Under the simulation scenarios, the order of the disturbance events was not a sufficient criterion to distinguish two landscape patterns statistically. While two landscapes may be generated by the same pattern-generating processes, their respective resultant patterns may differ. We would hypothesize that landscapes characterized by significantly different patterns would also be characterized by correspondingly different functional behaviour. These results suggest that a refinement of the original definition of 'ecological significance' of processes and patterns is appropriate.

Accurate evaluation of ecological processes may require considerations of several factors relating to disturbance (e.g., type, frequency and intensity) as well as the existing landscape pattern. When temporal order of disturbance events was reversed, the interaction of the process with pattern changed the final landscape pattern outcome. The first disturbance, be it fire or beetle infestation, acted to alter the landscape differently than did the second disturbance. Technically, it might be more suitable to modify our previous notion of 'sameness'. We may be best served to consider differences in landscape conditions both before and after the second disturbance rather than a single comparison of the final landscape pattern. The 'sameness' of a landscape would be defined based on a combination of disturbance attributes and the existing patterns. Essentially, the distinction between pattern and process becomes less distinct; in this approach, pattern is defined based on its potential response to various types and attributes of disturbance. In practice, this is usually not feasible; procuring pattern data before and after disturbance events is difficult because of the limited window over which imagery exists. However, interactive use of landscape simulations, GIS and field data promises to provide a better understanding of key factors involved.

Second, simulation results indicate that statistical significance does not correspond systematically to ecological significance. More specifically, while the spatial landscape metrics (total edge and nearest neighbour) distinguished the temporal order of disturbance on average, non-spatial statistical significance as measured by total mean basal area did not detect differences in temporal order of disturbance consistently. Deviations among the trends observed indicate that

the interactions existing between disturbance intensity and type play an important role in pattern determination. This observation suggests the existence of an observable set of threshold conditions (e.g., patterns were distinguishable only under conditions of severe drought for a single fire event and no drought under multiple fire events; Figures 31.2 a-c). In general, statistical significance was observed above and below certain levels of disturbance severity. Defining numerical and spatial bounds of significance may provide a useful means to map regions of detectable ecological and statistical significance.

Implications for Management

In the simulations discussed here, the initial landscapes were uncorrelated, that is, the simulation was designed such that each cell was independent of the other with respect to stand growth and mortality. In reality, both natural landscape patterns and human-derived disturbances create a correlated landscape at several scales. Landscape-level features such as topography contribute to fire spread and initiation, creating a mosaic of successional stages and composition across the landscape. Timber harvesting has imposed a severe and high-frequency disturbance regime on the landscape. The PNW landscape is now dominated by spatial correlation at the scale of individual harvest units and their aggregate (Franklin and Forman, 1987). Our simulation results indicate considerable variability resulting from a change in disturbance initiation site alone across an uncorrelated landscape. The creation of highly correlated landscapes by intense and sustained clear-cutting in the PNW has dramatically altered the potential for sites to be disturbed. This superpositioning of patterns on the landscape may predetermine and restrict the natural disturbance regime, and prevent new ecosystem management practices from effectively mimicking natural disturbance conditions. In essence, we may have rendered the landscape into a disturbance regime well beyond the limits of natural variability.

It seems clear that intensive efforts by ecologists and statisticians need to be directed to reassessing the concepts of ecological and statistical significance of pattern. Efforts need to be directed in two main areas: (1) identification and definition of ecological processes and units at the landscape level, and (2) quantitative sensitivity analyses relating changes in process attributes (e.g., disturbance intensity) to changes in spatial and non-spatial pattern. In the course of these efforts, it is likely we will be able to develop a fuller understanding of what is really meant by the 'pattern-process' paradigm.

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