Development of Landscape Metrics for Characterizing Riparian-Stream Networks

Michael J. Schuft, Thomas J. Moser, P.J. Wigington, Jr., Don L. Stevens, Jr., Lynne S. McAllister, Shannen S. Chapman, and Ted L. Ernst

Abstract

Sampling methods and functionally related landscape metrics were developed for characterizing riparian-stream networks using aerial photography and GIS. A sample area was empirically derived by using morphological characteristics of increasing portions of the stream network surrounding points selected on streams. GIS functions were used to band stream networks in 10-m increments to a distance of 300 m, within which land cover was interpreted from aerial photographs and digitized. Incremental banding is an effective approach for characterizing the composition and pattern of land cover as a function of distance from the stream network. Structural attributes that capture the linear nature of riparian-stream networks, such as the composition, width, longitudinal extent, and connectivity of woody vegetation, were characterized. The methods developed provide a flexible framework for deriving landscape metrics of functionally important structural attributes of riparian-stream networks for exploring relationships at varying spatial scales with indicators of stream ecological condition.

Introduction

Riparian areas along stream networks are one of the most dynamic parts of the landscape (Swanson *et al.*, 1988; Forman, 1997). They are critically important interfaces between terrestrial and aquatic ecosystems, having profound effects on the biological, chemical, and physical characteristics of streams. Although processes occurring throughout the watershed can affect stream ecological condition, the importance of riparian areas far exceeds their limited areal proportion in a watershed. Ecological functions provided by riparian plant communities are considered critical for maintaining stream ecological condition (Brinson *et al.*, 1981; Gregory *et al.*, 1991; Naiman, 1992; Malanson, 1993). These functions include (1) contributing large woody debris, (2) supplying fine organic matter, (3) stabilizing streambanks, (4) providing stream shading, and (5) regulating the flux of upland-derived sediments, nutrients, and other chemicals.

The principal structural attributes (i.e., spatial composition and pattern) of riparian corridors affecting the above functions include the composition, width, longitudinal extent, and connectivity of the vegetated component along the stream network, particularly woody vegetation (Brinson *et al.*, 1981; Barton *et al.*, 1985; Petersen, 1992; Malanson, 1993; Forman, 1997). Gaps and narrows in riparian woody vegetation can result in poorer stream ecological condition, depending on the stream type and the spatial relationships between the gaps and narrows and the intensity of external stresses (Forman, 1997). The zone of influence of riparian woody vegetation (i.e., ecologically effective width) for the functions listed above diminishes with distance from the stream network. Furthermore, the zone of influence for the functions are not likely equivalent and are differentially influenced by several factors, such as climate, topography, land use, stream type and structure, slope, soil type, and drainage characteristics (Barton *et al.*, 1985; Forman, 1997).

Considering our incomplete knowledge of the structural-functional relationships of riparian corridors, characterizing riparian-stream networks is a challenging task. Efficient tools for generating and exploring conceptually based landscape metrics need to be developed. Traditional landscape metrics (e.g., patch diversity, contagion) are easily derived from GIS land-cover databases, but lack clear structural-functional relationships and are inadequate for characterizing the linear nature of riparian-stream networks. Characterizing the structural attributes of woody vegetation, such as its composition, width, longitudinal extent, and connectivity have been used in conducting assessments of aquatic habitat. For example, Petersen (1992) describes a Riparian, Channel, and Environmental (RCE) Inventory method for assessing the biological and physical condition of small streams in lowland, agricultural landscapes. Of the 16 characteristics included in Petersen's field method, the most important determinants of stream condition are (1) land-use composition beyond the immediate riparian zone, (2) width of woody riparian vegetation, (3) completeness of the riparian vegetation along the stream, and (4) composition of riparian vegetation within 10 m of the stream. The first characteristic is related to the potential effects of land-use stressors on stream ecological condition, while the latter three characteristics are related to riparian vegetation functions. Woody riparian vegetation attributes of composition, width, longitudinal extent, and connectivity not only influence local (i.e., stream reach) stream ecological condition, but also exert considerable influence on downstream portions of the overall stream network (Barton *et al.*, 1985; Malanson, 1993; Forman, 1997).

Spatial scale is a critical consideration when assessing stream ecological condition through the use of land-cover information (Forman and Godron, 1986; Roth *et al.*, 1996). The ability to detect empirical relationships between land-cover metrics and stream ecological condition is also confounded by the level of classification used to describe the landscape elements and the aggregation of the land-cover classes into conceptually relevant metrics. Previous watershed-scale stud-

P.J. Wigington, Jr., is with the U.S. Environmental Protection Agency, U.S. EPA, NHEERL-WED, 200 SW 35th St., Corvallis, OR 97333 (pjw@mail.cor.epa.gov).

The remaining authors are with Dynamac Corporation, 200 SW 35th St., Corvallis, OR 97333.

Photogrammetric Engineering & Remote Sensing,
Vol. 65, No. 10, October 1999, pp. 1157–1167.

