Characterizing Forest Fragmentation and Vulnerability Based on Patch Characteristics

K. Bruce Jones, Timothy G. Wade, James D. Wickham, Kurt H. Riitters, Curtis M. Edmonds

Abstract—Loss and fragmentation of natural forests due to human activities represents one of the greatest threats to global biodiversity and the sustainability of the biosphere. Although we are aware of declines in natural forests, we lack comprehensive knowledge of the extent and magnitude of forest loss and fragmentation. Moreover, we lack methodology to assess the vulnerability of forests to human activities. This paper highlights a simple 2-step method to assess forest fragmentation and vulnerability due to human activities over a range of scales. The method is demonstrated in tropical forest zones of Central America, South America, and Africa, using 1-km global land cover data.

The shrinking and fragmentation of intact forests has become a major environmental concern worldwide (Turner et al. 1990; Groom and Schumaker 1993; Houghton 1994; Imhoff 1994; Ojima et al. 1994). These two factors have and continue to contribute to the loss of important forest resources and associated ecological services, including timber production (Franklin 1992), forest plant and animal diversity (Van Dorp and Opdam 1987; Bierregaard et al. 1992; Whitmore and Sayer 1992; Stouffer and Bierregaard 1995; Jullien and Thiollay 1996; Metzger 1997), and the processes of water interception, infiltration, and runoff that determine the magnitude of flooding, water storage, and the quality of drinking water (Peterjohn and Correll 1984; Saunders et al. 1991; Franklin 1992).

Shrinking and fragmentation of forests results primarily from human activities that convert natural land cover to anthropogenic uses, including agriculture, urban, and residential uses (Zipperer 1993; Ojima et al. 1994). As an area is developed, continuous forest stands are divided into smaller and smaller patches, and the proportion of individual forest patch edges juxtaposed to anthropogenic land cover increases until the patches are fully imbedded in a sea of human land use. Small patches that become imbedded within a sea of human land use are the most likely to be lost, or to become sufficiently small and/or isolated enough such that they no longer support an array of interior forests species. Unless checked by biophysical (e.g., slopes or geology), economic (e.g., a downturn in the economy), or social (e.g., preservation land) constraints, forests adjacent to developing areas continue to shrink in size, become more fragmented, and eventually are lost (Zipperer 1993).

By analyzing the size ranges of individual patches, the spatial pattern in the range of sizes, and the types of edges surrounding individual patches, it is possible to see fragmentation events and evaluate relative vulnerabilities of individual patches from composite images of land cover. Moreover, new digital coverages of land cover and advances in Geographic Information Systems (GIS) and other computer tools permit analysis of land cover pattern and forest fragmentation over relatively large areas (Jones et al. 1997; Riitters et al. 1997).

We developed a 2-step analysis process that uses a relatively simple set of landscape pattern statistics to evaluate the status of forest loss, fragmentation, and threats due to human use. We also developed a simple index of forest patch vulnerability based on patch sizes and edge characteristics. These indicators can be calculated and interpreted from a wide range of remote sensing imagery in a GIS. We demonstrate the application of these indicators and a vulnerability index in tropical zones of Central America, South America, and Africa using 1-km land cover databases distributed by the U.S. Geological Survey’s EROS Data Center.

Methods

A set of three continental images of land cover were obtained from the U.S. Geological Survey through the Global Land Cover Characteristics (GLCC) project and converted to Arc/Info GRID format. These data have a nominal one-kilometer spatial resolution, and were derived from satellite imagery (Advanced Very High Resolution Radiometer or AVHRR) from the time period of April 1992 to March 1993. We used the 17-class land cover grid (International Geosphere Biosphere Program, Lambert equal-area projection) for Central America (on the North American coverage), South America, and Africa (Belward and Loveland 1995).
To identify forest land cover, and to determine if forest land cover was adjacent to or divided by natural non-forest land cover, or anthropogenic land cover, we reclassified the 17 land cover classes into three classes (forest, anthropogenic, and non-forest natural, Table 1).

We used a two-step process to assess tropical forest fragmentation on three different continents; an initial step at the continental-scale to identify areas where forest fragmentation might be occurring, and a second step to evaluate the extent and nature of forest fragmentation and risk to individual forest patches in those areas identified in the first step.

