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MULTISCALE ADVANCED RASTER MAP ANALYSIS SYSTEM FOR MEASURING ECOSYSTEM HEALTH AT LANDSCAPE SCALE—A NOVEL SYNERGISTIC CONSORTIUM INITIATIVE

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Multiscale Advanced Raster Map Analysis System for Measuring Ecosystem Health at Landscape Scale - A Novel Synergistic Consortium Initiative*

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1. Setting the Stage

Geospatial data form the foundation of an information-based society. Remote sensing has been a vastly under-utilized resource involving a multi million dollar investment at the national levels. Even when utilized, the credibility has been at stake, largely because of lack of tools that can assess, visualize, and communicate accuracy and reliability in a timely manner and at desired confidence levels.

Consider an imminent 21*st* Century scenario: What message does a multi-categorical map have about the large landscape it represents? And at what scale, and at what level of detail? Does the spatial pattern of the map reveal any societal, ecological, environmental condition of the landscape? And therefore can it be an indicator of change? How do you automate the assessment of the spatial structure and behavior of change to discover critical areas, hot spots, and their corridors? Is the map accurate? How accurate is it? How do you assess the accuracy of the map? How do we evaluate a temporal change map for change detection? What are the implications of the kind and amount of change and accuracy on what matters, whether climate change, carbon emission, water resources, urban sprawl, biodiversity, indicator species, ecosystem health, human health, or early warning? And with what confidence? The proposed consortium research initiative is expected to find answers to these questions and a few more that involve surface maps and multi-categorical raster maps based on remote sensing and other geospatial data in measuring ecosystem health and in managing for healthy ecosystems.

2. Inferential Geospatial Informatics for Ecosystem Health

The satellite sensors provide databases of the surface of the earth. Using various technologies, it is now possible to provide snapshots of landscapes indicative of various features of interest pertaining to human societies, plant and animal communities, and aquatic networks. The information is synoptic and we subsequently get to see various kinds of maps of different kinds of regions of interest. These maps provide a basis for comparative assessments of regions within a policy- making and implementation context. It is also possible to extract meaningful profiles of management units, such as watersheds, that can be calibrated and compared to assess and manage watersheds of a region.

These multidimensional and multidisciplinary approaches call for linkages and collaborations beyond those traditionally applied in ecosystem health research. Thus, we propose that new consortia be forged to capture, analyze and model whole ecosystems or subsets of them. The results can be applied to holistic ecosystem management strategies. A purpose of this paper is to identify a timely need for a consortium initiative on environmental and ecological policy research using remote imagery and geospatial information with appropriate multiscale advanced raster map information science and technology to be accomplished within a short timeframe.

The proposed consortium initiative will help advance regional policy research and judge effectiveness and usefulness of potential or actual policies using satellite technology, computer technology, statistical technology, information technology, multimedia communication technology, and landscape ecology. Initial regional policy research will involve issues that are environmental, ecological, and societal, providing multiscale assessments for management purposes. The proposed initiative will begin with selected prototype case studies involving forests, watersheds, coastal areas, and other regions of interest for issues pertaining to biodiversity, watershed integrity, landscape vulnerability, surface water quality, ecosystem health, human health, global change and disturbance impacts, geographic surveillance, and others.

The urgency of the proposed consortium initiative lies in the disappointing software syndrome depicted in Figure 1. The program manager finds the report disappointing and wonders about the software used. It is important that we use space age analysis for space age data. Several nonstandard problems arise, and these require nonstandard tools (Patil, 1998; Patil and Myers, 1999). And in a timely manner. The proposed consortium initiative is expected to be cost-effective in this emergent need for assessment and management for ecosystem health at landscape scale.

This report is very disappointing. What kind of software are you using?

- Data: Space Age/Stone Age
- Analysis: Space Age/Stone Age

Data / Analysis	Space Age	Stone Age
Space Age	+	+
Stone Age	⊕	+

Figure 1. (a) Disappointing report, and (b) disappointing software.

