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Transitions in forest fragmentation: implications for restoration opportunities at regional scales

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Abstract

Where the potential natural vegetation is continuous forest (e.g., eastern US), a region can be divided into smaller units (e.g., counties, watersheds), and a graph of the proportion of forest in the largest patch versus the proportion in anthropogenic cover can be used as an index of forest fragmentation. If forests are not fragmented beyond that converted to anthropogenic cover, there would be only one patch in the unit and its proportional size would equal 1 minus the percentage of anthropogenic cover. For a set of 130 watersheds in the mid-Atlantic region, there was a transition in forest fragmentation between 15 and 20% anthropogenic cover. The potential for mitigating fragmentation by connecting two or more disjunct forest patches was low when percent anthropogenic cover was low, highest at moderate proportions of anthropogenic cover, and again low as the proportion of anthropogenic cover increased toward 100%. This fragmentation index could be used to prioritize locations for restoration by targeting watersheds where there would be the greatest increase in the size of the largest forest patch.

Introduction

Forests provide ecological goods and services (Westman 1977), including habitat (Lynch and Whigham 1984), a potential reservoir for atmospheric carbon (Wessman 1992), and stable soils and clean water (Hunsaker and Levine 1995). Despite the growing concern over human-induced fragmentation of forests in temperate North America (Wilcove et al. 1986), there are few regional-scale studies (Noss and Cooperrider 1993). Rather, forest fragmentation studies have been place-specific in scale, and have focused on the amount of habitat lost and the subsequent impact on specific taxa (Wickham et al. 1997a). We lack information on patterns of forest fragmentation and how these patterns relate to human occupancy of the landscape.

Where the potential natural vegetation is continuous forest across a region, an indicator of forest fragmentation and influence of human use on fragmentation patterns can be obtained by comparing the size of the largest forest patch to the amount of anthropogenic cover. To make the comparison, the region is divided into smaller units (e.g., counties, watersheds) and the proportion in the largest forest patch is plotted against the proportion in anthropogenic cover (e.g., agriculture, urban) for each unit. If forests are not fragmented beyond that converted to anthropogenic cover, there will be only one forest patch in each unit whose proportional size will equal 1 minus the percentage of anthropogenic cover. If all units were in this state (maximum possible case), then a graph of the proportion in the largest forest patch versus that in anthropogenic cover would have a slope of negative one (−1), i.e., the size of the largest forest patch is (exactly) inversely proportional to the amount of anthropogenic cover. If a landscape unit departs significantly from this expectation, then forest fragmentation is in excess of what has been lost to land cover conversion, suggesting that forests exist as smaller, isolated patches and that pattern as well as amount of anthropogenic cover is important.

We examined about 130 watersheds in the mid-Atlantic region of the eastern United States as a way to study the degree to which human land-cover patterns fragment forests over large regions. We also show how the approach can be used to target watersheds and areas within watersheds where re-introduction of forest would yield the greatest reduction in fragmentation.

Methods

Study area

The mid-Atlantic region study area included the states of Pennsylvania, Delaware, Maryland, Virginia, and West Virginia. The reasons for selecting this study area were three-fold. First, the potential natural vegetation of the area is almost entirely forest (Kuchler 1964; Whittaker 1975), except for comparatively minor components such as emergent wetlands. Where the assumption of continuous forest cannot be satisfied, interpretation of the impact of human occupancy on the size of the largest forest patch would be unclear. The approach described here cannot be universally applied across all climate-vegetation regimes. Second, significant human use gradients exist across the region (Wickham et al. 1997b). Third, a comprehensive land-cover database exists for the region (Vogelmann et al. 1998).

Data preparation

The land-cover data were divided into their component U.S. Geological Survey (USGS) eight-digit hydrologic accounting units (watersheds). The proportion of land-cover devoted to anthropogenic use was calculated as the amount of area in classes 2, 3, 4, 5, 6, 12, 13 and 15, divided by the total watershed area (Table 1). This ratio provides an anthropogenic use index (O'Neill et al. 1988). To calculate the proportion of each watershed in the largest forest patch, the land-cover map was re-classified so that all forest types (classes 7, 8, 9, 10) were one class. Arc/Info's regiongroup function was used to identify the largest forest patch in each watershed using the reclassified map. The regiongroup function assigns a unique value to thematic classes that share a common boundary. All eight nearest neighbors (cardinal directions and diagonals) were used to define connectivity between pixels. The file of forest patches was sorted in descending order, and the largest was then expressed as a proportion of total watershed area. Total area estimates excluded water, beaches, and emergent wetlands for the calculation of both proportions because their potential natural vegetation would not be forest.

