REPORT OF THE UNITED STATES ON THE CRITERIA AND INDICATORS FOR THE SUSTAINABLE MANAGEMENT OF TEMPERATE AND BOREAL FORESTS

Criterion 1: Conservation of Biological Diversity
Indicator 5: Fragmentation of Forest Types
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**Abstract**

As part of the U.S. 2003 National Report on Sustainable Forests, four metrics of forest fragmentation – patch size, edge amount, inter-patch distance, and patch contrast – were measured within 137,744 non-overlapping 5,625 ha analysis units on land-cover maps derived from satellite imagery for the 48 conterminous States. The perimeter of a typical forest patch is about 100 m from the perimeter of its nearest neighbor, except when there is not much forest, in which case that distance is 200 to 300 m. A typical analysis unit has from 10 to 40 percent as much forest edge as it could possibly have, given the amount of forest present. Most analysis units contain a large number of patches that are less than one hectare in size, and about 10 percent contain one or more 2,000 to 5,000 ha patches. Forest often defines the background landscape, and patch contrast is generally either very high or very low in eastern regions and intermediate in western regions. Many research needs were identified by this experimental analysis of available data and metrics.

**Introduction**

The Montréal Process identifies a comprehensive set of Criteria and Indicators for forest conservation and sustainable management of boreal and temperate forests (Montréal Process Working Group 1998). Indicators of forest fragmentation address the sustainability of biodiversity, and are considered separate from indicators of forestland extent and its protected status. Fragmentation indicators are designed to characterize wildlife habitat, particularly for forest-dwelling species, as an indicator of biodiversity (USDA Forest Service 2001).

The point of departure for this analysis was the Technical Work Group Indicator Analysis Report (hereafter, the "Work Group Report") that was facilitated by the Roundtable on Sustainable Forests (Roundtable 2002). The Work Group Report provided the rationale for interpreting the fragmentation indicator, reviewed the available data and the candidate measurements, and summarized scientific problems and concerns. The Work Group

Report recommended using land-cover maps derived from satellite imagery to measure four aspects of fragmentation – patch size, edge amount, inter-patch distance, and patch contrast. Any assessment was said to be at least partly subjective: there is no general agreement on the specific metrics available, other aspects of fragmentation (e.g., corridors) are important, and indicators of fragmentation are typically scale-dependent and correlated with each other. Furthermore, fragmentation by roads, ownership, and forest type are not reflected in an analysis of land-cover maps, and structural fragmentation does not imply functional fragmentation. Full interpretation is not possible because "baselines" representing normal or sustainable conditions, "thresholds" representing critical levels of fragmentation are largely unknown, and temporal trends are probably more meaningful than a snapshot of current conditions. The Work Group Report concluded that improvements in data collection and vegetation classification and mapping are needed.

According to official statistics, the conterminous United States contains about $2.501 \times 10^6$ $km^2$ of forestland (USDA Forest Service 2001) and there has been a slight overall increase in privately owned forestland area since 1982 (USDA Natural Resources Conservation Service 2000). Forest fragmentation remains an issue because the composition and spatial distribution of forests are changing. For example, between 1982 and 1997, ~90,000 $km^2$ of privately owned forestland were gained from abandoned farmland, mostly in the Midwest, and ~40,000 $km^2$ were lost to urban development, primarily along the eastern seaboard (USDA Natural Resources Conservation Service 2000). The change in privately owned forestland area from 1982 to 1997 exceeded ±3% in 25 States and ±10% in five States, and the absolute change exceeded 1,000 $km^2$ in each of 18 States (USDA Natural Resources Conservation Service 2000). All but two States on the Atlantic seaboard had net losses of privately owned forestland, and all but two States bordering the Mississippi and Ohio Rivers had net increases (USDA Natural Resources Conservation Service 2000).

Fragmentation may refer to both the amount of forest and its spatial pattern, both of which can be measured on raster land-cover maps derived from satellite imagery (Gustafson 1998). Since the advent of satellite technology in the mid-1970s, most regional and larger scale surveys of fragmentation have focused on forest extent, primarily in the tropics (Downton 1995). With some exceptions (e.g., Skole and Tucker 1993), most tropical surveys have treated fragmentation as a temporal change in forest extent, and not as a spatial property of the existing forest (Foody and Curran 1994). While the amount and pattern of forest are necessarily correlated to some degree, a given amount of forest can be arranged in many ways. In this report, fragmentation specifically refers to the spatial pattern and not to the amount of forest.

There have been many regional assessments of forest fragmentation in the United States. Each study has provided comparatively detailed information but none has fully addressed the literal interpretation of the Montréal indicator. It was not feasible to expand any of those studies to national coverage, but the approaches taken could be evaluated for future work. Regions considered by Forest Service and Federal Interagency assessments include, for example, the Chesapeake Bay watershed (Society of American Foresters

1998), the Columbia River Basin (Quigley et al. 1996), the mid-Atlantic region (Jones et al. 1997), and the Southern Region (Wear and Greis 2001). Some assessments have used data other than land-cover maps (e.g., land ownership maps, road maps) and/or have considered alternate indicators of fragmentation (e.g., protected status) that do not consider spatial pattern.

**Implementation**

This section describes the implementation of the recommendations contained in the Work Group Report. It considers data sources, analysis and assessment units, specification of the indicators including measurement protocols, and summarization procedures.

Data sources

The Work Group Report noted that three national maps could possibly provide all four of the recommended fragmentation indicators – a 1-km resolution map derived from AVHRR imagery that identifies 159 cover types including about 20 major forest types, a 80-m resolution map derived from MSS imagery (but without land-cover labels), and a 30-m resolution map derived from TM imagery that identifies three upland forest types and one woody wetland (including forested wetland) type. The practical tradeoff was between spatial resolution and thematic resolution, and a decision was made to start with the higher spatial resolution (TM-based) maps, recognizing that this would yield estimates of forest fragmentation, not forest *type* fragmentation, and that data would not be available for AK or HI. The decision was based partly on previous experience measuring fragmentation on these three types of maps, and partly on the data requirements for other Criteria and Indicators.