3. Measuring Ecosystem Health at Landscape Scale

The Mid-Atlantic Region studies demonstrate the feasibility and practicality of ecosystem health assessments (Brooks et al., 1998, 2001). This area provides an ideal case study because it is an ecoregion which is rich in synoptic data and it contains many of the geographical elements found in the eastern U.S., and other temperate regions. Its natural and human-induced landscapes, gradients, and boundaries provide a wealth of options to explore.

For example, Pennsylvania watersheds have been mapped at scales, ranging from 102 units for the State Water Plan to 9,855 units for individual named streams. These watershed units have been studied from diverse perspectives including non-point pollution, groundwater pollution potential, land cover, and animal habitats (Johnson, 1999, Johnson, *et al*., 1998, 1999ab, 2001ab, 2002; Johnson and Patil, 1998; Myers *et al*., 2000; Patil *et al*., 2000ab). Pennsylvania watersheds vary in their ecology, geology, hydrology, degree of human influence, etc. Representing this complexity synoptically in a format that enables one to address questions of ecosystem health, integrity and resilience is our key challenge and goal. Using the collective data from the Mid-Atlantic Region, we confront the following types of questions in this context: What is the health status of a particular watershed and how does this compare with a similar but less stressed system? To what degree is ecosystem degradation associated with cumulative effects from population growth and economic development within the watershed? Do changes in spatial biocomplexity of key indicators of ecosystem distress serve as an early warning sign of loss of resilience at regional scales? Which watersheds show the greatest degree of fragmentation? Do these watersheds also indicate a loss of ecosystem services such as water quality and habitat? Is the degree of fragmentation within watersheds correlated with the loss of ecosystems goods and services as measured by synoptic data on water quality, soil erosion, biodiversity, etc.?

Although spatial landscape analyses have been conducted for years, it has been difficult to compare different locations when using multiple indicators simultaneously. However with the application of insightful sophisticated quantitative methods, it is possible to create truly integrative measures that characterize the synergistic relationships among landscape patterns and indicators. In particular, we will explore the techniques described here in the multiscale advanced raster map analysis system for addressing multiple indicators, partial orderings, and multi-criterion decision support, along with echelons of spatial variation. This approach will allow us to search for and define consistent and recognizable landscape patterns, while at the same time, allowing us to define a set of reference conditions to understand the consequences, both favorable and unfavorable, that human actions have on biocomplexity.

There are several national and international projects in progress, such as the Atlantic Slope Consortium, that will benefit with their participation in the proposed geoinformatic methods and tools consortium discussed in this paper. Several of these projects will find this geospatial and temporal quantitative arm useful in their inhouse work in progress from day one of their participation. This paper constitutes a friendly call for this collaborative synergism in the form of a short course, workshop, project collaboration, and/or a proposal preparation.

4. Multiscale Advanced Raster Map Analysis System for Measuring Ecosystem Health

This section briefly describes applications of the emergent methodologies collectively known as the MARMAP System for landscape health assessments (Patil, 2000; Patil, 2001bcd; Patil, 2002abc. Also see http://www.stat.psu.edu/~gpp/newpage11.htm).

Modeling and Simulation of Thematic Raster Maps

A raster map depicts the landscape as a grid of uniform cells. Modeling and simulation of raster maps is employed for three general purposes. First, model fitting provides a set of estimated parameter values characterizing the spatial structure of the map (landscape). Second, simulation yields statistical confidence capability as well as response sensitivity to variation in the fitted parameter values. Third, model validation provides a check on tendencies to overfit the model. Three classes of map models are available. These address issues important to monitoring and diagnostics to determine and discriminate differing status with regard to degradation of habitat integrity across landscapes. From land cover maps derived by remote sensing, we examine naturalistic versus more strongly human disturbed situations through an index of conditional entropy to obtain profiles of disruption. See Figure 2. For more information, see Johnson (1999), Johnson and Patil (1998), Johnson *et al* (1998, 1999ab, 2001a), Patil *et al*. (2000ab), and Patil and Taillie (1999, 2000abc). The issues of landscape characterization and discrimination, patch structure and patch dynamics, scaling domains, spatial pattern heterogeneity detection, and others arise. The issues of assessment of accuracy and change detection of landcover and landuse maps also arise for a variety of ecosystems. These issues can be addressed by the methods and tools discussed in the proposed MARMAP System.