0099-1112/99/6510–1157$3.00/0

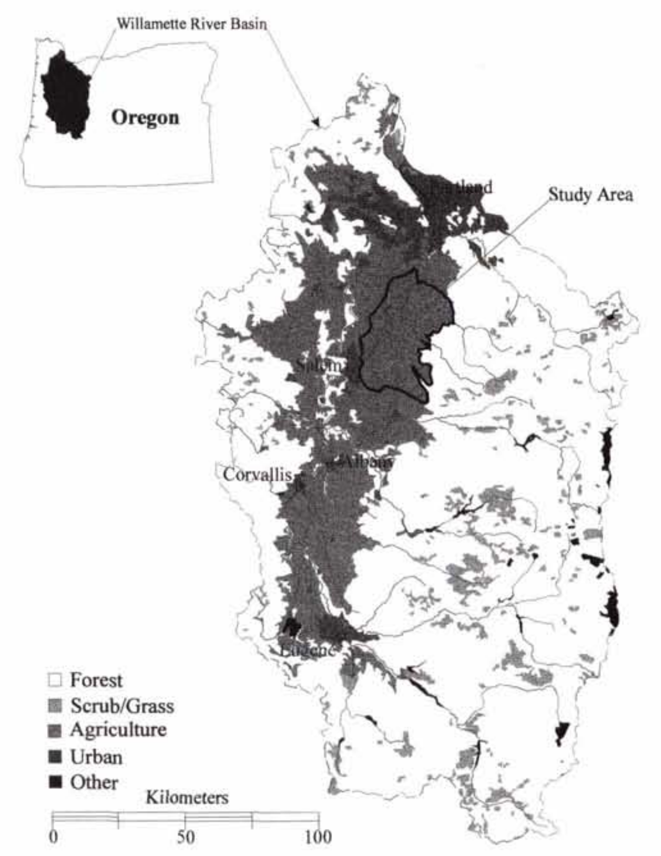


Figure 1. The Willamette River Basin and the location of the study area.

ies have used various metrics of riparian vegetation and other land-cover classes to demonstrate relationships with indices of stream ecological condition. In forest/urban watersheds of southern Ontario, Steedman (1988) reported that the index of biotic integrity (IBI) for streams was mostly a function of the proportion of the watershed in urban land use and the proportion of lower order streams with intact riparian forest vegetation. In another southern Ontario study, Barton *et al.* (1985) reported that the proportion of streambank forested within approximately 2.5 km of a site was most important in predicting maximum stream temperature and trout distribution. In an agricultural and urbanizing landscape of southern Michigan, Roth *et al.* (1996) reported that the proportion of the watershed in agricultural land use was the primary determinant of stream biotic integrity as assessed by IBI and habitat index scores. These researchers also reported that regressions of land use and riparian vegetation variables against IBI showed land uses at larger scales, whether the entire catchment upstream of a site or the entire riparian corridor upstream of a site, were more effective predictors of IBI scores than land use or riparian vegetation at local scales.

Little ecological research has been directed towards determining the status and ecological role of riparian systems in maintaining stream ecological condition in agricultural landscapes of Oregon's Willamette Valley (Van Deventer, 1990). Most riparian research in agricultural landscapes of the U.S. has occurred in the East or Midwest under conditions quite different from agricultural lands common in western Oregon and Washington. We don't know to what extent current riparian vegetation in the Willamette Valley affects the condition of aquatic habitat, or whether riparian functions are circumvented or overwhelmed by agricultural land uses and associated management practices. We also don't know what riparian vegetation composition or configurations (i.e., width, longitudinal extent, connectivity) along stream networks in agricultural landscapes of the Willamette Valley are most beneficial to stream ecological condition.

As part of the U.S. Environmental Protection Agency's Pacific Northwest Research Program (Baker *et al.*, 1995), a research project has been initiated to determine the effect of riparian areas on the ecological condition of small, perennial streams in agricultural landscapes of the Willamette Valley (Moser *et al.*, 1997). A focus of the research is the development of riparian metrics, based on medium-scale aerial photography and geographic information systems (GIS) technology, that are good indicators of stream ecological condition. In preparation for this research, a pilot study was conducted to develop sampling methods and assessment techniques for characterizing riparian-stream networks in agricultural landscapes across large areas. The scale of our desired land-cover mapping and the large extent of the Willamette Valley dictated that we consider a sampling strategy to characterize riparian-stream networks. We realized we could not comprehensively examine all of the riparian-stream network in the Willamette Valley, so we developed an approach for characterizing the structural attributes of riparian areas based on a thorough evaluation of smaller, randomly selected portions of the riparian-stream network. This paper presents the methods and landscape metrics developed in the pilot study and provides examples of their utility in characterizing the linear nature of riparian-stream networks.

Methods

Study Area

The pilot study was conducted in an approximately 1,000-km^2 area located in the north-central section of Oregon's Willamette River Basin (Figure 1). The boundary of the study area was selected to include a range of agricultural landscapes representative of those found in the Willamette Valley. The study area is dissected by about 850 km of low-gradient, meandering streams and provides a setting with a diverse land-cover mosaic of agriculture, forest, and residential patches. The study area contains some of the most agriculturally diverse lands in the Willamette Valley, including pastureland; several types of row, field, and orchard crops; as well as nurseries and dairies. Forested riparian patches range from being almost totally composed of conifers (*Pseudotsuga menziesii, Thuja plicata*) to pure hardwood forests comprised of *Populus trichocarpa, Acer macrophyllum, Fraxinus latifolia, Quercus garryana*, and others.

Determination of a Sample Area

Because a primary motivation for our research is developing methods and landscape metrics to assess stream ecological condition, the manner in which stream ecological condition is described becomes a determining factor in defining appropriate landscape metrics. We view stream ecological condition as a property that varies more or less continuously along the length of a stream. One may need to examine a substantial length of stream around a point in order to determine a value for a metric, but the resulting value becomes associated with the stream point. This perspective enables us to characterize a population of streams in terms of total length of streams meeting some criteria (e.g., kilometers of streams in the Willamette Valley with an IBI score indicating degraded condition) by characterizing a sample of stream points. The perspective that ecological condition is determined at a point in a stream (as opposed, say, to the ecological condition of a stream reach delimited by stream confluences) shapes the conceptualization of our landscape metrics.