This analysis used the land-cover maps for the lower 48 States from the National Land Cover Data (NLCD) database. The NLCD land-cover mapping project (Vogelmann et al. 2001) used Landsat Thematic Mapper (TM) data (circa 1992) to map 21 classes of land cover (Table 1) at a spatial resolution of 0.09 ha $pixel^{-1}$. There are a total of about $8 \times 10^9$ pixels on the NLCD map, of which about $2.8 \times 10^9$ pixels were labeled as forest. The TM data were mapped into the land-cover classes using a combination of digital image processing techniques and logical modeling using associated ancillary data (Vogelmann et al. 1998). The forest versus non-forest classification accuracy of the NLCD is 86% (based on omission error), and 94% (based on commission error) for the eastern seaboard (Yang et al. 2001).

For this analysis the 21-class NLCD map legend was aggregated to eight land-cover types including water, developed/urban, barren/disturbed, forest, shrubland, agriculture, grassland, and wetland (Table 1; see also Appendix 1). Four of the original NLCD types (deciduous forest, evergreen forest, mixed forest, and woody wetlands) were included in the forest class. Because the original NLCD legend provided no information about forest *types*, it was decided to lump all forest classes into one. The NLCD woody wetland class was treated as forest because it includes large regions that are traditionally considered to be forest, for example, forested wetlands in the northern lake states and riparian forested wetlands on the southeastern coastal plain. The aggregation scheme results in a legend that approximates Anderson Level I and is appropriate for analyzing fairly coarse-scale fragmentation over large regions.

For the purpose of calculating fragmentation statistics, no distinction was made between fragmentation by anthropogenic classes (e.g., agriculture, urban) and semi-natural classes (e.g., water, grassland, shrubland). Of special interest in this analysis is the NLCD "transitional" class. It includes forestland that is only temporarily cleared (timber harvest, wildfire), but it was included with the barren/disturbed class because it does not separate permanent (urban development) from semi-permanent (agricultural clearing) forest conversion (Appendix 1).

After aggregating four forest types together, the total amount of forest on the NLCD land-cover map was 2.503 x $10^6$ $km^2$. The comparable official estimate for 1992 was between 2.232 x $10^6$ $km^2$ and 2.501 x $10^6$ $km^2$ depending on definitions[1]. Close agreement was not expected because the NLCD map is of land cover whereas official statistics also consider land use, and because of differences in measurement scales and definitions of forest. The NLCD estimate is expected to be larger because more land has forest cover than is actually used as forestland, and because the minimum mapping unit is smaller. Generally speaking, the NLCD recognizes more than the official amount of forestland in the eastern U.S., and less in the western U.S.

Analysis units and assessment units

The analysis unit defines a spatial extent over which indicators are calculated and saved, and the assessment unit defines a spatial extent over which the analysis unit calculations are summarized and reported.

The Work Group Report discussion of the analysis unit notes that "… Computation of these metrics requires prior specification of the spatial unit over which the metric is to be calculated … Ideally this will require specification of a systematic grid across the U.S., with the grid cell large enough to accommodate an adequate sample of patches and the metrics calculated within each grid cell ... Assessing fragmentation with 80m or 30m pixels is likely to be adequate to reflect any impact relevant for most vertebrates and for many plants…".

Analysis units were defined by a grid of 142,602 non-overlapping 56¼ $km^2$ (7.5 km x 7.5 km) squares that tiled the NLCD map from a random starting point. Each tile potentially

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[1]Official forestland area statistics for 1992 (from the U.S. Forest Service, Forest Inventory and Analysis) came primarily from aerial photo interpretation of more than 4 million photo points over several years prior to 1992, with a minimum mapping unit of one acre (0.405 ha). The total forestland area in the United States was 3.023 x $10^6$ $km^2$ (USDA Forest Service 2001). The estimate of 2.501 x $10^6$ $km^2$ for the conterminous U.S. was obtained by subtracting 0.522 x $10^6$ $km^2$ of Alaska forestland; Hawaii was not included in official statistics. The estimate of 2.232 x $10^6$ $km^2$ was obtained by subtracting an additional 0.269 x $10^6$ $km^2$ of pinyon-juniper, chaparral, and non-stocked forestland to account for possible differences in definition of forestland.

contains 62,500 pixels on the NLCD land-cover map (i.e., each tile is 250 pixels x 250 pixels). This is a reasonable size for calculating many pattern indices given the data characteristics of the NLCD map (O'Neill et al. 1996). Partial tiles (containing less than 62,500 pixels) and water-only tiles (large inland lakes, large estuaries, and ocean) were then excluded, leaving 139,183 for further analysis. This step removed nearly all of the tiles that straddled the U.S. international borders with Canada and Mexico because land cover was not mapped for those countries. Coastal tiles remained because the NLCD map contains a buffer of water pixels in the Great Lakes and along the Pacific, Atlantic, and Caribbean coasts.[2]

To facilitate later association via geographic overlay with assessment units, the indicator values that were calculated for a given tile were assigned to the center point of that tile. Thus, the summary statistics for an assessment unit were designed to represent an "average tile" or "average analysis unit" for that assessment unit. After the data screening described above, the center points of some tiles still fell outside of all assessment units, and only those tiles with center points contained within county boundaries (defined by a US Geological Survey 1:2 million scale county map) were retained for analysis. As a result of this data screen, the final sample size was 137,744 tiles or analysis units.

The assessment units were taken to be the RPA reporting regions (Figure 1), excluding Alaska, Hawaii, and Puerto Rico. The following acronyms were used for RPA regions in this report: NO = North; PC = Pacific Coast; RM = Rocky Mountains, and; SO = South. All of the fragmentation indicators that were calculated within analysis units were summarized to the level of those four regions for this report. To support other assessments and correlation with other Montréal Process indicators, the database also contains lookup tables that cross-walk the analysis units with counties, states, USGS 8-digit hydrologic accounting units, USEPA 640 $km^2$ hexagons, and USFS (Bailey) ecoregion sections.

Indicators

The Work Group Report identifies four aspects of fragmentation to consider, and provides some discussion of alternatives, but does not specify exactly how the indicators should be obtained. The purpose of this section is to describe the decisions that were made and some of the algorithms that were used to arrive at a set of four primary indicators to address the four aspects of fragmentation. Databases produced to support this report contain additional indicators of forest patterns, and indicators from parallel analyses of shrubland and grassland.