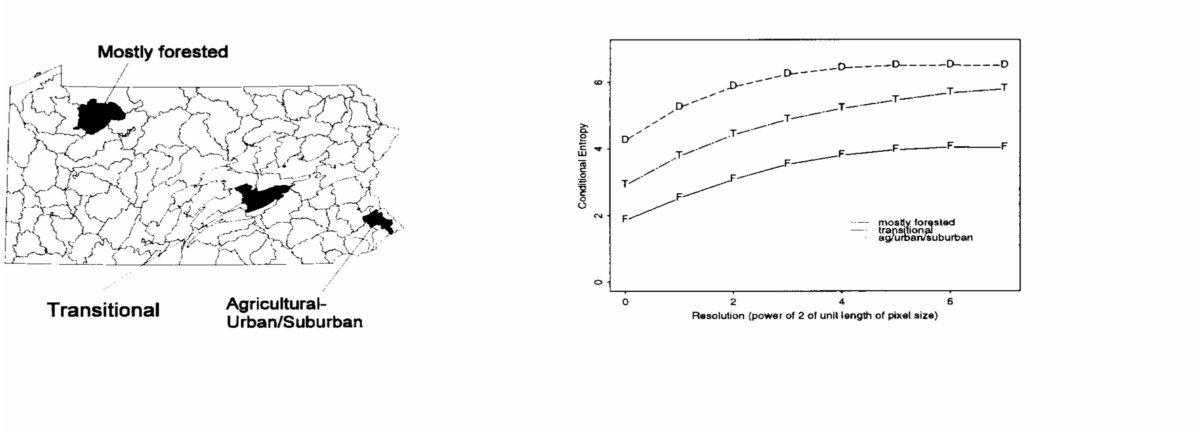

Figure 2. Fragmentation profiles for three Pennsylvania watersheds with distinct land cover patterns: mostly forested, transitional and mostly deforested (agriculture/urban/suburban).

Echelons of Spatial Variation, Critical Area Detection, and Delineation

Echelons frame local values of synoptically mapped environmental indicators in regional context for comparative purposes and objective analysis of complex hierarchies in spatial variation across landscapes. The environmental indicators are considered as surface variables in virtual (or real) topographies as depicted in Figure 3. Echelons are structural entities consisting of peaks, foundations of peaks, foundations of foundations, and so on in an organizational hierarchy. It is natural to cast the echelon hierarchy as a dendrogram, from which profiles of spatial complexity can be obtained and "principal families" determined as contiguous areas of criticality from perspectives of either pronounced ecosystem health or pronounced ecosystem distress. Echelons have proven effective for elucidating concentration and connectivity of biodiversity, complexity of landscape change induced by factors such as wildland fire, pattern of propagation for urban sprawl, etc. (Myers et al., 1995, 1997; Myers, Patil and Taillie, 1999; Kurihara *et al*., 2000; Smits and Myers, 2000; Patil and Myers, 2002).