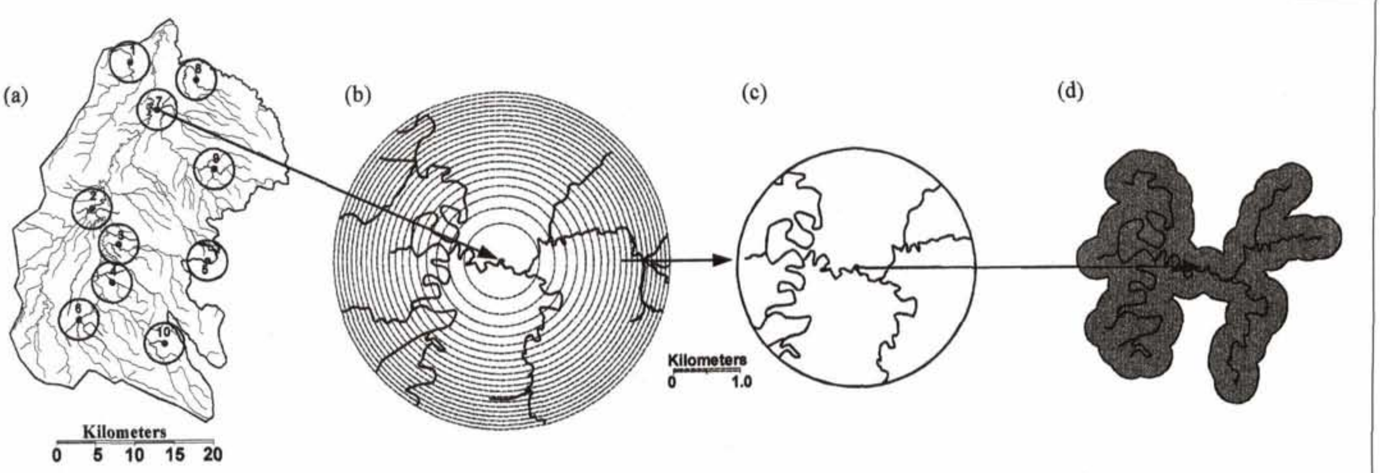


Figure 2. Location of the sample points within the study area and the method used to define an optimal sample area.

A landscape metric is invariably defined by the aggregation of a structural attribute over some bounded area. The size and shape of that bounded region can have substantial impact on the discernability of relationships between stream ecological condition and landscape metrics. The specification of the area and how it is related to the stream point necessarily becomes part of the definition of the metric. Thus, one of our first tasks was to determine a suitable area, which we called a sample area (SA), surrounding the stream point in which landscape metrics for characterizing riparian-stream networks could be defined. An appropriate SA would (1) adequately capture stream network structure, (2) be conceptually defensible in relation to the riparian functions being considered, (3) capture most of the riparian vegetation and an appropriate amount of the adjacent agricultural lands to allow for associative analyses, and (4) be cost efficient.

Ten sample points were selected on perennial or intermittent streams in the study area (Figure 2a). Six of the points were a subset of a larger set of stream-based, randomly selected points used in another study that fell within our study area. Four more points were chosen by inspection to fill out the range of stream sizes, to ensure that the points were evenly distributed geographically across the study area, and to cover a range of agricultural and riparian conditions that occur in the study area. Three sample points each were located on first- and second-order streams, two points were located on third-order streams, and one point each was located on fourth- and fifth-order streams (Strahler, 1957).

The delineation (i.e., size and shape) of the SA was determined in two steps. The first step consisted of defining a radius (Figure 2b) around the sample point suitable for capturing stream network structure. Thus, stream network structure was characterized using a fixed portion of the stream network, rather than a whole catchment. The second step consisted of defining a distance perpendicular to the stream network suitable for capturing attributes of riparian vegetation and adjacent agricultural lands associated with the stream network.

In Step 1, each sample point was bounded by 20 concentric circles increasing in area increments of 1 km^2 (Figure 2b). All perennial and intermittent streams within a radius of 2.52 km (a circle with an area of 20 km^2) of the sample point were delineated and digitized from color aerial photographs (scale 1:24,000) that were flown in late May and early June of 1993. GIS programs were used to delimit the stream network for each of the 20 concentric circles, resulting in 20 alternative stream networks, of increasing lengths, centered on the stream sample point. We defined the connected stream network as all streams not clipped or broken by the circles and connected either directly or through another stream stretch to the sample point. Several stream network metrics such as stream density (the total length of streams per unit area), stream frequency (the total number of streams per unit area), and density of stream confluences (the number of nodes per unit area) were calculated for each of the 20 alternative stream networks. Based on a visual examination of the cumulative distribution frequencies of the plotted means and standard deviations of these stream network metrics (Figure 3), a circle with an area of 10 km^2, centered on the stream-based sampling point, appeared to be of sufficient size to capture stream network structure (Figure 2c).

In Step 2, we examined the aerial photographs and 1992 thematic mapper imagery to determine the width of riparian area that needed to be studied. We found that most of the woody riparian vegetation, as well as a diversity of agricultural lands, were captured within 300 m of streams in agricultural landscapes of the Willamette Valley floor and foothills. Based on these examinations, an SA was defined as the area within a 300-m band around all connected perennial and intermittent streams lying within a 10-km^2 circle centered on the stream sampling point (Figure 2d).

The SAs ranged in area from about 204 ha to 770 ha. The SA area is largely a function of the total length of streams within the 10-km^2 circle. However, this relationship is confounded by the number of stream confluences and the degree of stream sinuosity, where the banding process tends to result in smaller areas for stream networks that are highly sinuous and dendritic because of overlap between bands. The SA configuration was also confounded by conceptual and operational issues regarding an edge effect. An edge effect occurred where streams intersected the 10-km^2 circular boundary or were within 300 m of the 10-km^2 circular boundary. A decision to maintain the integrity of the 300-m SA made it necessary to extend the SA beyond the 10-km^2 circular boundary when streams were less than 300 m from the boundary.

