Atkinson College, York University, Geographical Monograph No. 14.


GREG HALSETH (Ph.D., Queen’s University, Kingston, Ontario) is Assistant Professor in the Geography Program, Faculty of Natural Resources and Environmental Studies, University of Northern British Columbia, Prince George, B.C., Canada V2N 4Z9. His research interests include issues of community change, specifically public participation and debate, in rural and suburban settings.

MARK ROSENBERG (Ph.D., London School of Economics and Political Science) is Associate Professor in the Department of Geography, Queen’s University, Kingston, Ontario, Canada K7L 3N6. His current interests are population aging, medical geography, housing, and transportation, and their implications for public policy.

Forest Landscape Structure along an Urban-To-Rural Gradient*

Kimberly E. Medley
Miami University

Mark J. McDonnell
University of Connecticut

Steward T. A. Pickett
Institute of Ecosystem Studies

Human activities and forest-landscape structure are examined along a belt transect that extends 140 km from New York City to northwestern Connecticut. The study quantifies urban structures (population density, land use, transportation) and processes (population growth, urban land development) in the transect, and tests for relationships with the distribution, sizes, and shapes of forests. Our results identify distinct characteristics of urban and suburban environments based on the landscape structure of native forest vegetation. These findings are applicable to the management of natural areas along a gradient of urbanization. Key Words: conservation, forest ecology, landscape analyses, New York City, urbanization.

The altered environments of cities, coupled with the dynamic changes in land cover that occur when urban areas expand, profoundly influence the native vegetative cover of a landscape. Within most urbanized areas, human activities have resulted in a landscape that is characterized by a highly developed urban core and a trend toward diminishing anthropogenic influences at the periphery. It is evident that urban effects extend beyond city political boundaries or built-up areas of high human population density (Berry 1991). While

*Research support was provided to K. Medley through an AAG Research Grant and a postdoctoral appointment at the Institute of Ecosystem Studies. We thank T. Klak, E. McCann, R. V. Pouyat, C. Young, D. Lord, D. Hodge, and two anonymous reviewers for comments on earlier drafts. This paper is a contribution to the program for the Institute of Ecosystem Studies.

landscapes are commonly classified as urban, suburban, or rural on the basis of socioeconomic data and the presence of urban structures (e.g., Clawson 1971), their delineation with distance from an urban center (Fugitt et al. 1979) and the ecological implications of human activities within these regions (McDonnell and Pickett 1990) remain unclear.

Theoretical models of urban structure and analyses of socioeconomic parameters with distance from an urban core suggest a gradient of human influences. Along the gradient, urban structures and the urbanization process are principal factors disrupting the preexisting mosaic of land uses, and particularly the apportionment and spatial configuration of native vegetation (Godron and Forman 1983). Landscape patterns, therefore, provide an alternative measure of urban-rural change. The ecological implications of urban developments may be monitored by compositional, structural, or functional responses in the preexisting vegetative cover (Stearns and Montag 1974; Sukopp and Werner 1983; Rowntree 1988).

In this paper, we report findings from an integrative study of urban effects on landscape structure and forest ecology along a transect between New York City's urban core and rural northwestern Connecticut. Distance along the urban-rural transect provides a sampling framework to compare landscape structure and human activity, and thereby to identify the gradient of urbanization. Three principal questions are investigated: (1) how do the urban indicators, including human population, transportation, and land use, vary with distance from the urban core? (2) what are the trends in landscape structure, as measured by the distribution, sizes, and shapes of native forest patches? and (3) do statistically significant relationships exist between the urban indicators described above and forest-landscape structure along the transect? The study quantifies how humans change the environment with distance from an urban center and identifies ecological impacts of these human influences on native forest vegetation.

Study Area

A 20-km wide and 140-km long belt transect was established that extends from New York City to Litchfield County, Connecticut (Fig. 1). In order to control for environmental variability, the transect was positioned to follow a single geomorphic unit, the glaciated Appalachian highlands, and remain within the oak-hickory vegetation association. Landscape analyses focused on patterns of change along the transect and local differences among nine permanent, upland-oak forest sites that were used in a concurrent study of ecosystem properties (Fig. 1; see Pouyat and McDonnell 1991).