Before discussing the indicators, it is necessary to define two basic elements of the analysis, patches and edges, upon which three of the four indicators are based.

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[2] Included are about 50 tiles (at the same latitude in NM; e.g., Figure 1) that were removed but should have been included. The "cookie-cutting" algorithm in the GIS could not fully populate those tiles with land cover when exporting files for analysis.

*Patch*

The Work Group Report defines a patch as "a block of contiguous pixels (in remotely sensed data) or of minimum mapping units (MMU) (other spatial data) of the same forest type." For this report, a patch was defined as a block of contiguous pixels of forest land-cover, where contiguity was evaluated in four cardinal directions (i.e., by using the "four-neighbor" rule)[3]. Individual patches were truncated at the boundaries of analysis units. Thus, the upper size limit of individual patches is the size of the analysis unit (62,500 pixels or 5,625 ha). Inter-patch distance calculations only considered patches within a given analysis unit.

*Edge*

The Work Group Report defines the amount of edge as the "frequency (or relative frequency) of pixels in a patch that abut other pixels or MMUs of a different type". In other words, on land-cover maps made up of pixels, edge refers in general to adjacent pairs of pixels, or more simply to the imaginary line that separates any two adjacent pixels, and forest edge specifically refers to edge that separates a forest pixel from a non-forest pixel. For consistency, only edges in the four cardinal directions from a given pixel were considered. Thus, the nominal length of a single edge is 30 meters. Furthermore, each edge was counted only once, and the order of the two pixels in a given pair was not preserved (see discussion of computational issues by Riitters et al. 1996). Because the outside edges of analysis units were considered to be missing values, the total number of edges in an analysis unit is 124,500.

*Inter-patch distance*

The Work Group Report defines inter-patch distance as "average distance between patches, with distance measured from patch centroid to patch centroid, or nearest neighbor distance estimated as an edge-to-edge distance". The second definition was implemented for this report as follows. After individual patches were delineated within an analysis unit, every pair of patches within the analysis unit was examined to determine the minimum distance between their perimeters. Because some patches have "holes" that may contain other patches, both "inside" and "outside" perimeters were tested[4]. For consistency with patch definition by the four-neighbor rule, the distances were measured from the center points (not the edges) of the perimeter pixels[5].

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[3] Computationally, the standard "flood-filling" algorithm (e.g., Hill 1991) was employed to delineate patches.

[4] Computationally, the "left-strutting turtle" algorithm (e.g., Timmins and Hunsaker 1996) was used to identify pixels on outside perimeters, and a modification that may be called the "right-strutting turtle" was used to identify pixels on inside perimeters.

[5] Other alternatives lead to inconsistencies; for example, assigning an inter-perimeter distance of zero to two patches with perimeter pixels that share a common corner point would imply that there is really only one patch. Thus, the minimum inter-patch distance equals 1.4142 (i.e., $\sqrt{2}$) pixel units, for the case of two patches having perimeter pixels that share a common corner point. Similarly, the inter-perimeter distance between two patches that are separated by one full pixel is exactly two pixel units.

Once the minimum distances between all pairs of patches were determined, the "minimum spanning tree" (e.g., Hillier and Lieberman 1990) was constructed in each analysis unit. The minimum spanning tree has two key properties: (1) each patch is connected to another patch by the shortest possible distance, and; (2) the total length of all connections is minimized. If M is the total length of all connections on a minimum spanning tree, and N is the number of patches, then the quantity M / (N – 1) is the average nearest neighbor distance. That quantity was taken as the estimator of this indicator.

*Amount of Edge*
The Work Group Report defines the amount of edge as the "frequency (or relative frequency) of pixels in a patch that abut other pixels or MMUs of a different type". Relative frequency was implemented in this report and the indicator was taken to be the absolute amount of forest edge (i.e., the number of adjacent forest/non-forest pixel pairs), divided by the total amount of forest (i.e., the number of forest pixels). This will be referred to as the "number of edges per unit area." Note that the definition is relative to the area of *forest*, not the *total* area of the analysis unit. For analysis units containing only one patch, the indicator is simply a measure of perimeter-to-area ratio for that patch. For analysis units containing more than one patch, the indicator is interpretable as an estimate of the average perimeter-to-area ratio for all forest patches in the analysis unit.

*Average Patch Size*
The Work Group Report discusses estimation problems with skewed patch size frequency distributions but gives no technical specification of this indicator. Alternatives were discussed with other Criterion and Indicator authors, and as a result the indicator was taken to be the area-weighted average patch size (i.e., the indicator is not the usual arithmetic average patch size). From a statistical perspective, the arithmetic average is among the worst possible choices because frequency distributions are so highly skewed. From a biological point of view, an area-weighted average may better characterize how an organism perceives patch sizes when moving or flying between analysis units. In this particular application, the standard formula for a weighted average reduces to the sum of squared forest patch sizes, divided by the total number of forest pixels in an analysis unit.[6]

*Patch Contrast*
This indicator was the most problematic of the four aspects of fragmentation considered here, and no "off-the-shelf" approach was available. According to the Work Group Report, "There is no general agreement on how to best measure patch contrast. It is intended to reflect the idea that a patch may be in physiognomic structure quite similar to,

[6]The standard formula has, in the numerator, the sum of the quantity times the weight given to that quantity, and in the denominator, the sum of the weights. In this application, the quantity (patch size) and weight are identical, and the denominator is the sum of patch sizes or equivalently, the total number of pixels in all patches. From a statistical point of view, the median forest patch size in each analysis unit would have been a useful indicator.

or very different from, that of the matrix in which it is embedded. A contrast index would most likely characterize the physiognomic structure of patch and matrix and express the contrast as the relative difference between the two."