Land-Cover Classification

Land cover within the SAs was interpreted from the 1993 color aerial photographs. The photos covering the SAs were scanned, spliced together, and georeferenced to provide a seamless digital image with a pixel resolution of about 2 m. Because there is little terrain relief in our study area, this approach was an alternative to the more costly analytical approach based on photogrammetry for creating digital ortho-

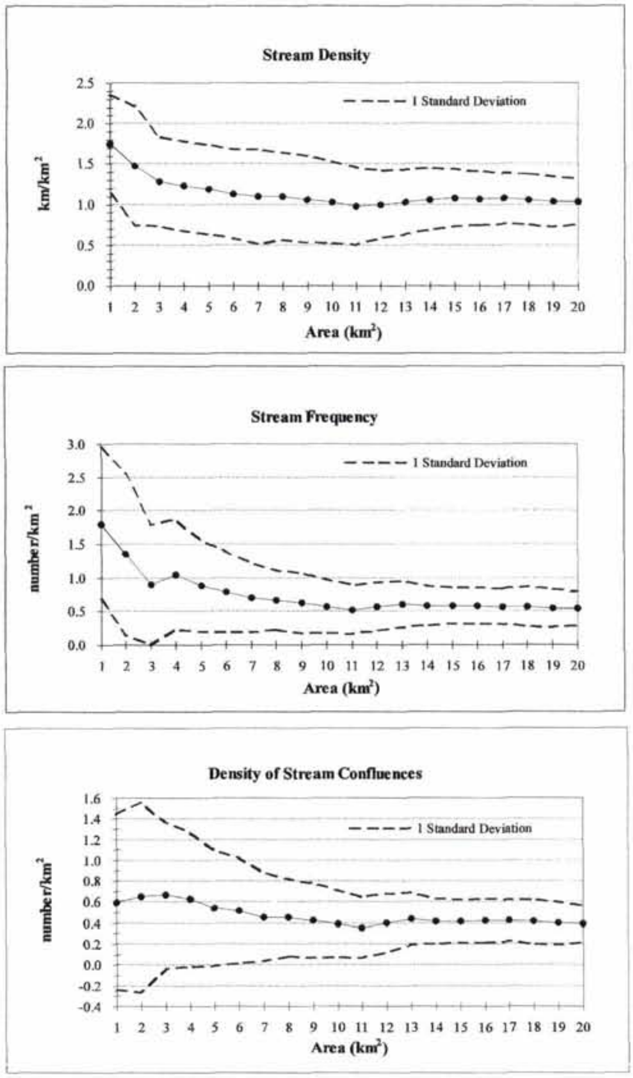


Figure 3. Stream network metrics used to determine an optimal sample area.

photographs. However, distortion is introduced through this process. For example, warping does not account for terrain distortion, as does an analytical approach based on a photogrammetric model of the viewing geometry (Lillesand and Kiefer, 1987). To estimate this distortion, we selected eight to ten evenly distributed points from each of five of our photo mosaics. We located each of these points on the ground and recorded global positioning system (GPS) coordinates. The coordinates were differentially corrected to improve their accuracy. We made triangles by connecting the points collected with GPS and the corresponding points located on the photo mosaics. The triangles were arranged so that they crossed the photo mosaics in several directions. On average, the areas of the triangles differed by 1.75 percent. The standard deviation was 1.71 percent, with a maximum difference of 9.34 percent. The difference in the length of the perimeters of the triangles was on average 0.83 percent. The standard deviation was 0.86 percent, with a maximum difference of 3.31 percent.

The scanning, splicing, and georeferencing of the aerial photos was done in preparation for on-screen digitizing of land cover, transportation, and streams. On-screen digitizing proved to be an effective tool to collect thematic information from the aerial photos. The photo mosaics were used as a backdrop, allowing the delineation of features of interest directly on the computer screen. The images were magnified several times so that very small and narrow features could be delineated. Aerial photo prints were also used to identify polygon boundaries between land-cover types. The ability to digitize on-screen and to interpret features in stereo from the original aerial photo prints provided a powerful tool for the interpretation and digitizing of features. The method combined the cognitive, pattern recognition abilities of the interpreter, with the automated computer tools provided by a GIS program.

Land cover was classified according to a modified Anderson *et al.* (1976) classification system (Table 1). The modified classification system reflects the land-cover and land-use classes that we could consistently interpret with reasonable confidence. For example, because we could not reliably distinguish grassed pasture from natural areas covered by grass/forb, grassed pastureland was included in the grass/forb class. Because it was not possible to distinguish a riparian zone (and, consequently, riparian vegetation) using aerial photographs, we adopted an operational definition of riparian vegetation (referred to as adjacent woody vegetation) which includes non-cultivated, woody vegetation which is juxtaposed to a perennial or intermittent stream at some point within the sample area. Adhering to this definition, adjacent woody vegetation may include one or more of the nine forest classes, plus shrub/scrub (Table 1). Although we could have presented metrics for each of the individual forest classes and shrub/scrub, we used the adjacent woody vegetation aggregation for ease of display in our figures.

Because of the difference in time between the date when our interpretation was completed (September 1996) and the date the aerial photography was flown (May-June, 1993) and the dynamic nature of agriculture in the study area, we concluded that we could not assess the accuracy of our interpretation except at the highest level in the classification hierarchy (Table 1). We used a stratified random sampling procedure to assess classification accuracy of our land cover interpretation for the ten SAs. We drew a random sample of 30 polygons per class (forest, shrub/scrub, grass/forb, agriculture, urban/built-up, and water) from the population of polygons within the ten SAs to be verified in the field. We did not select any samples from barren or other classes because there were very few polygons classified in these classes. We were unable to visit every selected polygon due to inaccessibility because of private land ownership. For example, for the shrub/scrub class we were only able to visit 16 of the 30 randomly selected polygons. The overall classification accuracy was 94 percent. The user's accuracy for individual classes was forest 100 percent, shrub/scrub 81 percent, grass/forb 89 percent, agriculture 97 percent, urban/built-up 93 percent, and water 100 percent.