Our study transect extends from the core of one of the oldest, most densely populated cities in the United States and extends towards a forested landscape. New York City had a population of 350,000 by 1835 (Berry 1973) and now the metropolitan area has a population of about 7.32 million in 780 km². The

Figure 1: Location of the urban-rural belt transect in the Northeastern United States. The nine permanent forest study areas are shown with black circles.
physical environment is characterized by high relative relief, and its low agricultural productivity reduces non-urban pressure on the growth of forest. Danbury, Connecticut, a much smaller city located east of the transect at about 70 km, is the only other urban center that may possibly influence urban developments in the study area.

Spatial patterns measured along this urban-rural transect would probably differ from those at similar distances to cities of different ages or central population densities (Adams 1970), and in different environmental or cultural settings (Bourne et al. 1984). The construction of the highway network, the early history of elite developments in Westchester County, New York, and a topographic setting that restricted large single-housing projects set the framework for a pattern of urban development that was quite different from that characteristic of the coastal plain in New Jersey, for example (Jackson 1985). Landscape changes from an urban to a forest matrix along the study transect are profound, attributable to the characteristics of the urban core, the physical geographic setting, and the history of urban development.

### Data and Methods

We measured urban and landscape characteristics at coarse (1:250,000) and fine (1:24,000) resolutions within the urban-rural transect (Table 1). At a coarse resolution, the 140-km transect was divided into 5-km transect sections (n=28), and circular landscape

#### Table 1 Data and Landscape Parameters used to Quantify the Urban-Rural Transect

<table>
<thead>
<tr>
<th>Source Data</th>
<th>Data Description</th>
<th>Landscape Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. Bureau of Census (1980, 1990)</td>
<td>Number of individuals by county subdivisions</td>
<td>Population density—means extracted from county subdivisions in sample (weighted by area)</td>
</tr>
<tr>
<td>(1:250,000)</td>
<td></td>
<td>Log 10 transformation of population density (LOGPOP)</td>
</tr>
<tr>
<td>USGS Planimetric Maps (1:250,000 and 1:100,000)</td>
<td>State and interstate highways</td>
<td>Annual population growth rate (1960–1990) (GROWTH)</td>
</tr>
<tr>
<td>New York Department of Transportation (1990) and Connecticut Department of Transportation (1990) Traffic Volume Reports</td>
<td>Annual average # vehicles/day on state and interstate highway sections</td>
<td>Traffic volume—mean of average annual # vehicles/day for road sections in sample</td>
</tr>
<tr>
<td>U.S. Geological Survey Land Use-Land Cover Digital Data (USGS 1986)</td>
<td>Land-use categories adapted from the Level II classification: residential, urban-mixed (commercial, industrial, and residential), upland forest (deciduous, coniferous, mixed, and urban), agriculture, water, wetland, and abandoned land</td>
<td>Log 10 transformation of traffic volume (LOGTRAF)</td>
</tr>
<tr>
<td>(1:250,000)</td>
<td></td>
<td>Land-use proportions—compiled with the exclusion of surface water coverage</td>
</tr>
<tr>
<td>USGS 7.5' Topographic Quadrangles (1:24,000)</td>
<td>Major and minor roads</td>
<td>Log 10 transformation of residential-urban % (LOGRESURB)</td>
</tr>
<tr>
<td>Aerial Photos 1987–1991</td>
<td>Classification of urban land: residential, urban-mixed (commercial, residential), heavy and light industry, public institutions, outdoor developed land, urban construction</td>
<td>Mean forest patch size (ha)</td>
</tr>
<tr>
<td>New York State Land Use and Natural Resource Inventory (1967–1970)</td>
<td></td>
<td>Log 10 transformation of mean forest-patch size (LOGAREA)</td>
</tr>
<tr>
<td>Connecticut 1970 Land Use Maps (1:24,000)</td>
<td></td>
<td>Number of forest patches per 100 km² (PATCH)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Forest patch shape (P.A FRACTAL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Percent of total forest edges adjacent to urban-residential land uses (UREDGES)</td>
</tr>
</tbody>
</table>

*Abbreviations for parameters used in the correlation and regression analyses are listed in italics.
units of about 75 km² were centered on the forest study sites (n=9). Data for the transect sections and circular landscape units were compiled from planimetric maps of state and interstate highways, population census and traffic volume reports, and USGS land use-land cover data. Population densities were mapped by county subdivisions, and mean densities, weighted by area, were extracted for the sampling areas using a geographic information system. Traffic volumes, recorded as the average annual number of vehicles per day, were averaged for all highway segments that crossed a sampling unit. The USGS data, compiled from 1:80,000 air photos taken between 1983–1984, were grouped into seven categories from the original Level II classification scheme: residential (low-high density), urban-mixed (commercial, industrial, residential-urban), upland forest (deciduous, evergreen, mixed, other urban), agriculture, abandoned land, water, and wetland (USGS 1986). Field checks verified that, in most cases, forests in the city were classed in the “other urban” category. At a fine resolution, for 16 km² land units that were centered on the forest study sites (n=9), we used USGS 7.5 minute topographic quadrangles, recent air photos (1985–1990), and 1970 land-use inventories to measure the total length of roads and urban-land proportions.