The following descriptions from the 1997 FGDC Vegetation Classification Standards and related documents will help to understand why this indicator is problematic. "Physiognomy generally refers to the structure and life form of a plant community, and considers both structure (height, spacing, and shape of the vegetation) and growth forms of the dominant species (gross morphology and growth aspect of the plants). It can also include characters such as seasonality, phenology, duration, size, shape, and leaf texture of dominant or component plants. The basic unit of many physiognomic classification systems is the formation, a 'community type defined by dominance of a given growth form in the uppermost stratum of the community**,** or by a combination of dominant growth forms' (Whittaker 1962)." In the 1997 FGDC Vegetation Classification Standards, Physiognomic Class is "a level in the classification hierarchy defined by the relative percent canopy cover of the tree, shrub, dwarf shrub, herb, and nonvascular life form in the uppermost strata during the peak of the growing season.

Based on those descriptions, it is plausible to assert that the Physiognomic Class of a given pixel can be loosely approximated with 8-class land-cover maps, but quantification of finer categories in the FGDC Standards (e.g., Group, Sub-Class) is probably not tractable. But the problem is even more complicated than that, because the Work Group Report calls for an index of *contrast among patches* of different physiognomic classes. This assumes that there is an identifiable background "matrix" of some particular physiognomic class, upon which forest patches appear as distinct entities. As a practical matter, it is not reasonable to assume that forest patches always appear in such a fashion. Indeed, it is probably more reasonable to assume that forest itself forms the background matrix and that other patch types are superimposed upon it (Riitters et al. 2002). In many places, a background matrix is simply not identifiable (Wickham and Norton 1994).

Implementing this particular indicator with the available data proved to be so problematic that only an approximate approach was possible. A transparent approach based loosely on Wickham and Norton's (1994) concept of landscape pattern types was used (see also Jones et al. 1997). The approach is described here as it applies to forest, grassland, and shrubland, but this report only summarizes statistics obtained for forest. In this approach, the background matrix was first characterized in terms of the relative percentages of different land-cover types within an analysis unit. Contrast coefficients were then defined for forest, shrubland, and grassland, depending on assumptions of physiognomic classes of those land-cover types relative to the background matrix.

The details of the approach are as follows. The first step was to condense the land-cover legend from eight to four categories – forest, grassland, shrubland, and other (including water, developed/urban, barren/disturbed, agriculture, and wetland). The rationale is that physiognomic class and thus contrast coefficients with a physiognomic interpretation are easier to guess for forest, shrubland, and grassland in comparison to the other land-cover types. Physiognomic class probably has little meaning for some of the "other" land-cover types (e.g., developed/urban) but they cannot simply be ignored since in many cases they constitute the background matrix. The percentage of each of these four land-cover types was then measured within each analysis unit.

The second step employed a rule set (Table 2) to define "matrix types" in terms of those percentages. This step labeled each analysis unit by a matrix type representing the background matrix. For example, an analysis unit with 46% forest land-cover and 30% grassland cover has the "Forest-Grassland" matrix type (symbolized as "FG"). The order of names in the matrix type has no meaning (e.g., matrix types FS and SF are equivalent).

The third step was to define a set of contrast coefficients (Table 2) that specify the forest contrast when it is embedded in a particular matrix type. For simple matrix types (F, S, G), the contrast coefficients for forest are based loosely on physiognomic class as defined by height of the dominant vegetation (forest is taller than shrubland, and shrubland is taller than grassland). For six of the seven complex matrix types (FS, FG, FO, SG, SO, GO), the contrast coefficient is simply the average of the applicable simple matrix types (e.g., FS uses the average of F and S). For the seventh complex matrix type (HP), an arbitrary contrast coefficient was assigned that recognizes only that the forest is different from the matrix type. For the example given earlier, the contrast coefficient is 2.0.

The contrast coefficient for a given analysis unit was taken as the indicator of patch contrast. It is best interpreted as a categorical variable representing potential forest patch contrast. The variable represents *potential* contrast because it is defined for all analysis units whether or not there is forest present in every one. However, this analysis will focus on those analysis units that actually contain forest. The variable is *categorical* because there are only seven possible values and the values are arguably arbitrary. It may also be reasonable to assume an *ordinal* ranking of categories, depending on the plausibility of the contrast coefficients in Table 2.

The interpretation is further simplified by visualizing the contrast coefficient in terms of adding forestland to analysis units that are in different categories, as opposed to characterizing the forestland that is already present. Analysis units contain different amounts of forestland even when the contrast coefficient is the same, and weighting the coefficients by the amount of forest present (for example) leads to conceptual contradictions. The inference is a little cleaner when considering adding a new unit of forest somewhere, and when that choice is characterized in terms of the present contrast differences among analysis units. This mental model at least provides a basis for summarizing many analysis units that have different amounts of forest. In summary, there are significant conceptual and computational issues associated with this indicator that probably cannot be resolved by using the available data.

*Supplemental Indicators*

Two supplemental indicators were also used in this analysis to provide for better interpretation of the primary indicators. *Percent forest* is simply the proportion of forest pixels in an analysis unit that were the forest land-cover type. It was included because many fragmentation measures are correlated with the amount of forest present. The *matrix type* is a categorical indicator that is obtained as an intermediate step in the computation of the patch contrast indicator, before assigning contrast coefficients. The list of possible matrix types is shown in Table 2.

**Results and discussion**

Distribution of forest land-cover

The geographic distribution of percentage of forest (Figure 1) is generally consistent with what is known about forestland distribution across the lower 48 States. The percentage forest within analysis units varied from 0.0 to 1.0 in all RPA regions (Table 3). In all regions, but particularly in the RM region, a relatively large number of analysis units contained little (<5%) or no forest. Less than 5% of analysis units in any region contained more than 95% forest.

Some measures of forest fragmentation are naturally correlated with the amount of forest present, especially when the population of analysis units includes both lightly- and heavily-forested units. This might be a reason to identify separate subpopulations when assessing some measurements. However, there is not much theoretical justification for partitioning this sample based solely on the amount of forest[7], and preliminary inspection of frequency distributions of percent forest for all analysis units (not shown here) did not suggest natural breakpoints. Except for analysis units with less than 5% forest, the frequency distributions were roughly uniform over the range of percentage forest (results not shown). Therefore, a decision was made to restrict some of the analyses (as noted below) to those analysis units containing at least 5% forest land-cover. In those cases, the total sample size was reduced by about 40% (from 137,744 to 84,318).