Calculation of Landscape Metrics

In this study, we focused on developing a small set of landscape metrics that are linked to the ecological condition of streams and seem to be common to riparian zone functions and riparian vegetation attributes. These include land-cover composition as a function of distance from the stream network and the width, longitudinal extent, and connectivity of adjacent woody vegetation along the stream network.

Incremental banding was used to characterize the spatial distribution of land-cover composition and pattern as a function of distance from the stream network. GIS functions and programs were used to band the stream network for each SA in 10-m increments to a distance of 300 m (Figure 4). The bands were used to define the land cover within the band distance on both sides of the stream network. New data lay-

TABLE 1. LAND-COVER CLASSIFICATION SYSTEM.

- I. *Forest*
  - 1. Coniferous Forest
    - a. Coniferous Forest (closed canopy) = 70% to 100% areal canopy cover
    - b. Coniferous Forest (partially closed canopy) = 40% to 69% areal canopy cover
    - c. Coniferous Forest (open canopy) = 10% to 39% areal canopy cover
  - 2. Deciduous Forest
    - a. Deciduous Forest (closed canopy) = 70% to 100% areal canopy cover
    - b. Deciduous Forest (partially closed canopy) = 40% to 69% areal canopy cover
    - c. Deciduous Forest (open canopy) = 10% to 39% areal canopy cover
  - 3. Mixed Forest
    - a. Mixed Forest (closed canopy) = 70% to 100% areal canopy cover
    - b. Mixed Forest (partially closed canopy) = 40% to 69% areal canopy cover
    - c. Mixed Forest (open canopy) = 10% to 39% areal canopy cover
  - 4. Clear Cut
  - 5. Tree Farm

- II. Shrub/Scrub = land dominated by woody shrubs (greater than 50% shrub/scrub cover), with less than 10% areal tree canopy cover

- III. Grass/Forb (includes grassed pastureland) = land dominated by grass and forbs (greater than 50% grass/forb cover), with less than 10% areal tree canopy cover

- IV. Agriculture
  - 1. Cropland
    - a. Field Crops (e.g., grass and legumes grown for seed, small grains)
    - b. Row Crops (e.g., vegetables, low growing berry crops)
    - c. Orchards (e.g., tree fruit and nuts, hops, vineyards)
  - 2. Christmas Tree Farms
  - 3. Confined Animal Feeding Operations (e.g., dairy operations, poultry farms)
  - 4. Nurseries
    - a. Tree and Shrub Dominated Nurseries
    - b. Greenhouse Dominated Nurseries
  - 5. Farmsteads
  - 6. Other Agricultural Land (e.g., farm wasteland)

- V. Urban/Built-up
  - 1. Residential
  - 2. Roads, Freeways, and Railroads
  - 3. Industrial and Commercial
  - 4. Other (e.g., cemeteries, golf course, parks)

- VI. Barren Land (land of limited ability to support vegetation)

- VII. Water

- VIII. Other

ers consisting of land cover within each band distance were created using GIS clipping functions. Composition metrics, such as proportional area as a function of distance from the stream network, were easily calculated from the banded land-cover data. As shown in Figure 4, we calculated proportional land-cover areas in two ways: (1) a cumulative distribution of the area of a class was calculated by dividing the class area within a band by the total class area within the entire SA, and (2) the proportion of each class area within each incremental band was calculated by dividing the area of the class by the area within each incremental band.

Two methods were used to estimate the mean width of adjacent woody vegetation. In the first method, we averaged width measurements (about 20/km of stream) of adjacent woody vegetation from lines drawn perpendicular to the stream to a designated band distance (Figure 5). Perpendicular lines were extended on both sides of the stream when the stream was delineated with a single line. When the stream was delineated with two lines (i.e., when streams were greater then 10-m wide or when the stream entered a pond, lake, or impoundment), perpendicular lines were extended from adjacent stream banks. In the second method, the proportional area of adjacent woody vegetation within the designated band was multiplied by the band width to estimate the mean width of adjacent woody vegetation.

Three metrics were used to estimate the completeness of adjacent woody vegetation along the stream network banks, namely, longitudinal extent, number of gaps, and mean gap length. Longitudinal extent of adjacent woody vegetation along the stream network was easily calculated by dividing the total length of streambank occupied by adjacent woody vegetation by the total length of the stream network's streambank. We defined a gap as land-cover patches not included in our operational definition of adjacent woody vegetation that were directly adjacent to the streambanks and that were at least 5 m in length. The number of gaps/km of streambank between adjacent woody vegetation patches was calculated by dividing the number of non-adjacent woody vegetation patches immediately adjacent to the streambanks by the streambank length. The mean length of gaps between adjacent woody vegetation patches along the streambanks was calculated by averaging the lengths of all non-adjacent woody vegetation patches immediately adjacent to the streambanks.