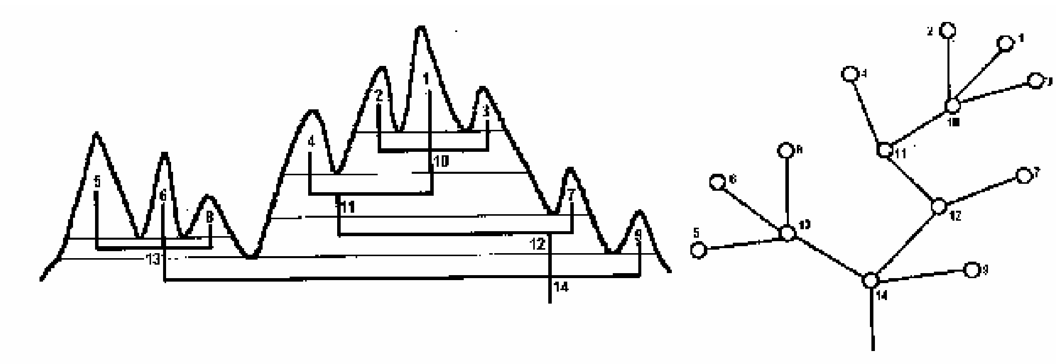

Figure 3. (a) Echelon decomposition of a surface and (b) associated echelon tree.

Contemporary study of human disease as a component of ecosystem health entails a spatial scan statistic (Kulldorff and Nagarwalla, 1995) for detecting geographic clusters of disease and other responses that are significantly elevated with respect to the regional setting. In conjunction with the spatial scan statistic, echelon analysis is expected to more clearly delineate the cluster boundaries for focus of investigation (Patil and Taillie, 2001d), as depicted in Figure 4.

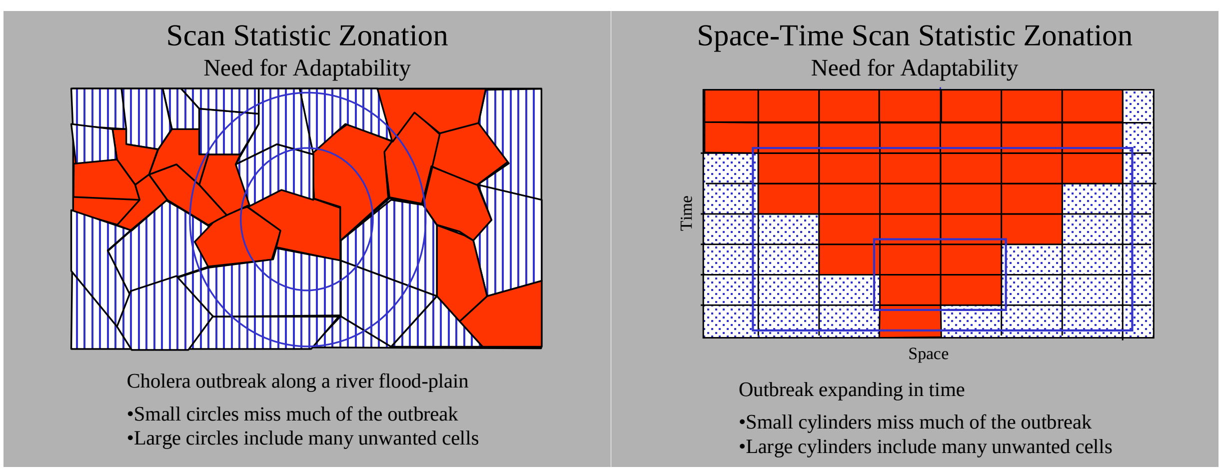

Figure 4. (a) Scan Statistic Zonation and (b) Space-Time Scan Statistic Zonation

Pattern-based Landscape Change Analysis

Landscape change analysis is becoming increasingly important for ecosystem monitoring. Deforestation, habitat fragmentation, and land-use conversion are growing concerns for conservation, landscape ecology, and planning. Effective and parsimonious methods are needed to make the combinatorial challenges of comparative analysis manageable. Composite mosaics of multiple images derived by pattern-based segmentation have proven particularly advantageous for extracting and representing change from remotely sensed image sequences, where previously analysis was largely restricted to consideration of image pairs taken at two times with the same sensor (Myers, 2000; Patil *et al*, 2000b).