When streams separated forest patches that otherwise would have been connected, the total area of the divided forest patch was used. In tidal areas, principally the lower portions of the Potomac, James, Rappahannock, and York Rivers, some watersheds were split in two along the center line of the stream. This was done primarily for visual convenience, since each watershed was examined individually on a CRT for forest patches split by streams.

Graphical indicator analysis

Percolation theory (Stauffer 1985) provides a starting point for selecting a model to describe the relationship between the size of the largest forest patch and the amount of anthropogenic cover. In landscape studies, it has been used as a tool to find critical thresholds in connectivity (principally habitat) to make inferences about pattern-process relationships (Gardner and O'Neill 1991). Since connectivity is related to size, percolation theory is also useful for modeling the relationship between size of the largest forest patch and amount of anthropogenic cover.

Percolation theory predicts a non-linear relationship between the size of the largest forest patch and the amount of non-forest. For the eight nearest neighbor case, the size of the largest patch follows the maximum possible case until the amount of non-forest reaches about 0.5. At 0.5 the size of the largest patch bends away slightly from the maximum possible case, and then drops off dramatically as one minus the critical percolating threshold (P_c) is approached. For the eight nearest neighbor case, P_c is 0.4072 (Plotnick and Gardner 1993). For the cardinal directions only case, the curve is shifted to the left, reflecting the stricter connectivity rule (see Gardner et al. 1987, Table 2).

An equation that describes the relationship between the size of the largest forest patch and the amount of anthropogenic cover is:

$$Y = (1 - x)e^{-bx^a} \quad (1)$$

Table 1. Land-cover categories

(1) Water	(6) Probable row crops	(11) Emergent wetlands
(2) Low-intensity developed	(7) Conifer forest	(12) Barren; quarry areas
(3) High-intensity developed	(8) Mixed forest	(13) Barren; coal mines
(4) Hay/pasture/grass	(9) Deciduous forest	(14) Barren; beach areas
(5) Row crops	(10) Woody wetlands	(15) Barren; transitional

where x is the proportion of the watershed in anthropogenic cover, and Y is the proportion in the largest forest patch. This model constrains the size of the largest forest patch to be one (100%) when anthropogenic cover is zero and zero when anthropogenic cover is one, and contains the curvature predicted from percolation theory. The equation was fit by visual estimation, with b equal to -7 and a equal to 4. Solving for Y using the first derivative of equation 1 provided instantaneous slope estimates over the range of x, and a plot of the first derivative over x provided a graphical device for estimating when the slope departed from negative one (-1), the maximum possible case.

Simple screen visualization overlays were then used to evaluate the potential of adding forest patches to increase connectivity toward the maximum possible case, using a subset of 50 watersheds. This was done simply by 'painting' the largest forest patch in a transparent color on top of a color-coded land-cover map of the watershed on a CRT and panning and zooming around the watershed to find a forest patch that was close but disjunct from the largest. The second through fifth largest patches were always searched first.

Disjunct patches had to be within about 320 m of the largest patch to be considered connectable. This rule was based on observations by Healy and Short (1981), who noted that land parcellation in rural areas seems to have a prevalence for 5-acre lots. This small lot size, and rather strict connectivity rule, was chosen to increase the likelihood of restricting targets for hypothetical reforestation to land under single ownership. The 320 m distance is about equivalent to the width of a square 5-acre parcel.

Results

The proportion of the watershed in the largest forest patch versus the proportion in anthropogenic cover is shown in Figure 1. The points closely approximate the slope of the maximum possible case (-1) until the proportion of anthropogenic cover reaches about 15%. Departures from the maximum possible case become more consistent and dramatic beyond 20%, resulting in a steeper slope and greater variability.