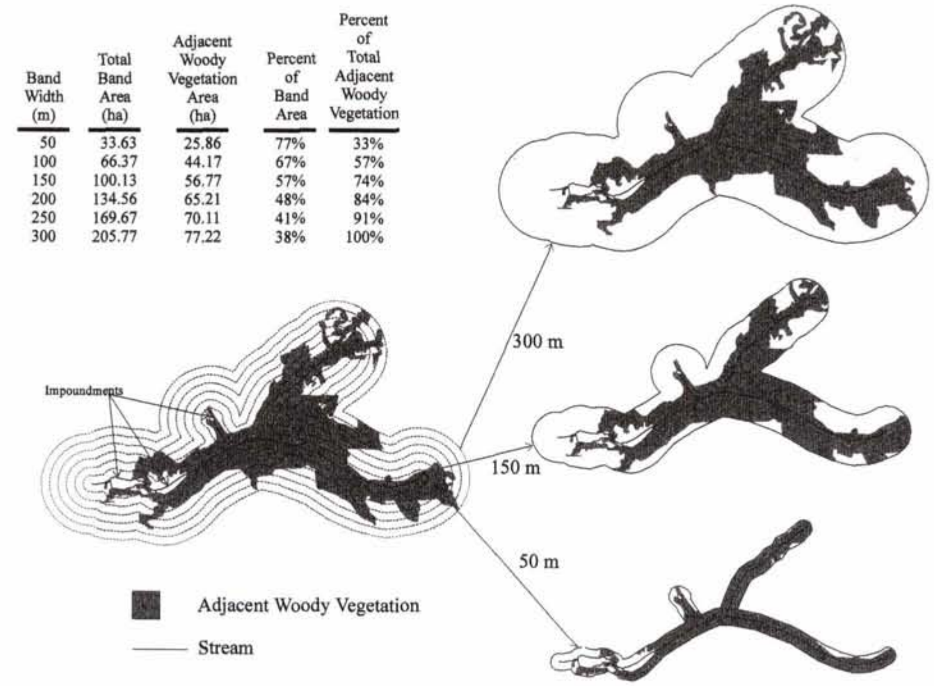
The land-cover data generated from the sampling bands can be used to describe not only the areal distribution of land cover as a function of distance from the stream network, but also as a method for estimating the dispersion of adjacent woody vegetation edge as a function of distance from the stream network. As shown in Figure 6, we calculated what we term "edge dispersion" by dividing the length of the band boundary occupied by adjacent woody vegetation by the total length of the band boundary.

Results and Discussion

Sample Area

The determination of a sample area is an important issue in the development of sampling approaches. As described by Gregory *et al.* (1991) and Stanford and Ward (1992), riparian-stream networks are multi-dimensional ecosystems dependent upon longitudinal, lateral, vertical, and temporal connectivity along a continuum. In our study, we attempted to define a sample area by characterizing the longitudinal and lateral dimensions of the riparian-stream network. The longitudinal dimension of the stream network was characterized by using various metrics such as stream density, stream frequency, and density of stream confluences. These metrics exhibited a consistent pattern, such that the means and standard deviations ($n = 10$) tended to stabilize for the alternative stream network circumscribed by a 10-km^2 circle centered on the stream sample point (Figure 3). Although not shown, the means and standard deviations for other stream network metrics, such as sinuosity (stream length divided by valley length) and bifurcation ratios (the ratio of the number of stream segments of a given Strahler stream order to the number of stream segments of the next higher Strahler stream order), remained constant over the range of 20 alternative stream networks.

The lateral dimension of the riparian-stream network was addressed by characterizing the proportional area of adjacent woody vegetation as a function of distance from the stream network. Because of the potential effects of agricul-



Band Width (m)	Total Band Area (ha)	Adjacent Woody Vegetation Area (ha)	Percent of Band Area	Percent of Total Adjacent Woody Vegetation
50	33.63	25.86	77%	33%
100	66.37	44.17	67%	57%
150	100.13	56.77	57%	74%
200	134.56	65.21	48%	84%
250	169.67	70.11	41%	91%
300	205.77	77.22	38%	100%

Figure 4. Example of the characterization of adjacent woody vegetation land cover using incremental banding.

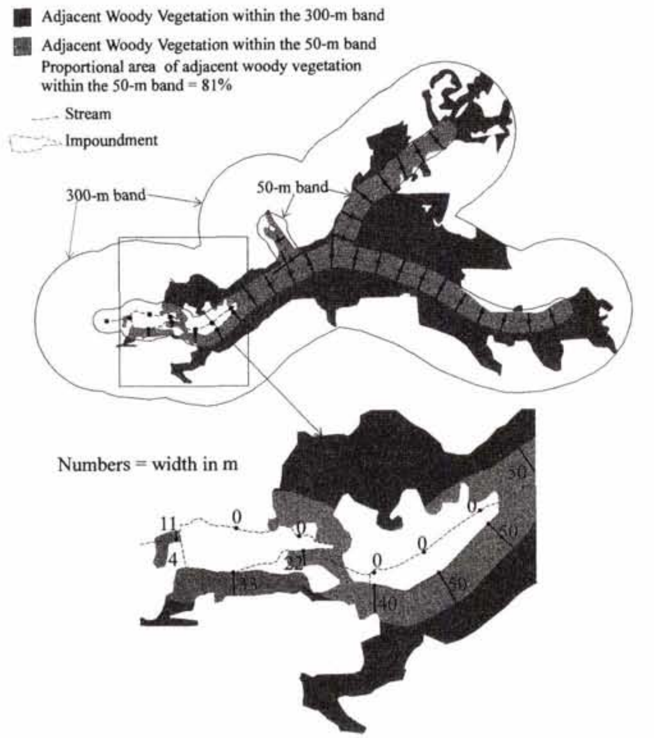
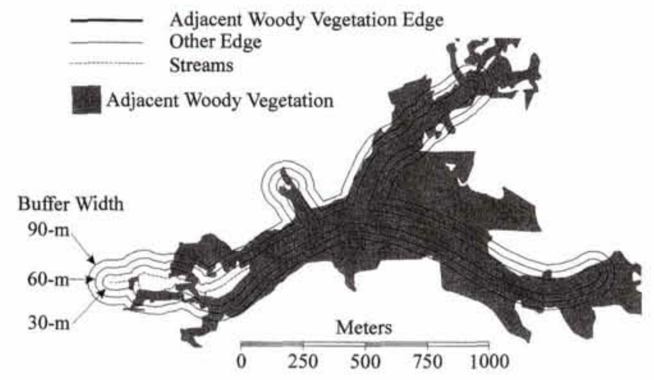


Figure 5. Example of the characterization of adjacent woody vegetation width within the 50-m band using perpendicular lines drawn along the stream network.