Inter-Patch Distance

A total of 124,843 analysis units contained at least two forest patches as required to estimate this indicator. This indicator was clearly dependent on the percentage of forest in the sense that analysis units with less than 5% forest exhibited nearly the full range of possible values while those with more than 5% exhibited a much narrower range (Table 4). Therefore, the subpopulations of analysis units with less than, and more than 5 % forest cover were separately summarized.

As expected, the average minimum inter-patch distance was smaller in units with more forest (Table 4). In the North region, the forest patches in units with less than 5% forest appear to be closer together than in other regions, but there was not much evidence for regional differences in this indicator for units with at least 5% forest. The statistics reported here are not indicative of within-analysis unit variation in inter-patch, only between-unit variation in the average of within-unit values. At the risk of over-

[7] Percolation theory (e.g., Stauffer 1985) suggests breakpoints corresponding to 40% and 60% forest, but only for the measures of forest patches, and only for the case of analysis units with random spatial distributions of forest.

simplification, it might be said that a typical forest patch is about 100 meters from its nearest neighbor, except when there is not much forest, in which case that distance is 200- 300 meters depending on the region. Regional values do not reflect local conditions everywhere. For example, these “typical” distances approach 1-10 kilometers for individual analysis units.

Amount of Edge

A total of 127,012 analysis units contained at least some forest as required to estimate this indicator. The maximum value is 4.0 since an isolated pixel has four edges, but physical packing constraints mean that the maximum cannot be obtained in analysis units that are more than half forested. After accounting for that constraint, the observed values are generally not near the maximum and the implication is that over-dispersed patterns such as checkerboards never span entire analysis units. Using mean or median values as a guide, typical analysis units roughly have from 10% to 40% as much edge per unit forest area as they could have, depending on the region (Table 5). Regional values do not reflect local conditions everywhere. For example, these values commonly approach 40% to 90% of maximum for individual analysis units, and also are often much less. The geographic distribution of amount of edge is shown in Figure 2, where it is evident that the highest values are obtained in the least-forested regions (compare to Figure 1).

Area-weighted Average Patch Size

For the 127,012 analysis units containing at least some forest, the area-weighted average patch size metric was also dependent on the amount of forest present (results not shown). The median value of the average patch size metric varied among RPA regions from three ha in the RM region to 1,126 ha in the SO region (Table 5). At least 30 percent of the analysis units in each region (up to 70 percent in the RM region) had metric values less than 10 ha (results not shown). The average patch size metric is typically highest in areas that are mostly forested and relatively remote (see Figure 1). Again, regional values do not reflect local conditions everywhere. For example, individual units with area-weighted patch size from 50-100 ha are common in all regions (results not shown).

Additional insight can be gained by adjusting patch size for the amount of forest present in each analysis unit (Wickham et al., 1999). Here, the metric values were divided by the maximum possible value for the given amount of forest in each analysis unit. The frequency distributions of the “standardized” metric are bi-modal in all regions (Figure 3). After adjusting for the actual forest amount, typical analysis units in all regions have either relatively large or relatively small area-weighted average patch size. The implication is that a given amount of forest tends to be arranged either as compactly as possible (large standardized metric value) or as dispersed as possible (small standardized metric value).

Patch Contrast

The definition of matrix types was an intermediate step in the computation of patch contrast. A brief characterization of matrix types will provide background information to help interpret the patch contrast results. Analysis units are typically dominated by one of the four condensed land-cover types (Table 6). In the NO region, nearly all analysis units were either "Forest" or "Other" matrix types, and the "Other" matrix type is associated with agricultural and urban land-cover types because shrubland and grassland land-cover were not very common in that region. In contrast, the other regions all contained significant percentages of "Shrubland," "Grassland," and "Other" matrix types because of the different land-cover types present in those regions. The "Forest" matrix type characterized about 40 to 50 percent of the analysis units except in the RM region where about 15 percent of the analysis units were the "Forest" matrix type. Forest land-cover is often the dominant land-cover type, and the concept of forest patches on a background of some other land-cover type may not be an appropriate model in those instances.

The analysis of the patch contrast metric was limited to the 127,012 analysis units that contained forest. Patch contrast values are either very low or very high in the NO region where forest tends to appear either as part of the background matrix, or in combination with dominant agriculture and/or urban land-cover types (Table 7). In the PC region, patch contrast was 2.0 or less for about 75 percent of the analysis units. The RM region was unique among RPA regions in that intermediate metric values were more common than extreme metric values. The SO region was similar to the NO region but had more intermediate metric values and fewer high values.

## Summary

Four primary indicators and two supplemental indicators were measured on land-cover maps derived from satellite imagery to characterize the fragmentation status of forests for the lower 48 States. A grid of about 140,000 squares of size 56.25 $km^2$ defined the basic units of analysis, within which each of the indicators were calculated for a single type of "forest". Results for individual analysis units were summarized to the level of four RPA assessment regions (North, Pacific Coast, Rocky Mountain, and South).

The key points that emerged from the analysis are summarized as follows.

1. There is at least some forest land-cover nearly everywhere in the lower 48 States, with the exception of many locations on the Great Plains and in the intermountain west.
2. Except for sparsely forested regions, if a location has at least some forest land-cover, then it is likely to also have sufficient forest to characterize it as "mostly forested." In other words, forest is most often dominant where it does occur.
3. Indicators of inter-patch distance, edge amount, and average patch size are correlated with the amount of forest actually present, but in different ways and to different degrees.

4. Despite correlations with amount of forest, fragmentation appears to be a separate property of forest spatial distribution in the sense that it cannot be predicted by knowing only the amount of forest.
5. Regional average indicator values do not reflect local conditions; fragmentation indices within individual analysis units can be an order of magnitude (or more) higher or lower than a regional average.
6. The average inter-patch distance indicator suggested that a typical (or median) forest patch is about 100 meters from its nearest neighbor, except when there is not much forest, in which case that distance is 200-300 meters.
7. The amount of edge indicator suggested that a typical analysis unit roughly has from 10% to 40% as much edge per unit forest area as it could possibly have.
8. The area-weighted average patch size indicator suggested that a typical analysis unit contains either a couple of very large patches along with an indeterminate number of small patches, or no large patches along with a very large number of small patches.
9. The patch contrast indicator suggested that forest appears most often as part of the background matrix, as opposed to appearing as identifiable patches on a background matrix of some other land-cover type. Patch contrast is generally either very high or very low in the eastern U.S., and intermediate over much of the western U.S.
10. Considering all four indicators together, the general picture of forest fragmentation has two parts. First, in places where forest is generally dominant, a background of very large regional forest patches (probably defined by moisture and temperature constraints) is typically fragmented by a large number of "holes" that increase edge amount per unit area without creating new patches, except near the edges of those large patches where a large number of small patches are in close proximity to the large patches. Second, in regions where forest is not generally dominant, forest appears as a highly fragmented land-cover type set against background of other land-cover types.