Figure 2 shows the instantaneous rate of change in the slope of Equation 1. The slope reached negative 1.1 between 15 and 20% anthropogenic cover. This range of percentage anthropogenic cover may be generally interpreted as a threshold where there is a change in the state of forest connectivity. State transitions have been described as components of ecosystem modeling (Holling 1973), hierarchy theory (O'Neill et al. 1989), disturbance (Turner et al. 1993), and ecotone structure and dynamics (Milne et al. 1996, Loehle et al. 1996).

The potential for increasing forest connectivity as a function of percentage anthropogenic cover is shown in Figure 3. The results suggest that the biggest gains in forest connectivity occur when percentage anthropogenic cover is between 20 and 40%, although some exceptions do occur. A general interpretation of this pattern is when the proportion of anthropogenic cover is high, forests tend to occur as numerous small, disjunct patches, and connecting any two does not yield large improvements in the size of the largest forest patch. Conversely, when the amount of anthropogenic cover is small, forests are already connected. When the proportion of anthropogenic cover is moderate, large gains in forest connectivity can occur because there is a greater likelihood of connecting large forest patches.

Exceptions to the general rule seemed to be the result of topography when anthropogenic cover is low. The two watersheds that have a low percentage of anthropogenic cover but larger increases in connectivity were both located in the Appalachian Mountains. In both cases, a large forest patch was separated from the largest by a river valley devoted to primarily agricultural and urban uses. When anthropogenic cover was high, large gains in forest connectivity seemed to be due to chance. There were 14 observations where anthropogenic cover was 50% or greater. Large forest