Land-use data were input into raster-based geographic information systems (IDRISI and IMAP) and a spatial analysis program developed at the Rocky Mountain Forest and Range Experiment Station (see Flather et al. 1992). Grid-cell resolution equaled 4 ha for the USGS land-use data, which is comparable to that used in the original mapping of urban land uses (USGS 1986), and 1 ha for the data on urban developments compiled from the air photos and 1970 resource-inventory maps. At these grid-cell sizes, we assumed that planted street and yard trees were not included in the forest class. Structural differences in the landscape pattern of native forest vegetation were determined from measures of forest area, the number and mean size of forest patches, forest-patch shapes, and edge adjacencies between forest patches and urban-residential land uses (Table 1). We calculated these parameters from the USGS land use-land cover data using GIS, a spreadsheet program (for mean patch areas), and the spatial analysis program. The perimeter-area fractal was used to measure the complexity of forest-patch shapes. The index (D), which can vary between 1 (simple geometric shape) and 2.0 (extremely complex shape), is equal to the slope of regressing polygon area against perimeter (Krummel et al. 1987). We could only calculate the index for sampling units that had at least three patches not contiguous with the sample boundary. Together these parameters identified landscape disturbances along the urban-rural transect as related to forest-land apportionment, the degree and nature of forest fragmentation, and forest-patch shape and position.

Data analyses were twofold. First, we documented trends of human (urban) activity with distance from the urban core. We hypothesize that population density, state and interstate traffic volumes, density of major and minor roads, and urban-residential land apportionment, as structural features of the urban environment, should decline with distance from the urban core. Population growth rates and change in urban-land proportions (i.e., urban development) should be greatest where the processes of urbanization are greatest. In order to identify the nature and significance of linear or logarithmic urban-rural trends, urban- and forest-landscape parameters were plotted against distance and regression coefficients (r²) were calculated. Second, we examined the degree to which urban structures and processes explained variation in forest-landscape structure within the urban-rural transect. Our central hypothesis is that urban structures and processes are positively related, through landscape fragmentation and modification, with the number of forest patches and forest-edges adjacent to urban land uses, and negatively related with the mean area of forest patches and their fractal dimensions. Forest cover should decline and vary from large patches of complex shapes in an undisturbed landscape to small patches of simple geometric shapes with increasing urban influences (cf. Krummel et al. 1987). Correlations and regressions were computed between the set of urban and forest-landscape indicators. We examined partial correlations in order to determine the degree to which highly significant relationships were independent of distance along the transect.
Results and Discussion

Quantifying the Urban-Rural Transect

Human population density, highway traffic volume, density of the road system, and urban-residential land uses decrease with distance from the urban core (Fig. 2). At 35–55 km, a sharp change from a landscape dominated by urban-residential land uses to a forest matrix is evident. The urban environment, as measured by these indicators, declines directly with distance from the urban core. Only at 80 km is the trend noticeably disrupted, with increases in all structural features probably attributable to the city of Danbury, Connecticut, located east of the transect. In contrast, urban processes reflected in the annual rate of population growth and urban-land development show nonmonotonic trends (Fig. 3). Greatest population growth rates occur at about 60–95 km from the urban core. Changes in urban land development are greatest at about 25–65 km. These contrasting patterns between indicators of urban structure and urbanization processes are also suggested by the correlation coefficients (Table 2). Declines in population, traffic volume, road density, and urban-residential land apportionment with distance are logarithmic and correlations are large ($r < -0.88$). The correlation of distance with population growth rate is comparatively lower ($r = 0.57$) and the correlation of distance with urban land development is not statistically significant.