**Criticisms and suggestions for future work**

This list summarizes comments from the peer review and public review processes that could not be addressed in this report. The list is in no particular order and is expected to grow with further review and discussion of the results presented here.

1. The report characterizes forest fragmentation in terms of indicators measured on land-cover maps, but it does not interpret the fragmentation indicators with respect to the sustainability of biodiversity. Characterizing fragmentation is a necessary first step towards this goal.
2. This analysis did not distinguish between 'natural' and 'anthropogenic' sources of fragmentation, mostly because the available data do not definitively distinguish 'natural' from 'anthropogenic' land-cover. While some degree of fragmentation is surely 'natural', especially in the west, full interpretation of potential impacts of fragmentation on biodiversity requires better information of what is normal and

what is not. The background fragmentation obviously varies across the country from almost none in Appalachia to quite a lot in the high-elevation Rockies. The differences in natural fragmentation mean a lot to focal and keystone species but are not adequately accounted for in this study. It may not be possible to make such an accounting with these data, but a strong caveat about its importance will be useful.

3. Some of the indicators would benefit from a fuller discussion of the results including hypotheses for the observed differences among and within RPA assessment regions. This comment relates to interpretation of the fragmentation indicators in terms of land cover patterns, which is different from interpretation with respect to biodiversity.
4. Median patch size may be superior to average patch size (however the average is defined) because forest patch size distributions are typically lognormal within analysis units. If interest centers on knowing how many patches exceed a certain size threshold(s), then it will be necessary to add a fuller characterization of the patch size distributions within analysis units, for example by recording the quartiles or deciles of the distributions.
5. The land-cover maps used here are not adequate for characterizing the patch contrast indicator as intended by the Santiago Indicator. While the approach adopted here added relatively little information about fragmentation, it did provide a potentially useful supplemental indicator for interpreting the other fragmentation indicators. Knowing which cover types are adjacent might be more important than knowing how different they are.
6. The report should discuss what would be gained by knowing forest type fragmentation in addition to overall forest fragmentation.
7. It might be useful to describe the parallel analysis of grassland and shrubland in more detail and provide parallel databases for those land-cover types.
8. Most of the Figures need better captions.
9. The Technical Work Group should have added forest connectivity (the extent of connection compared to maximum possible connections) as a fifth indicator. This indicator characterizes the degree of forest clumping on a pixel-to-pixel basis and provides information that is not provided by the other four indicators.
10. The data and analysis units used here were probably not fully adequate for the patch-based indicators. Future work could consider using larger analysis units, and/or finer scale delineation of patches through expansion of the land-cover legend, and/or the use of alternate data sources (e.g., road maps) to delineate individual patches.
11. This work was conducted at one set of scales that was chosen based on expert opinions of the finest scale that could be supported, given the data characteristics, and of biologically relevant scales. There is no preferred scale, and future work should consider multiple scale approaches.
12. RPA assessment regions were mandated for this work but individual regions contain too much variety of mostly-forest and mostly-nonforest sub-regions for regional average values to have much meaning. Alternate approaches based on preliminary aggregation to say, ecoregions, may be preferred.

13. The distinction between plantation forest and semi-natural forest is not accounted for by the MRLC/NLCD land cover map. This distinction is very important to biodiversity.
14. Analysis units defined at finer scales by land use, cover type, or geohydrological pattern might be more interesting than square, fixed-size analysis units.
15. It would theoretically be possible to do this job without any computer at all. A technician could visit each of the sample points, and evaluate forest fragmentation in the surrounding landscape. Whether done on foot, on aerial photographs, or even on the MRLC/NLCD maps, looking at 140,000 50-$km^2$ landscapes would be an exhausting task. While people are good at reading landscapes and computers are not, human fatigue or observer differences could introduce bias. It would be easy to count a given marginal case one way when wide-awake and another way when tired. Unlike people who only make mistakes when they are tired, computers make mistakes all the time. Still, even if the absolute numbers are biased, we hope the relative numbers will show useful differences. (Adapted with tongue in cheek from: Neudorf, J. and Garan, S.A. 2000. Automated imaging microscope system. Linux Journal 70:32-35.)

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Table 1. Definition of eight land-cover types for the fragmentation analysis, from the 21-class NLCD legend. See Appendix 1 for descriptions of NLCD land-cover types.

| Aggregated category for fragmentation analysis | Original NLCD categories |
|---|---|
| Water | Open Water<br>Perennial Ice/Snow |
| Developed/urban | Low Intensity Residential<br>High Intensity Residential<br>Commercial/Industrial/Transportation<br>Urban/Recreational Grasses |
| Barren/disturbed | Bare Rock/Sand/Clay<br>Quarries/Strip Mines/Gravel Pits<br>Transitional |
| Forest | Deciduous Forest<br>Evergreen Forest<br>Mixed Forest<br>Woody Wetlands |
| Shrubland | Shrubland |
| Grassland | Grasslands/Herbaceous |
| Agriculture | Pasture/Hay<br>Row Crops<br>Small Grains<br>Fallow<br>Orchards/Vineyards/Other |
| Wetland | Emergent Herbaceous Wetlands |

Table 2. Rule set used to define the matrix type and forest patch contrast metric. $P_f$, $P_s$, $P_g$, and $P_o$ are the area percentages of forest, shrubland, grassland, and other land-cover types, respectively.