Band Width	Total Band Length (m)	Length Occupied by Adjacent Woody Vegetation (m)	Percent of Band Length Occupied by Adjacent Woody Vegetation
30	7173	4941	69%
60	6497	4013	62%
90	6615	3310	50%

Figure 6. Example of the characterization of adjacent woody vegetation edge dispersion.

tural land use on stream ecological condition, we were also interested in determining the proximity of agriculture to the stream network. Most (if not all) of the woody riparian vegetation, as well as the diversity of agricultural lands, were captured within 300 m of streams in agricultural landscapes of the Willamette River Basin. Therefore, our empirically derived SA, encompassing a 300-m band around perennial and intermittent streams within a 10-km² circular area, adequately represented stream network structure and land cover for making inferences about riparian-stream networks in agricultural landscapes of the Willamette River Basin. However, a more detailed analysis of lateral land cover demonstrates that we probably could use a much smaller band distance than 300 m to delineate our SA. For example, the plots in Figure 7 show the cumulative mean and standard deviation of the proportions of adjacent woody vegetation and agriculture as a function of distance from the stream network for the ten SAs. These plots reflect the linear nature of the adjacent woody vegetation patches along stream networks in agricultural landscapes of the north-central Willamette River Basin, where adjacent woody vegetation is the predominant land cover near the stream network, but diminishes rapidly with increasing distance from the stream network. On average, approximately 80 percent of the adjacent woody vegetation and 40 percent of the agriculture within the maximum band distance (i.e., 300 m) occurs within 150 m from the stream network (Figure 7a). Approximately 85 percent of the land cover within 10 m of the stream is adjacent woody vegetation, but decreases to about 40 percent within 100 m of the stream network (Figure 7b). Mean agricultural area surpasses mean adjacent woody vegetation area at approximately 160 m from the stream network (Figure 7b). Decreasing the size of the SA is significant because interpretation time can be reduced considerably. This time savings would result in reduced costs or allow for more samples to be done over the same geographic area.

An initial focus of the pilot study was to develop sampling techniques which could be applied to large regions (e.g., Willamette Valley). Hence, we developed an approach for calculating landscape metrics to assess stream ecological condition using portions of the stream network. Metrics that rely on exhaustive coverage become increasingly difficult to apply as the extent of the target region increases. Metrics that lend themselves to a sampling approach instead of a census (e.g., describing the ecological condition of streams in the Willamette Valley, not by visiting every meter of stream in the Valley, but by inferring population characteristics from a random sample) are more easily applied to large regions. Using ecological stream condition metrics (e.g., IBI) derived from a point on a stream and demonstrating relationships with conceptually based landscape metrics is consistent with large regional applications, because it is relatively easy to use a GIS to select a random sample of points on a stream network within a region. However, landscape metrics are influenced by the spatial configuration and arrangement of the SAs in relation to the point where stream condition is determined. Because of the importance of connectivity in riparian-stream networks, deriving landscape metrics from a sample area defined as the stream network upstream from the sampling point may provide more relevant indicators linked to riparian functions that affect stream ecological condition, than would our approach of sampling portions of the stream network, above and below a sample point.

Landscape Metrics

Banding stream networks in 10-m increments provided a framework for developing landscape metrics for estimating the composition and pattern of land cover along the stream network. Incremental banding of the stream network is an effective tool for characterizing the differences in landscape composition among the SAs, as well as the patterns of change in land cover with increasing distance from the stream network. For example, Plate 1 compares the areal distributions of four land-cover classes for two SAs. There are clear distinctions that can be seen between these two SAs, particularly in the spatial patterns of adjacent woody vegetation and agriculture as a function of distance from the stream network. First, the rate of decline in adjacent woody vegetation with increased distance from the stream is approximately 15 percent greater for SA 2 than SA 1 within the first 100 m of the stream network. Second, the spatial pattern of agriculture is markedly different, with SA 2 having a greater proportion of agricultural land use in close proximity to the stream network than SA 1. As illustrated in Plate 1, agriculture becomes the dominant land cover at about 90 m from the stream network for SA 2 while, for SA 1, agriculture does not become dominant until about 250 m from the stream network. Because studies have shown that land-cover composition is a major determinant of stream ecological condition (Roth *et al.*, 1996; Steedman, 1988; Petersen, 1992; Barton *et al.*, 1985), the ability to effectively characterize spatial patterns of adjacent woody vegetation and agricultural land cover as a function of distance from the stream network may prove useful for assessing stream ecological condition.