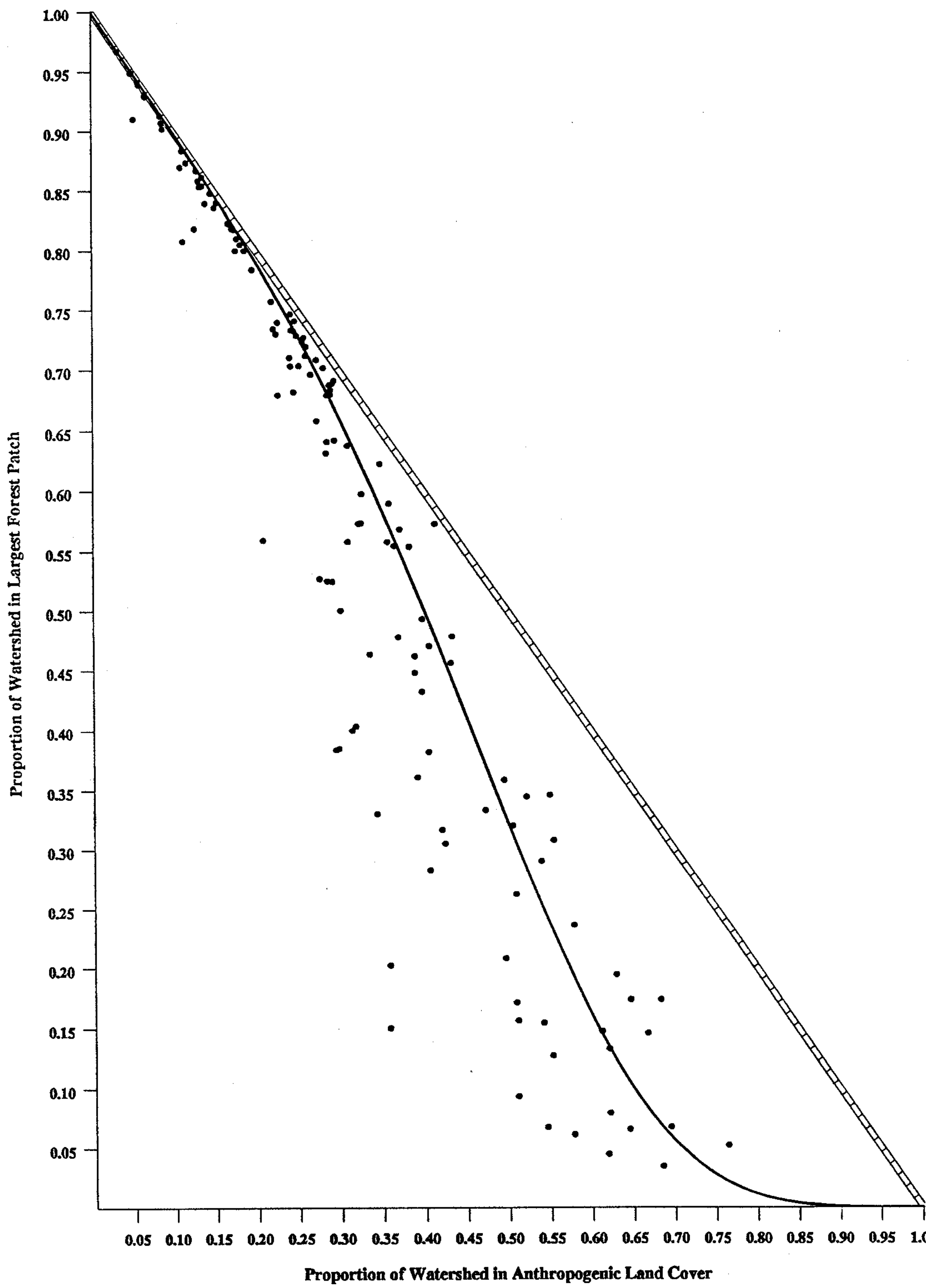

Figure 1. Proportion of the watershed in the largest forest patch versus the proportion that is anthropogenic cover. Solid line is from Equation 1. Double line with hatches denotes the maximum possible case of one minus the proportion of anthropogenic cover.