Forest-landscape structural characteristics are also statistically related to distance from the urban core (Fig. 4). Mean forest-patch size (Fig. 4A) and the percent of forest edges adjacent to urban land uses (Fig. 4D) are positively and negatively related to distance, respectively. The decline in mean patch size at 80 km may be related to the higher proportion of agriculture in this area and/or the increase in urban-residential land, possibly associated with development from Danbury, Connecticut. The relatively lower percentages of forest-urban edges near the urban core may be related to the position of forests along the coastline (Fig. 4D;
Table 2  Pearson Correlations (r) and Coefficients of Determination (r²) based on Relationships between Urban- and Forest-Landscape Parameters, and Distance along the Transect

<table>
<thead>
<tr>
<th>Landscape Parameters</th>
<th>Sample</th>
<th>r</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Urban</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOGPOP</td>
<td>n=28</td>
<td>-0.97</td>
<td>0.93²</td>
</tr>
<tr>
<td>LOGTRAF</td>
<td>n=28</td>
<td>-0.90</td>
<td>0.80²</td>
</tr>
<tr>
<td>LOGROADS</td>
<td>n=9</td>
<td>-0.88</td>
<td>0.77²</td>
</tr>
<tr>
<td>LOGRESURB</td>
<td>n=28</td>
<td>-0.91</td>
<td>0.83²</td>
</tr>
<tr>
<td>GROWTH</td>
<td>n=28</td>
<td>0.57</td>
<td>0.33²</td>
</tr>
<tr>
<td>DEVELOP</td>
<td>n=9</td>
<td>0.03</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td><strong>Forest</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOGAREA</td>
<td>n=28</td>
<td>0.03</td>
<td>0.68²</td>
</tr>
<tr>
<td>PATCH</td>
<td>n=28</td>
<td>-0.53</td>
<td>0.28²</td>
</tr>
<tr>
<td>P_A FRACTAL</td>
<td>n=25</td>
<td>0.30</td>
<td>0.09</td>
</tr>
<tr>
<td>UREDGES</td>
<td>n=28</td>
<td>-0.92</td>
<td>0.84²</td>
</tr>
</tbody>
</table>

¹Landscape parameters are defined in Table 1.
²Statistics are based on data compiled for the 5 x 20-km transect sections (n=28) or the 16-km² landscape units centered on the forest study areas.
³Statistically significant at 0.01 level.
⁴The P_a fractal was only calculated in those transect sections that had at least three forest patches not contiguous with the boundary.

Figure 4: Forest-landscape characteristics along the urban-rural gradient: (A) mean area of forest patches; (B) number of forest patches per 100 km²; (C) forest-patch shape; and (D) percent of total forest edges adjacent to urban-residential land uses. Data were compiled from the USGS land use-land cover data and plotted for 5 x 20-km transect sections and 75-km² land units centered on the forest study sites.
Fig. 1). Still, much of the variation in these two parameters can be accounted for by distance from the urban core. Statistically significant relations are observed for urban-rural distance and the log of the mean area of forest patches \( r = 0.83 \), and for urban-rural distance and the percent of forest edges adjacent to urban land uses \( r = -0.92 \); Table 2.

In contrast, the correlation is low between urban-rural distance and the number of forest patches \( r = -0.53 \) and not statistically significant for forest-patch shapes. Forest-patch numbers vary greatly (from 12-71 patches/100 km²) over short distances up to 100 km along the transect, but they are consistently low (<14) at the rural end of the transect (Fig. 4B). While a negative trend toward fewer patches is documented, the explanatory power of the linear model is not great. To some extent, differences in patch numbers may be obscured by the sampling design, 100-km² transect sections and 75-km² forest-study units, which presents a problem for distinguishing different patches from a single patch that overlaps the sample boundary at more than one location (inflating total numbers). P-a fractals (Fig. 4C) increase up to 40 km and are highest between 40-80 km. Forest-patch shapes at the rural end are difficult to interpret because P-a fractals are based only on patches that occur in the sampling units and therefore do not measure the complexity of background forest cover that is contiguous with the respective sample boundaries. For our samples, a linear relationship between distance and the complexity of forest-patch shapes is not observable from the plot or supported by statistical analysis.

### Urban-to-Forest Landscape Relationships

Correlations between the urban and forest-landscape parameters differ according to the nature of the urban effect (Table 3). Correlations with urban structural features such as population densities, traffic volumes, and road density are high for the mean area of forest patches, the adjacencies between forests and urban-residential land, and, to a lesser degree, the number of forest patches. In contrast, forest-patch shape is best correlated with the urban process of population growth.

In support of our central hypothesis, mean forest-patch areas decrease and the number of forest patches and forest edges adjacent to urban land increase with population density, traffic volume, and road density (Table 3). Population growth rate, however, shows statistically significant positive relationships with mean forest-patch areas and shapes, and negative relationships with the percentage of forest edges adjacent to urban land. The population growth rate between 1960-1990 is negatively related to the level of forest-landscape disturbance, a result at least partially explained by the low-to-negative population growth of the urban core.