The first step involved converting the 3-class land cover grid into individual patches using the Regiongroup command in GRID. This command grouped cells with the same land cover class into patches with unique values. Cells may be connected in any direction (including diagonals). Figure 1 provides an example for South America. We then identified three areas, one in central America (southern Honduras), one in South America (central Amazon), and one in Africa (southeastern Ivory Coast and southwest Ghana), where large block tropical rain forests have been fragmented into smaller patches by human land uses. We also used this process to identify an area in South America where little fragmentation was evident (control).

We zoomed into the smaller, subarea within each continent by clipping them out of the larger continental grids in Arc/Info GIS. Grided versions of patches for each of the three areas were then converted into polygons. Using the relationship between arc and polygon topologies, the proportion of adjacent land cover was calculated for each forest polygon.

The proportion of anthropogenic/forest edge was calculated as: anthropogenic edge/(anthropogenic edge + natural edge) x 100. We included the entire area of all patches located at the edges of the study areas rather than artificially cutting them off. This reduced the impact of the study area boundary on the patch statistics. For example, a patch of several hundred cells might have been clipped so that only a few patches were in the study area. In this case, the edge values (and area) for the entire patch were used in the calculations. Shorelines of rivers, bays, and oceans were counted as natural edge (Figure 1).

Quintiles were calculated for the edge values, with anthropogenic edge proportions of 20% and less being classified as 1 (least risk) to proportions of over 80% which were classified as 5, or highest risk.

Patch area was also split into categories on the assumption that large patches are at lower risk than small patches, even if they have a high proportion of anthropogenic edge. Patches of 3 pixels (300 Hectares) or less were classified as 3, or highest risk, patches between 3 and 300 pixels were classified as 2, and patches over 300 pixels were classified as 1.

An index was generated by multiplying the values for area and edge. The resulting index values ranged from 1 to 15, and were displayed in 5 colors. Darker green represents the lowest risk, values 1-3, light green shows values 4-6, yellow 7-9, pink 10-12, and red 13-15 (greatest risk, see Figure 2). Natural land cover was displayed as light blue, and anthropogenic use as black. It is possible to evaluate and display forest vulnerability across an entire continent and then zoom into areas of interest. Figure 3 illustrates how one can zoom into the central Amazon Basin from an entire view of South America.

### Results

Identification of individual forest patches through the GRID Regiongroup command permits an initial screen of forest fragmentation across an entire continent. Figure 1 illustrates how one can use the continental-scale forest patch map as an initial screen to find areas that might be undergoing significant forest loss and fragmentation. The example provided in Figure 1 is of South America and it clearly shows significant patterns of forest loss and fragmentation in the central Amazon. A similar method was used to screen areas of significant forest fragmentation in Central America and Africa. As a result of this screening, central Amazonia of South America, the southern Honduras area of Central America and the southeast area of the Ivory Coast and southwest Ghana of Africa were selected for the second level of analysis.

Comparison of patch characteristics for forested areas in the central Amazon, southern Honduras, and southeast Ivory Coast/southwest Ghana show that the three areas differ in terms of forest/human spatial pattern and risk. All three of these areas contain tropical forests whose loss and fragmentation due to human activities is of primary concern. Figure 4 illustrates the spatial distribution of forest patches by degree of risk (five quintiles or levels of risk). As expected, based on our methods, forest patches at greatest risk were small and fully imbedded within anthropogenic land cover (Figure 4). Forest patches classified as moderate-high and moderate risk varied in size from a 5 or 6 pixels up to 35-40 pixels, and have from approximately 50% to 100% of their edges adjacent to anthropogenic cover (Figure 4). Larger forest patches that fell into moderate-high and moderate risk classes tended to be fully imbedded within anthropogenic cover whereas smaller patches in these two classes tended to have a lower percentage of edge adjacent to anthropogenic cover (Figure 4). Forest patches in the two lowest risk classes tended to be large (>50 pixels) and had a