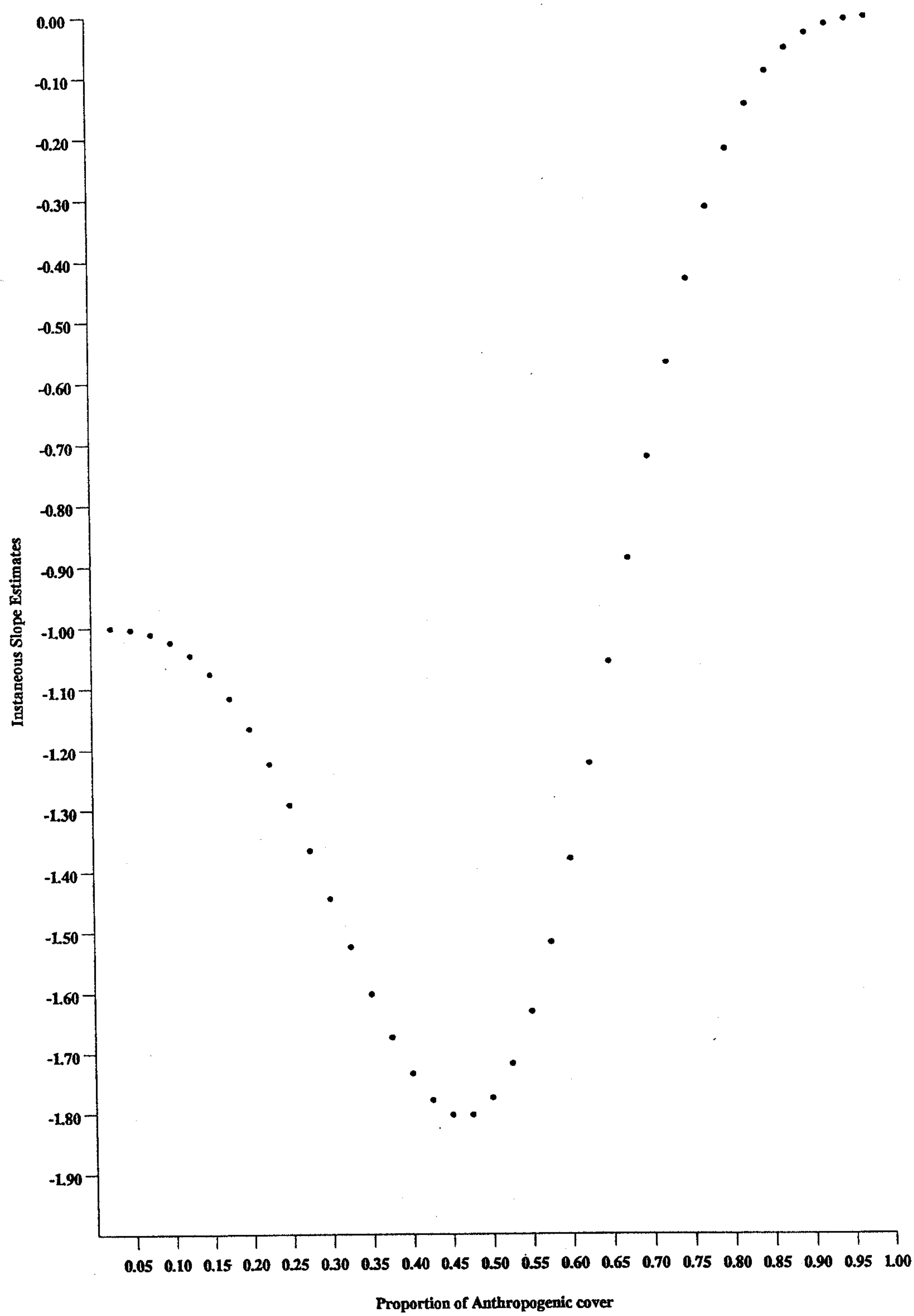

Figure 2. Instantaneous slope estimates from Equation 1.