Geospatial Data Compression, Segmentation, and Classification.

Remote sensing is generating spatial data at a rapidly increasing rate. The increase in data flow has a three-fold nature due to increasing spatial resolution, increasing spectral richness, and more frequent acquisition. These data have potential informational utility that often remains unrealized. Facilitating the realization of such potential informational utility is one of the major challenges facing modern information technology, and provides the underlying motivation for emergence of data mining. Data mining is essentially a search for pattern that may have some interpretability, but it is too often an aimless search that is lacking conceptualization of what constitutes pattern. When dealing with image data, however, space and time offer organizing paradigms that have been under exploited.

From both theoretical and practical perspectives, landscapes have a mosaic nature with particular pattern elements emerging at different scales. This compound mosaic nature is fundamental as a basis for landscape ecology. The process of mosaic pattern extraction is one of image segmentation, where the operative partitioning takes place in the spectral domain. The determination of spatial mosaic segments is a direct consequence of partitioning as spectral subspaces. Accomplishment of such segmentation must take into account both distinctiveness and expansiveness of mosaic elements. Distinctiveness is most important for perceptual purposes, and the expansiveness for analytical purposes (Myers, 2000).

Geographic Surveillance, Disease Mapping, and Evaluation

Disease mapping is about the use and interpretation of maps showing the incidence or prevalence of disease. Disease data occur either as individual case events or as groups of case events (count data) within areal units, such as census tracts, zip codes, counties, etc. Any disease map must be considered with the appropriate background population which gives rise to the incidence. Maps answer the question: where? The maps in conjunction with the underlying data reveal spatial patterns not easily recognized from lists of statistical data (Kulldorff et al., 1997, 1998; Lawson and Williams, 2001). For example, use of remote sensing data and other relevant geospatial data can help evaluate surrounding landscape characteristics that may be precursors for vector-borne diseases leading to early warning, involving landscape health, ecosystem health, and human health.

Urban Heat Islands, Urban Sprawl, and Environmental Justice

The urban heat island may be visualized as a temperature dome on urban area. It contributes to the formation of ozone, which is a major urban air pollutant that has serious human health consequences. Analysis of thermal energy characteristics helps us understand how we can modify the city landscape to lessen the impacts of the urban heat island and its subsequent effects on air quality. (Quattrochi and Luvall, 1999; Quatrocchi, *et al*., 2000; Quattrochi and Gillani, 2001). Three main objectives may be involved: (1) Characterization of thermal landscape in the metropolitan area. This aims at evaluating not only the strength of the urban heat island but also the spatial variance within the heat island. (2) Evaluation of the relative roles of land cover characteristics and urban structures. This involves the quantification of land cover characteristics and urban structures such as percent impervious surfaces, biomass density, urban canyon geometry, and roadway density. (3) Linking localized thermal characteristics to human health outcome. This attempts to directly and indirectly link illnesses, such as pediatric asthmatic attacks and heat strokes, to localized thermal stress.

Multiple Indicators, Partial Orderings, and Multi-Criterion Decision Support

To prioritize and rank means to linearize. Rather than derive a composite index, we will prioritize without having to integrate the indicators. This is now possible, and the approach is relatively novel and innovative. We have developed it for nationwide prioritization for UNEP with land, air and water indicators measuring the human environment interface at national level (Patil, 2001a; Patil and Taillie, 2001bc). For another example, a landscape atlas published by

U.S. EPA (1997) considers 33 indicators of ecological condition on 123 watersheds (7-digit HUCs) of the Mid-Atlantic region and attempts to rank the watersheds using clustering and quintile-frequency methods. We address the question of ranking such a collection of objects when a suite of indicator values is available for each member of the collection. The objects can be represented as a cloud of points in indicator space, but the different indicators (coordinate axes) typically convey different comparative messages and there is no unique way to rank the objects. A conventional solution is to assign a composite numerical score to each object by combining the indicator information in some fashion. Consciously or otherwise, every such composite involves judgements (often arbitrary or controversial) about tradeoffs or substitutability between indicators.