<table>
<thead>
<tr>
<th>IGBP class</th>
<th>New classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evergreen needleleaf forest</td>
<td>Forest</td>
</tr>
<tr>
<td>Evergreen broadleaf forest</td>
<td>Forest</td>
</tr>
<tr>
<td>Deciduous needleleaf forest</td>
<td>Forest</td>
</tr>
<tr>
<td>Deciduous broadleaf forest</td>
<td>Forest</td>
</tr>
<tr>
<td>Mixed forest</td>
<td>Forest</td>
</tr>
<tr>
<td>Closed shrublands</td>
<td>Non-forest natural</td>
</tr>
<tr>
<td>Open shrublands</td>
<td>Non-forest natural</td>
</tr>
<tr>
<td>Woody savannas</td>
<td>Non-forest natural</td>
</tr>
<tr>
<td>Savannas</td>
<td>Non-forest natural</td>
</tr>
<tr>
<td>Grasslands</td>
<td>Non-forest natural</td>
</tr>
<tr>
<td>Permanent wetlands</td>
<td>Non-forest natural</td>
</tr>
<tr>
<td>Croplands</td>
<td>Anthropogenic</td>
</tr>
<tr>
<td>Urban and built-up</td>
<td>Anthropogenic</td>
</tr>
<tr>
<td>Cropland/natural mosaic</td>
<td>Anthropogenic</td>
</tr>
<tr>
<td>Snow and ice</td>
<td>Non-forest natural</td>
</tr>
<tr>
<td>Barren or sparsely vegetated</td>
<td>Non-forest natural</td>
</tr>
<tr>
<td>Water bodies</td>
<td>Non-forest natural</td>
</tr>
</tbody>
</table>
Figure 1.—Individual patches at the continent scale and the Amazonia study area boundary.
Three-class rankings of forest patches based on area.

- Over 3,000 hectares
- 300 to 3,000 hectares
- 300 hectares or less

Quintile rankings of forest patches based on the proportion of edge adjacent to anthropogenic cover.

- 0 - 20%
- 20 - 40%
- 40 - 60%
- 60 - 80%
- 80 - 100%

Patch risk index map derived by multiplying area and edge maps.

- Lowest Risk
- Low-Moderate Risk
- Moderate Risk
- Moderate-High Risk
- Highest Risk

Figure 2.—Combining landscape themes to evaluate forest vulnerability in Central Amazonia.
Figure 3.—Forest patch vulnerability in Central Amazonia at three scales.
Figure 4.—Forest patch vulnerability in three tropical zones of the world.
significant proportion of their edges adjacent to natural non-
forest land cover, such as woodland savannah (Figure 4).

Of the three areas, forest patches in the central Amazon
had the highest average risk score (Table 2). It also had a
relatively high proportion of its forest patches in the max-
imum risk class, as did the African site (Table 2). Figure 4
also shows that the Amazon site has the greatest amount of
anthropogenic cover of the three sites and has a large
number of forest patches fully imbedded within anthropo-
genic cover. The central American site had the lowest per-
centage of forest patches in the maximum risk category and
adjacent to anthropogenic cover, but it had a higher average
patch risk score than the African site (Table 2). All three
areas had a considerably higher percentage of forest patches
in the high risk category than the relatively undisturbed site
(Table 2). Based on average risk scores of forest patches, one
could conclude that forest patches in the central Amazon are
at greatest risk, followed by the southern Honduras, and the
African site. However, the African site had a greater number
of high risk forest patches than did the southern Honduras
site (Table 2).

Discussion

The two-step analysis process highlighted in this paper
provides a way to evaluate forest fragmentation across
entire continents, and to evaluate the extent and nature of
fragmentation in specific areas. Moreover, the approach
evaluates the relative risk of forest loss and fragmentation
based a simple index of forest patch size and the percentage
of an individual patch edge that is adjacent to anthropogenic
cover. This assumes that areas with numerous small forest
patches imbedded in a sea of anthropogenic cover are more
likely to be undergoing rapid forest fragmentation and forest
loss than larger forest patches imbedded within natural
land cover (patches that are naturally fragmented). Based
on patterns of deforestation reported in other studies (Zipperer 1993), this assumption seems reasonable. Unlike
more traditional remote sensing methods that evaluate
forest loss from a set of imagery obtained over a range of
dates (Tucker et al. 1984; Iverson et al. 1989; Hall et al. 1991;
Vogelmann 1994; Jones et al. 1997), our method provides a
way to evaluate ongoing fragmentation from a single land
cover product, such as the global 1-km land cover database
produced by the U.S. Geological Survey's EROS Data Center.