The explanatory power of statistical relationships between forest and urban parameters is in some instances greater than those measured with distance from the urban core (see Table 2). Population density explains nearly 80% of the variation in mean forest-patch area \( r^2 = 0.79, p < 0.01 \), in contrast to the 68% explained by distance to the urban core. Population growth rate explains 34% of the vari-

#### Table 3 Pearson Correlations Between Urban and Forest-Landscape Parameters

<table>
<thead>
<tr>
<th>Forest-Landscape Parameters</th>
<th>LOGPOP</th>
<th>LOGTRAF</th>
<th>ROADS</th>
<th>GROWTH</th>
<th>DEVELOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOGAREA</td>
<td>-0.89°</td>
<td>-0.86°</td>
<td>-0.59</td>
<td>0.41¹</td>
<td>-0.16</td>
</tr>
<tr>
<td>(n=28)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UREDGES</td>
<td>0.89⁰</td>
<td>0.83⁰</td>
<td>0.80</td>
<td>-0.66⁰</td>
<td>0.25</td>
</tr>
<tr>
<td>(n=28)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PATCH</td>
<td>0.57°</td>
<td>0.53°</td>
<td>0.72</td>
<td>0.03</td>
<td>-0.09</td>
</tr>
<tr>
<td>(n=28)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_a FRACTAL</td>
<td>-0.41°</td>
<td>-0.32°</td>
<td>0.66</td>
<td>0.59</td>
<td>-0.19</td>
</tr>
<tr>
<td>(n=25)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Correlations are based on the 5-km transect sections for the correlations with population density (LOGPOP), traffic volume (LOGTRAF), and population growth (GROWTH). Correlations with road length (ROADS) and urban development (DEVELOP) are based on landscape units centered on the nine forest study sites.

¹Statistically significant at 0.01 level.

²Statistically significant at 0.05 level.

³The P_a fractal is only calculated for landscape samples that contain at least three forest patches not contiguous with the boundary.
ation in patch shapes ($r^2 = 0.34; p < 0.01$), in contrast to the 9% explained by distance. After controlling for distance effects, the partial correlations between these urban and forest parameters are $-0.63$ ($p < 0.01$) and $0.54$ ($p < 0.01$), respectively. Urban-to-forest landscape relationships, while related, are not solely dependent on distance from the urban core. These urban structures and processes are ecologically-relevant measures of the urban environment that are likely to better predict the areal extent, degree of fragmentation, and patch characteristics of native forest vegetation in different geographic settings.

**Urban-Suburban-Rural Environments**

In addition to documenting a measurable gradient of human influences along the urban-rural transect, certain patterns emerge from the study that may be used to characterize urban, suburban, and rural environments. The environmental conditions of urban centers are greatly influenced by structural features (high population densities, urban land cover, and transportation) and less influenced by landscape changes attributable to rapid growth in populations and urban land developments. Forest patches at the urban end of the transect are small, of typically simple geometric shapes, and adjacent to urban land uses. In contrast, a suburban zone, identified broadly at about 25–100 km along this transect, is both temporally and spatially more dynamic. We measured high rates of urban change, steep distance gradients in urban structures, high variability in forest-patch sizes, and greater complexity in forest shapes. The rural end of the transect is a forest matrix, with a low number of large (more than 500 ha) forest patches that account for well over 50% of the land area. The gradient of change in landscape structural attributes is greatest within the suburban zone.

**Conclusions**

We conclude from this study that the nature of the urban environment and its relationship with native forest-landscape structure show quantifiable differences within an urban-rural transect between New York City and northwestern Connecticut. A decline in forest area is only one aspect of change that shows an association with urban structures and processes in this region. The structural configuration of forest patches (number and mean size), relative exposure to the urban environment, and potential for further fragmentation are also important characteristics that influence their ecology.

The structure of the urban environment, as measured by population density, traffic volume, road density, and urban-residential land use, declines logarithmically with distance from the urban core. Between 35–55 km, land use changes abruptly from an urban-residential matrix at greater than 80% cover to a forest matrix at greater than 70% cover. Accordingly, the mean sizes of forest patches increase and the percent of forest-urban edges decrease with distance from the core. The number of forest patches is much lower at the rural end of the transect. In contrast, urban processes such as population growth rate and urban land development show nonlinear trends, with maximum rates between 60–95 km and 25–65 km, respectively. Patch shapes, calculated only for patches within and not contiguous with the sample boundaries, are most complex at 40–80 km. Distance, as an independent variable, clearly documents the idiosyncrasies of this urban-rural transect, but only partially explains forest-landscape structure.