| Rule set | Matrix type | Forest contrast metric |
|---|---|---|
| Rule 1. If any one of the four land-cover types occupies more than half of the analysis unit, then the matrix type is that land-cover type. | | |
| If $P_f > 50\%$ | Forest (F) | 1.0 |
| Else if $P_s > 50\%$ | Shrubland (S) | 2.0 |
| Else if $P_g > 50\%$ | Grassland (G) | 3.0 |
| Else if $P_o > 50\%$ | Other (O) | 4.0 |
| Rule 2. Otherwise, if any two occupy more than three-fourths of the analysis unit, then the matrix type is a combination of those two land-cover types. | | |
| Else if $P_f + P_s > 75\%$ | Forest-Shrubland (FS) | 1.5 |
| Else if $P_f + P_g > 75\%$ | Forest-Grassland (FG) | 2.0 |
| Else if $P_f + P_o > 75\%$ | Forest-Other (FO) | 2.5 |
| Else if $P_s + P_g > 75\%$ | Shrubland-Grassland (SG) | 2.5 |
| Else if $P_s + P_o > 75\%$ | Shrubland-Other (SO) | 3.0 |
| Else if $P_g + P_o > 75\%$ | Grassland-Other (GO) | 3.5 |
| Rule 3. Otherwise, at least three land-cover types are needed to occupy three-fourths of the analysis unit and the matrix type is not well defined. | Mixed (M) | 2.0 |

Table 3. Characterization of the amount of forest within 5,625 ha analysis units, by RPA assessment region.

| RPA region | Number of analysis units (percent of all regions) | Proportion of analysis unit that is forest | | Analysis units with no forest | | Analysis units with less than five percent forest | | Analysis units with more than 95 percent forest | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Median | Number | Percent of region | Number | Percent of region | Number | Percent of region |
| NO | 30,261 (22) | 0.44 | 0.39 | 1 | < 1 | 4,063 | 13.4 | 1,432 | 4.7 |
| PC | 14,786 (11) | 0.37 | 0.24 | 816 | 5.5 | 5,644 | 38.2 | 655 | 4.4 |
| RM | 53,639 (39) | 0.15 | 0.01 | 7,492 | 14.0 | 35,392 | 66.0 | 401 | 0.7 |
| SO | 39,058 (28) | 0.44 | 0.46 | 2,423 | 6.2 | 8,327 | 21.3 | 1,453 | 3.7 |
| All regions | 137,744 (100) | 0.32 | 0.17 | 10,732 | 7.8 | 53,426 | 38.8 | 3,941 | 2.9 |

Table 4. Summary statistics for the average minimum inter-patch distance for forest patches within 5,625 ha analysis units that contained at least two forest patches, by RPA assessment region.

| | Analysis units with less than five percent forest | | | | | Analysis units with at least five percent forest | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| RPA Region | Number of analysis units | Mean distance ( m ) | Range ( m ) | Standard deviation ( m ) | Median distance ( m ) | Number of analysis units | Mean distance ( m ) | Range ( m ) | Standard deviation ( m ) | Median distance ( m ) |
| NO | 4,059 | 219 | 51 – 2,591 | 121 | 189 | 26,130 | 90 | 42 - 636 | 29 | 82 |
| PC | 4,573 | 577 | 42 – 8,783 | 799 | 310 | 9,128 | 87 | 42 - 392 | 28 | 79 |
| RM | 26,526 | 512 | 42 – 9,518 | 749 | 256 | 18,245 | 90 | 42 - 704 | 27 | 84 |
| SO | 5,556 | 493 | 42 – 8,323 | 723 | 239 | 30,621 | 86 | 42 - 503 | 23 | 81 |
| All regions | 40,714 | | | | | 84,124 | | | | |

Table 5. Summary statistics for the edge amount and weighted average patch size metrics within 5,625 ha analysis units that contained forest, by RPA assessment region.

| | | Edge amount (number of forest edges per unit forest area) | | | | Area-weighted average patch size (hectares) | | | |
|---|---|---|---|---|---|---|---|---|---|
| RPA region | Number of analysis units | Mean | Range | Standard deviation | Median | Mean | Range | Standard deviation | Median |
| NO | 30,260 | 0.81 | 0.001 – 4.00 | 0.69 | 0.64 | 1,687 | 0.09 – 5,623 | 1,977 | 495 |
| PC | 13,970 | 1.42 | 0.002 - 4.00 | 1.24 | 1.04 | 1,737 | 0.09 – 5,620 | 2,094 | 235 |
| RM | 46,147 | 1.81 | 0.004 - 4.00 | 1.11 | 1.82 | 676 | 0.09 – 5,617 | 1,426 | 3 |
| SO | 36,635 | 0.86 | 0.000 - 4.00 | 0.91 | 0.48 | 1,893 | 0.09 – 5,625 | 1,932 | 1,126 |
| All regions | 127,012 | | | | | | | | |

Table 6. Percent of 5,625 ha analysis units with different matrix type designations, by RPA assessment region. See text for explanation of matrix types.

| RPA region | Number of analysis units | Percent of analysis units in a region having the given value of matrix type | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | F Forest | G Grassland | S Shrubland | O Other | FS Forest-Shrubland | FG Forest-Grassland | FO Forest-Other | GS Grassland-Shrubland | GO Grassland-Other | SO Shrubland-Other | M Mixed |
| NO | 30,261 | 43.2 | 0.0 | 0.0 | 56.3 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 |
| PC | 14,786 | 38.8 | 4.6 | 29.0 | 16.3 | 2.0 | 0.9 | 0.8 | 0.7 | 0.5 | 1.6 | 4.8 |
| RM | 53,639 | 14.3 | 27.0 | 29.9 | 20.7 | 1.1 | 0.9 | 0.2 | 1.1 | 1.4 | 0.8 | 2.5 |
| SO | 39,058 | 46.9 | 5.5 | 8.8 | 30.0 | 0.3 | 0.5 | 1.2 | 0.8 | 1.6 | 0.6 | 3.9 |
| All regions | 137,744 | 32.5 | 12.6 | 17.3 | 30.7 | 0.7 | 0.6 | 0.6 | 0.7 | 1.0 | 0.6 | 2.6 |

Table 7. Percent of 5,625 ha analysis units with different values of the forest contrast metric, for analysis units that contain forest, by RPA assessment region. See text for explanation of the forest contrast metric.