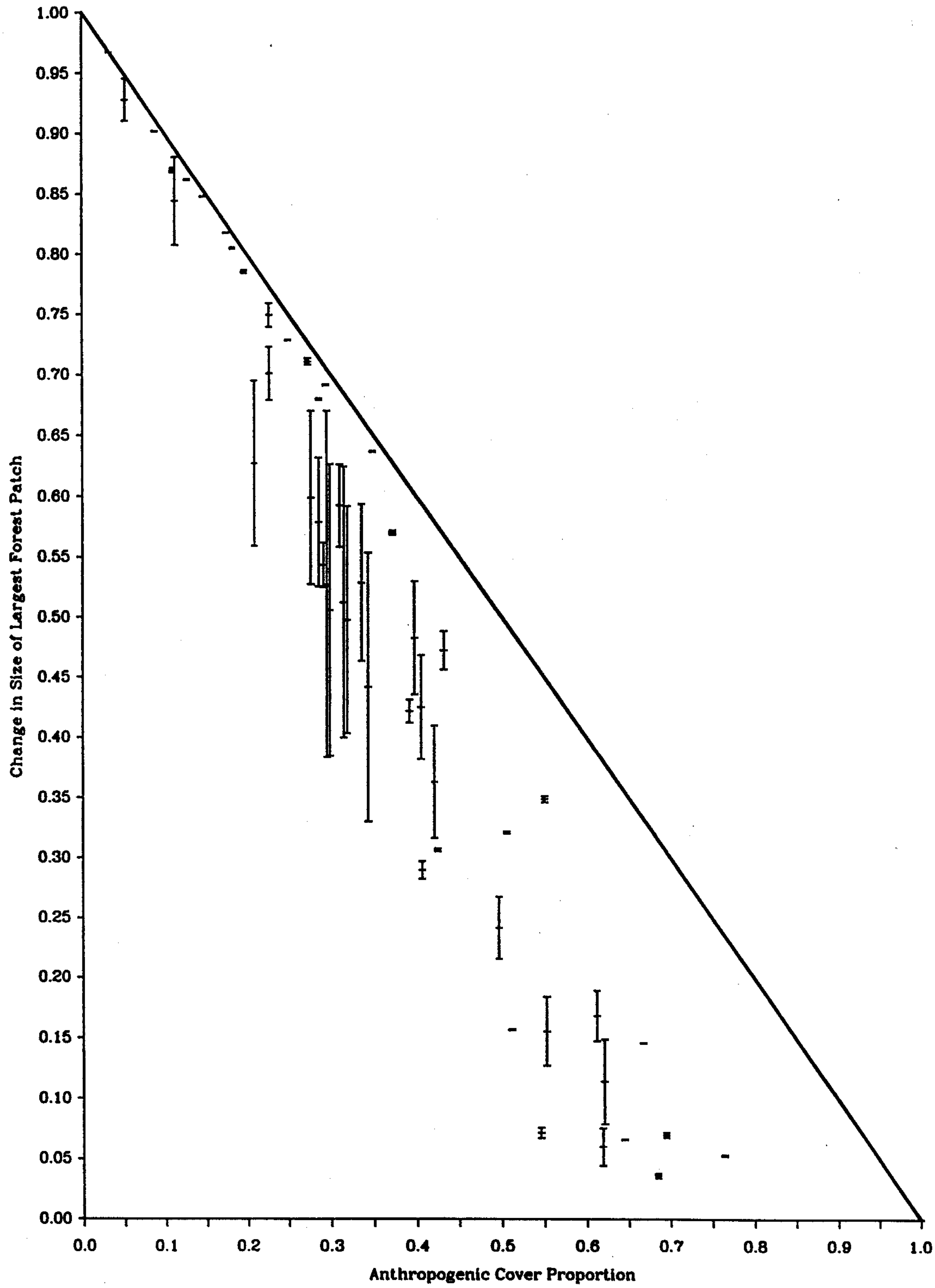

Figure 3. Potential for increasing forest connectivity as a function of the proportion of anthropogenic cover in the watershed. The potential is expressed as a line between two hatch marks, with the lower hatch indicating the proportional size of the largest forest patch, and the upper hatch indicating the proportional size after the largest forest patch is connected to the next largest within 320 m. The hatch in the middle of the line is simply the mid-point.