We accept our central hypothesis that, in most cases, urban structures are positively related with the number of forest patches and edges adjacent to urban land uses, and negatively related with the mean area of forest patches and their fractal dimensions. Maximum population growth rates, however, occur in less-disturbed areas; consequently, we predict greater fragmentation at those locations with time. Statistical relationships between urban parameters and forest-landscape structure are comparable (for forest-urban edges) or better than those identified with distance. These urban structures and processes are likely to better predict forest-landscape structure in different geographic settings.

Based on landscape patterns along the distance gradient and urban-forest landscape relationships, we are able to distinguish between the environmental conditions of forests in urban and suburban landscapes. Forests near the urban core are small in size, simple in shape, and greatly exposed to the structural features of the urban environment (e.g., high popula-
tions, traffic volumes, developed land). The land apportionment and spatial configuration of forests near the urban core are not likely to change, but protection and restoration from stresses imposed by pollutants, high human activity, and an altered climatic regime are critical for their longterm sustainability (e.g., Pouyat and McDonnell 1991; Oke 1988; Driestadt et al. 1990). In the suburban zone, high rates of urban change and steep gradients of change in urban structures influence landscape pattern. Forest vegetation in this region increases greatly in mean-patch size and adjacencies to urban land use, shows great variation in patch numbers, and has relatively more complex patch shapes. Suburban landscapes are much more susceptible to structural changes over space and through time. Nature conservation in this region, therefore, depends on managing forest-land apportionment, fragmentation effects, and spatial configuration across the urbanizing landscape (Hansson and Angelstam 1991; Saunders et al. 1991; Matlock 1993). These differences support management strategies that are directed, in urban areas, at the restoration of small forest areas that show decline or stress attributable to the urban environment, and, in suburban areas, at the acquisition of a sustainable forest-landscape structure. Thus, our study contributes toward a landscape classification of urban-rural gradients that is applicable to the design of ecologically sensitive land management strategies.

**Literature Cited**


Approaches to River Channel Sensitivity*

P. W. Downs
University of Nottingham

K. J. Gregory
Goldsmith's College, University of London

Much research in the physical and human sciences has addressed the concept of sensitivity to adjustment, including the analysis of geomorphological adjustment in fluvial systems. However, geomorphological sensitivity has been defined in numerous ways, partly because current conceptual understanding of the fluvial system exceeds modeling capabilities. Using published literature and analogies from materials behavior as a background, previous definitions are standardized and four hierarchically based interpretations are developed. The four interpretations, which relate to ratios, thresholds, recovery times, and sensitivity analysis, are explained and illustrated using a table that could be modified to apply to other environmental systems. Such standardized definitions of sensitivity should facilitate more precise communication between geomorphologists and guarantee effective use of the concept in analyses of the fluvial system. Key Words: sensitivity, river channel change, thresholds, sensitivity analysis.

Geomorphological contributions to environmental management require an improved understanding of the dynamics of landscape change. Achieving this understanding depends on the integration of knowledge obtained from reductionist studies of geomorphic processes. Geomorphological investigations of river channels have demonstrated that channels can adjust in response both to a variety of natural environment stimuli and to influences associated with human activity (Gregory 1987a). Numerous texts exist documenting the natural behavior of rivers (e.g. Richards 1982); for human activities, the effects of river impoundment (Petts 1984) and channelization (Brookes 1988) have received particular attention (see Downs 1994). For environmental management purposes, geomorphologists must determine the combined impact on individual river reaches of the effects of separate natural and human influences throughout the drainage network. Such analysis should include the ability to explain why river channels that appear similar react in different ways to similar stresses—that is, why individual river reaches display temporally and spatially differentiated nonlinear dynamical responses (Phillips 1992).

The integration of impacts accruing from separate natural and human controls on the drainage basin requires a method by which the relative impact of each control can be assessed and then combined. In this regard, the concept of sensitivity can potentially provide the basis for a powerful analytical tool for relating geo-

*The comments of two anonymous referees are gratefully acknowledged in the revision of this paper. This work developed from research undertaken while Downs was in receipt of NERC studentship GR4/88/AAPS/43, CASE with the National Rivers Authority Thames Region.