| RPA region | Number of analysis units | Percent of analysis units in a region having the given value of the forest contrast metric | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 |
| NO | 30,260 | 43.2 | 0.0 | 0.0 | 0.5 | 0.0 | 0.0 | 56.3 |
| PC | 13,970 | 41.1 | 2.2 | 32.5 | 1.5 | 6.4 | 0.5 | 15.8 |
| RM | 46,147 | 16.6 | 1.3 | 31.1 | 1.4 | 26.8 | 1.5 | 21.2 |
| SO | 3,6635 | 50.0 | 0.3 | 11.7 | 2.0 | 4.9 | 1.5 | 29.5 |
| All regions | 127,012 | 35.3 | 0.8 | 18.3 | 1.4 | 11.9 | 1.0 | 31.4 |

List of Figures

**Appendix 1**.

NLCD Land Cover Classification System, Land Cover Class Definitions (Source: NLCD Land Cover Classification System Key - Rev. July 20, 1999). Major classes are underlined and minor classes are numbered; the numbers shown are the original NLCD data codes.

<u>Water</u> - All areas of open water or permanent ice/snow cover.

11. Open Water - All areas of open water; typically 25 percent or greater cover of water (per pixel).
12. Perennial Ice/Snow - All areas characterized by year-long cover of ice and/or snow.

<u>Developed</u> - Areas characterized by a high percentage (30 percent or greater) of constructed materials (e.g. asphalt, concrete, buildings, etc).

21. Low Intensity Residential - Includes areas with a mixture of constructed materials and vegetation. Constructed materials account for 30-80 percent of the cover. Vegetation may account for 20 to 70 percent of the cover. These areas most commonly include single-family housing units. Population densities will be lower than in high intensity residential areas.
22. High Intensity Residential - Includes highly developed areas where people reside in high numbers. Examples include apartment complexes and row houses. Vegetation accounts for less than 20 percent of the cover. Constructed materials account for 80 to100 percent of the cover.
23. Commercial/Industrial/Transportation - Includes infrastructure (e.g. roads, railroads, etc.) and all highly developed areas not classified as High Intensity Residential.

<u>Barren</u> - Areas characterized by bare rock, gravel, sand, silt, clay, or other earthen material, with little or no "green" vegetation present regardless of its inherent ability to support life. Vegetation, if present, is more widely spaced and scrubby than that in the "green" vegetated categories; lichen cover may be extensive.

31. Bare Rock/Sand/Clay - Perennially barren areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, beaches, and other accumulations of earthen material.
32. Quarries/Strip Mines/Gravel Pits - Areas of extractive mining activities with significant surface expression.
33. Transitional - Areas of sparse vegetative cover (less than 25 percent of cover) that are dynamically changing from one land cover to another, often because of land use activities. Examples include forest clearcuts, a transition phase between forest and agricultural land, the temporary clearing of vegetation, and changes due to natural causes (e.g. fire, flood, etc.).

Forested Upland - Areas characterized by tree cover (natural or semi-natural woody vegetation, generally greater than 6 meters tall); tree canopy accounts for 25-100 percent of the cover.

41. Deciduous Forest - Areas dominated by trees where 75 percent or more of the tree species shed foliage simultaneously in response to seasonal change.
42. Evergreen Forest - Areas dominated by trees where 75 percent or more of the tree species maintain their leaves all year. Canopy is never without green foliage.
43. Mixed Forest - Areas dominated by trees where neither deciduous nor evergreen species represent more than 75 percent of the cover present.

Shrubland - Areas characterized by natural or semi-natural woody vegetation with aerial stems, generally less than 6 meters tall, with individuals or clumps not touching to interlocking. Both evergreen and deciduous species of true shrubs, young trees, and trees or shrubs that are small or stunted because of environmental conditions are included.

51. Shrubland - Areas dominated by shrubs; shrub canopy accounts for 25-100 percent of the cover. Shrub cover is generally greater than 25 percent when tree cover is less than 25 percent. Shrub cover may be less than 25 percent in cases when the cover of other life forms (e.g. herbaceous or tree) is less than 25 percent and shrubs cover exceeds the cover of the other life forms.

Non-natural Woody - Areas dominated by non-natural woody vegetation; non-natural woody vegetative canopy accounts for 25-100 percent of the cover. The non-natural woody classification is subject to the availability of sufficient ancillary data to differentiate non-natural woody vegetation from natural woody vegetation.

61. Orchards/Vineyards/Other - Orchards, vineyards, and other areas planted or maintained for the production of fruits, nuts, berries, or ornamentals.

Herbaceous Upland - Upland areas characterized by natural or semi-natural herbaceous vegetation; herbaceous vegetation accounts for 75-100 percent of the cover.

71. Grasslands/Herbaceous - Areas dominated by upland grasses and forbs. In rare cases, herbaceous cover is less than 25 percent, but exceeds the combined cover of the woody species present. These areas are not subject to intensive management, but they are often utilized for grazing.

Planted/Cultivated - Areas characterized by herbaceous vegetation that has been planted or is intensively managed for the production of food, feed, or fiber; or is maintained in developed settings for specific purposes. Herbaceous vegetation accounts for 75-100 percent of the cover.

81. Pasture/Hay - Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops.
82. Row Crops - Areas used for the production of crops, such as corn, soybeans, vegetables, tobacco, and cotton.
83. Small Grains - Areas used for the production of graminoid crops such as wheat, barley, oats, and rice.
84. Fallow - Areas used for the production of crops that are temporarily barren or with sparse vegetative cover as a result of being tilled in a management practice that incorporates prescribed alternation between cropping and tillage.
85. Urban/Recreational Grasses - Vegetation (primarily grasses) planted in developed settings for recreation, erosion control, or aesthetic purposes. Examples include parks, lawns, golf courses, airport grasses, and industrial site grasses.

Wetlands - Areas where the soil or substrate is periodically saturated with or covered with water as defined by Cowardin et al.

91. Woody Wetlands - Areas where forest or shrubland vegetation accounts for 25-100 percent of the cover and the soil or substrate is periodically saturated with or covered with water.
92. Emergent Herbaceous Wetlands - Areas where perennial herbaceous vegetation accounts for 75-100 percent of the cover and the soil or substrate is periodically saturated with or covered with water.