Because of costs associated with data collection and pro-
cessing at continental scales, geographic “targeting” ap-
proaches, such as that highlighted in this paper, are needed
to assess forest resource conditions over large areas at
multiple scales. Jones et al. (1997) used landscape data to
evaluate watershed conditions at a regional scale, and to
target those areas that potentially needed additional eval-
uation. Using a regional scale land-cover database, Wickham
et al. (1998) ranked watersheds relative to their potential for
forest restoration and increased connectivity.

The approach can be applied to land cover data at varying
scales, including land cover derived from satellites, as well
as aerial photography. However, because the scale of the
imagery can affect index value for a given area (see Lillesand
and Kiefer 1994), comparisons among areas should be lim-
ited to a single scale of imagery.

This paper makes no attempt to analyze the consequences
of forest patch vulnerability on ecological resources or associ-
ated processes. To do so would require the application of
ecological, biological, and hydrological process models,
depending upon the ecological resource of concern. For ex-
ample, one could evaluate the consequences of losing high
risk forest patches on biota through the use of metapopulation
and biogeography process models (Whitcomb et al. 1981;
Fahrig and Merriam 1985; Schumaker 1996; Keitt et al.
1997). Similarly, watershed models are needed to assess the
consequences of forest patch loss on water quality.

The vulnerability index applied in this paper could be
improved by adding thematic data layers on slope and
elevation and protected areas. For example, some forest
patches with high amounts of anthropogenic edge might be
less likely to be developed because they are on areas with
steep slopes and hence are unsuitable for development, or
because they are protected by law. Cost grids of these
additional characteristics could be calculated in a GIS and
incorporated into the index. For example, forests in pro-
tected areas would have risk values at or near zero because
these sites are not likely to be developed. Similarly, forests
on steep slopes would have lower scores than forests in
relatively flat areas. The threshold for slopes (the point at
which development probably would drop substantially) could
be determined from existing patterns of development. Addi-
tionally, it may be possible to improve the index by separat-
ing internal from external edge, since the former represents
an internal erosion of forest patches and the later a periph-
eral erosion (Zipperer 1993).

Finally, it may be possible to improve the initial screening
process of each continent by applying a spatially filtering
approach (Riitters et al. 1997). For the purpose of this study,
we located the three study sites by visually inspecting patch
maps for the three continents. However, fragmented forests

Table 2.—Comparison of forest patch statistics and risk for central Amazonia (CA), southern Honduras (SH), southeast Ivory Coast/ southwest Ghana (IC), and a relatively undisturbed forest area in the Amazon (CN). Maximum risk patches were those with
index values between 13 and 15 (see Methods section).

<table>
<thead>
<tr>
<th>Area</th>
<th>Number forest patches/ total number patches</th>
<th>Average forest patch area</th>
<th>Average anthropogenic edge</th>
<th>Forest patches at maximum risk</th>
<th>Average index value of patches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>km²</td>
<td>percent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SH</td>
<td>84/210</td>
<td>13.87</td>
<td>64.25</td>
<td>19.05</td>
<td>3.09</td>
</tr>
<tr>
<td>CA</td>
<td>94/164</td>
<td>17.66</td>
<td>85.56</td>
<td>35.11</td>
<td>2.51</td>
</tr>
<tr>
<td>IC</td>
<td>57/220</td>
<td>34.60</td>
<td>79.00</td>
<td>35.09</td>
<td>1.25</td>
</tr>
<tr>
<td>CN</td>
<td>2/109</td>
<td>2111.5</td>
<td>4.72</td>
<td>0.0</td>
<td>1.00</td>
</tr>
</tbody>
</table>

1Weighted by area.
are difficult to see at the continental scale because the image is relatively fine-scaled (see Figure 1). The spatial filtering approach utilizes a "windowing" concept which can be implemented in a GIS. One sets the window size based on the scale at which wants to analyze fragmentation. For example, a window of 100 x 100 pixels would analyze forest patch characteristics on area of 10,000 km² around each pixel (assuming a one Km pixel). The window starts from the top left part of the land cover patch map and moves one pixel at a time until it reaches the bottom right pixel in the grid. Next, one could calculate the average patch size or edge to area ratio or number of patches in the window. The result would be a new map of average patch size or edge to area ratios for forest patches in the window. The new map would result in a better visualization of forest fragmentation across each continent, and a way to target areas for more detailed analysis. The same spatial filtering approach could be used to display forest patch risk at a continental scale.

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Literature Cited