Rather than trying to impose a unique ranking, we take the view that the relative positions in indicator space determine only a partial ordering and that a given pair of objects may not be inherently comparable. Working with Hasse diagrams of the partial order, we study the collection of all rankings that are compatible with the partial order and arrive at the ranking and prioritization as in Figure 5, using cumulative rank frequency (CRF) operator specially developed for the purpose (Patil and Taillie, 2001a).

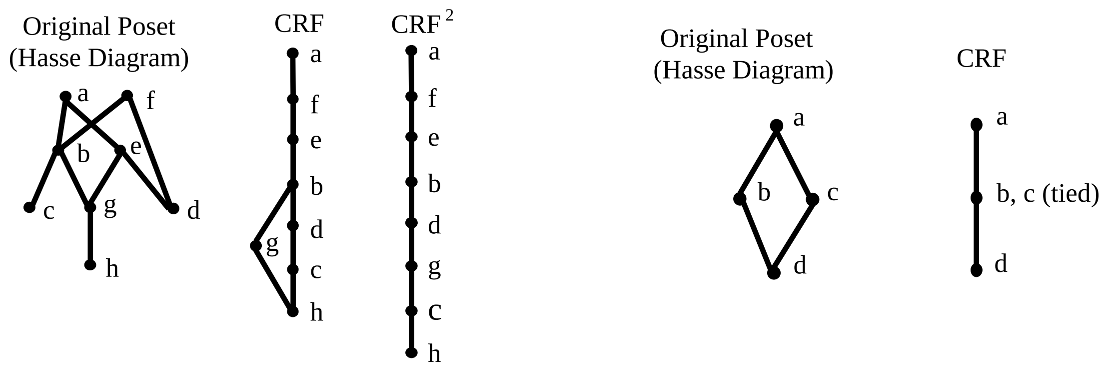

Figure 5. *The three diagrams on the left show the linearizing effect of the CRF operator. The two diagrams on the right show how ties can emerge during linearization. A poset is a partially ordered set.*

Hierarchical Structure Analysis

Trees and other nodal graph structures arise in map modeling, echelons, and posets of MARMAP. Also important is the coupling of related structures. For example, when a suite of indicators is partitioned into subgroups (e.g., stressor, integrity, socioeconomic), the Hasse diagrams have a common set of labeled nodes but perhaps different edges (Patil, 2001cd).

Mining Geospatial Data

Data structures and algorithms are under investigation for exploring associations between ecosystem degradation and spatial patterns employing higher-level models for detecting changes and finding interesting spatio-temporal patterns and trends (Rodriguez, 2001).

Interface Design and Visualization Toolbox

The main goal is to promote the discovery of inherent structures and patterns, enable the study of particular facets and dimensions of data, and provide means to visually assess the utility and accuracy.

5. Project MARMAP Consortium: Synergistic Integration and Technology Transfer

An essential part of this proposed consortium initiative is to introduce concepts and methods at the core of MARMAP to researchers in ecology, environment, socioeconomics, and quality of human life. It is timely to think of multidisciplinary groups for ecosystem health measurement at landscape level. It will be productive and cost-effective to initiate synergistic collaboration, whether in the form of a short course, workshop, project research, and/or proposal preparation.

The experiences gained from the collaborative studies will feed back into refinements of methods. At the end of the day, the thrust of this enterprise will have quantification of ecosystem health at landscape scales from subwatersheds to major watersheds as an essential, replicable method of assessing our progress towards sustainability (Rapport *et al*., 1999). You are invited to visit the MARMAP website http://www.stat.psu.edu/~gpp/newpage11.htm and contact gpp@stat.psu.edu for your participation in this unusual consortium initiative to manage for healthy ecosystems in the spirit of digital governance of the 21st Century.

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