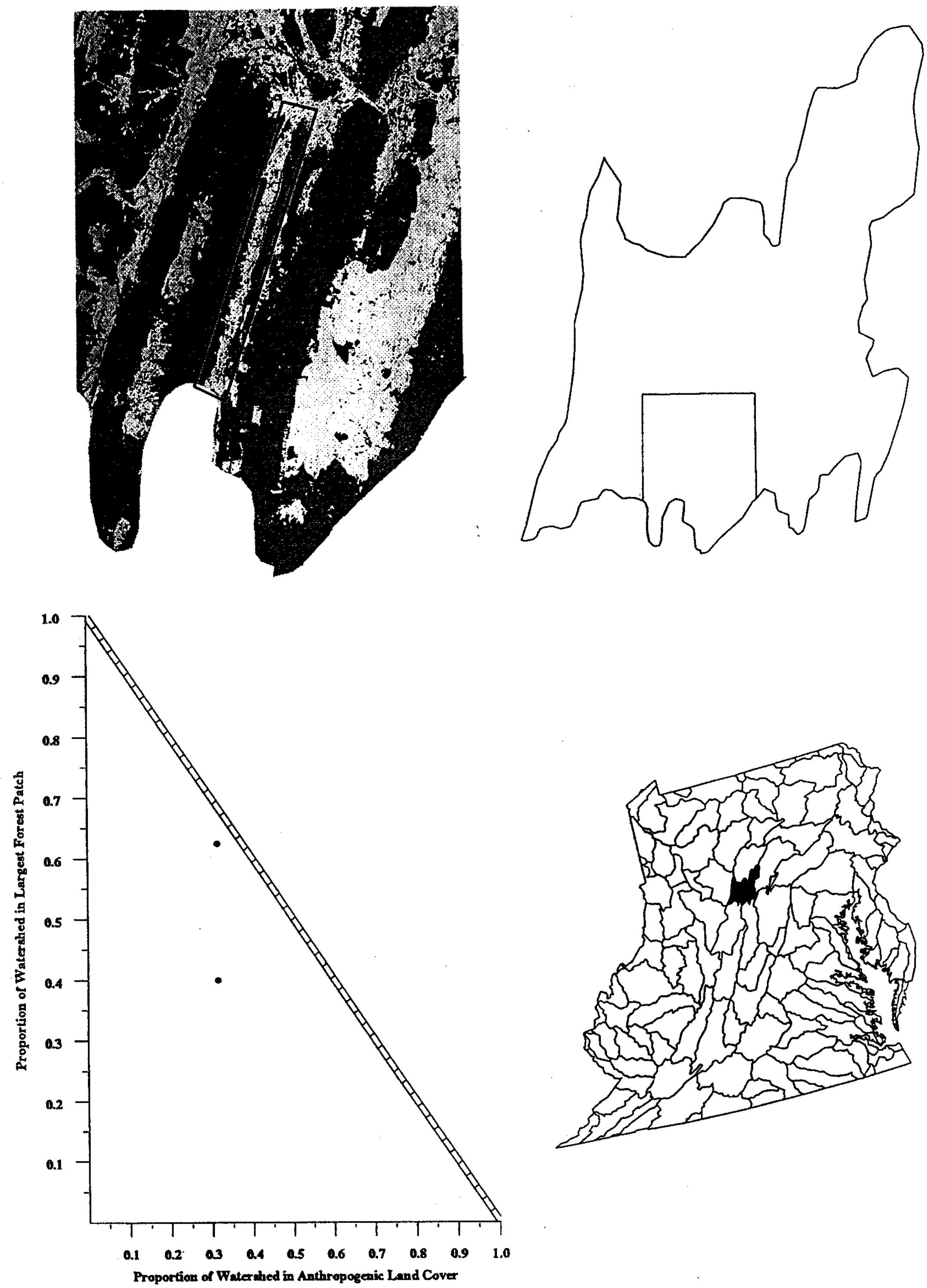

Figure 4. An example watershed in south-central Pennsylvania where the proportional size of the largest forest patch could be increased by 22% by re-introducing forest across an agricultural valley. Re-introduction of a forest patch anywhere along the light gray area inside the box (but spanning its width) would connect two disjunct forest patches and increase the proportional size of the largest forest patch from about 40 to 65%.

patches were within 5 acres of the largest 5 out of 14 times.

Figure 4 shows the location of where forest could be re-introduced to connect two large forest patches for a watershed in south-central Pennsylvania. Re-introduction of a forest patch anywhere within the agricultural valley (light gray area inside the box) would increase the proportional size of the largest forest patch from about 40 to 65%, which would be close to the maximum possible case of 1 minus the proportion of anthropogenic cover.

Discussion

Departures of the proportional size of the largest forest patch from the maximum possible case increased at an increasing rate as the percentage anthropogenic cover changed from 0 to 45%. Use of the first derivative was a convenient tool to define a change in the rate (threshold) of forest fragmentation. Although the parameters for Equation 1 were derived empirically through visual estimation, its functional form is based on that predicted from percolation theory. As a null model, percolation theory (using eight nearest neighbors) predicts that departure of the largest forest patch from the maximum possible case would not occur until anthropogenic cover reached 50%, with significant departure occurring as one minus the percolation threshold is approached ($1 - P_c = 0.5928$).

The transition threshold of 15 to 20% found in this study agrees with a 20 percent threshold found by Vogelmann (1995) for forest fragmentation in New England. Vogelmann also found a non-linear relationship. The results of both studies suggest that significant transitions in forest connectivity occur at relatively low levels of conversion to non-forest cover.

The relationship between the potential for increasing forest connectivity and percentage anthropogenic cover was investigated as a possible tool for targeting where re-introductions of forest would have the greatest impact. Targeting whole watersheds first and then areas within watersheds for re-introduction of forest is an example of multi-scale restoration. If the two largest forest patches in each watershed were connected through local re-introductions of forest, the dispersion of points in Figure 1 would more closely approximate the maximum possible case. Local re-introductions would improve forest connectivity regionally, and potentially change the regional relationship described in equation 1. There are relatively few studies showing how information can be passed across scales (but see King et al. 1989).

There is a large volume of literature on human impacts on the environment (see, for example, Ehrlich et al. 1977; McDonnell and Pickett 1993). However, there is little information on how human activity impacts the spatial pattern of resources in the environment. The results found here suggest that the impact of land use conversion on spatial patterning of forests are not considered when land use decisions are made, or that forest fragmentation is not a real concern in practice.

Summary

Since the potential natural vegetation is forest nearly everywhere in the eastern United States, a simple graph of the proportion of the largest forest patch versus the proportion of anthropogenic cover can be used to assess the degree of fragmentation across a region. Based on available land-cover data, a graph of this relationship for the mid-Atlantic region suggested that forest fragmentation tended to become more severe between 15 and 20% anthropogenic cover. This range agrees with a 20% threshold in forest fragmentation found in New England (Vogelmann 1995). The potential for improving forest connectivity by connecting close but disjunct patches was greatest between 20 and 40% anthropogenic cover. Below this range forests tend to be well connected, and above this range forests tend to occur as numerous small patches. In general, the relationship between percentage increase in forest connectivity and percentage anthropogenic cover provides a method to identify and prioritize where local re-introductions of forest would yield the greatest improvements in forest connectivity region-wide, and also shows how information can be passed across scales.

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