Because agricultural management practices (e.g., fertilizer and pesticide inputs, irrigation, tillage) are not equal for all agricultural systems, there tends to be a continuum of management intensity that ranges from high to low levels of human inputs (Krummel and Dyer, 1984). Lowrance and Vellidis (1995) and Spence *et al.* (1996) discuss several mechanisms by which agricultural land-use practices directly or indirectly affect the ecological condition of streams. Because high intensity agricultural cropping areas are likely greater potential sources of stress to stream systems than low intensity agricultural cropping areas, more detailed land-use clas-

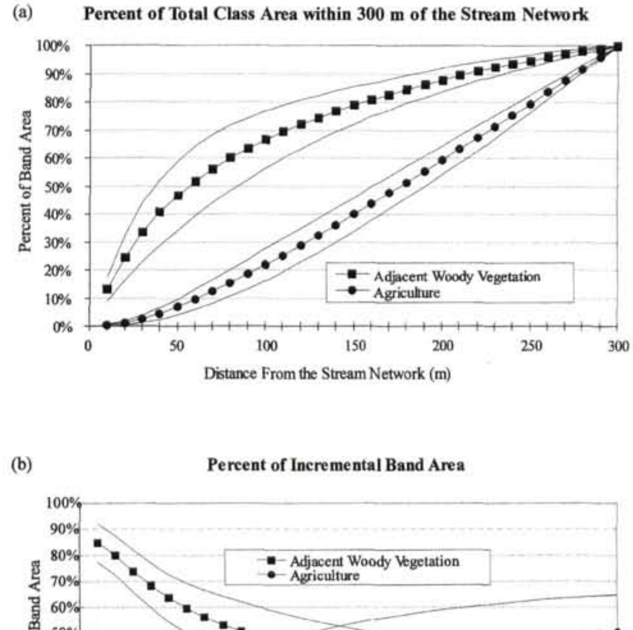


Figure 7. Cumulative mean and standard deviation ($n = 10$) of the proportions of adjacent woody vegetation and agriculture as a function of distance from the stream network.

sifications may prove useful in assessing stream ecological condition. Steedman (1988) proposed that his predictive models for rural streams in southern Ontario would likely have been improved if greater detail were obtained on agricultural land use and streamside vegetation. Although there are other factors (e.g., slope, soil type, precipitation intensity and duration, spatial configurations among agriculture, adjacent woody vegetation, and stream network) that influence the volume of sediment and agricultural chemicals reaching the stream network, ratios of the area in agricultural land-use types to the area in riparian vegetation as a function of distance from the stream network are potentially important explanatory variables for assessing stream ecological condition. For example, Table 2 shows that the ratio of the area of high intensity row cropping systems (i.e., irrigated, annual tillage, moderate to high levels of nutrient and pesticide inputs) to the area of adjacent woody vegetation is substantially greater in SA 2 than SA 1 along the entire 300-m lateral distance from the stream network, possibly an indication that this stream network is at greater risk from agriculture than is SA 1. In addition, because row cropping systems in the Willamette Valley are dependent upon summer irrigation, the greater area of row cropping systems in close proximity to the stream network in SA 2 is an indication of large withdrawals of water from streams. Irrigation withdrawals from small streams can adversely affect fish and macroinvertebrates by reducing summer water levels and flows, increasing water temperature and turbidity, and decreasing dissolved oxygen concentrations in streams (Spence *et al.*, 1996).

Table 2. Ratios of the Area of Selected Agricultural Classes to the Area of Adjacent Woody Vegetation as a Function of Distance from the Stream Network for Two SAs.

Distance from the Stream Network (m)	SA 1			SA 2		
	Row Crops	Field Crops	Orchard Crops	Row Crops	Field Crops	Orchard Crops
30	0.01	0.01	0.00	0.11	0.12	0.02
60	0.02	0.05	0.01	0.29	0.29	0.06
90	0.03	0.10	0.03	0.46	0.42	0.08
120	0.04	0.15	0.06	0.62	0.54	0.09
150	0.05	0.22	0.09	0.78	0.66	0.11
180	0.06	0.29	0.11	0.94	0.76	0.11
210	0.08	0.35	0.12	1.07	0.87	0.13
240	0.10	0.42	0.13	1.17	0.95	0.14
270	0.11	0.48	0.15	1.26	1.03	0.14
300	0.13	0.53	0.17	1.34	1.11	0.15

The contribution of riparian vegetation to stream ecological condition diminishes with distance from the stream (Beschta *et al.*, 1987; McDade *et al.*, 1990; Van Sickle and Gregory, 1990; Castelle *et al.*, 1994). The width of riparian vegetation, particularly woody vegetation, along stream networks is a key attribute for assessing riparian function (Forman, 1997). Width has been shown to be an important determinant of all the functions provided by riparian vegetation. In a largely agricultural basin of the Midwest, Roth *et al.* (1996) found that using a 30- or 50-m buffer to characterize woody and herbaceous vegetation land cover along 1,500-m stream reaches allowed maximal discrimination among their study sites.

We used the 50-m band distance to compare two methods (i.e., perpendicular line and proportional area) of estimating mean width because most SAs had high adjacent woody vegetation coverage near the stream network (less then 30 m) and low adjacent woody vegetation coverage at distances greater then 100 m from the stream network. The proportional area method is an attractive alternative for measuring mean width because it can be quickly calculated using existing GIS data for any band increment and the average difference in width estimates between the two methods was only 4.3 percent (Figure 8). The disadvantage of this method is that the variability of adjacent woody vegetation width over the stream network cannot be calculated, as it can in the perpendicular line method (Figure 8). The disadvantage of the perpendicular line method is that it is more labor intensive and can be more subjective, because width can be measured in more than one way in areas along the stream network where they are sinuous or where there are confluences.

Landscape metrics addressing the completeness (i.e., longitudinal extent and connectivity) of streamside vegetation along the entire length of the stream network are relevant to aquatic habitat functions provided by riparian vegetation. The percent of stream network banks occupied by woody vegetation captures two of the most important determinants used in the RCE Inventory of stream condition (Petersen, 1992), namely, the composition and completeness of riparian vegetation within 10 m of the stream. The occurrence of gaps in streamside vegetation determines the connectivity of the riparian corridor. Table 3 lists the longitudinal extent and

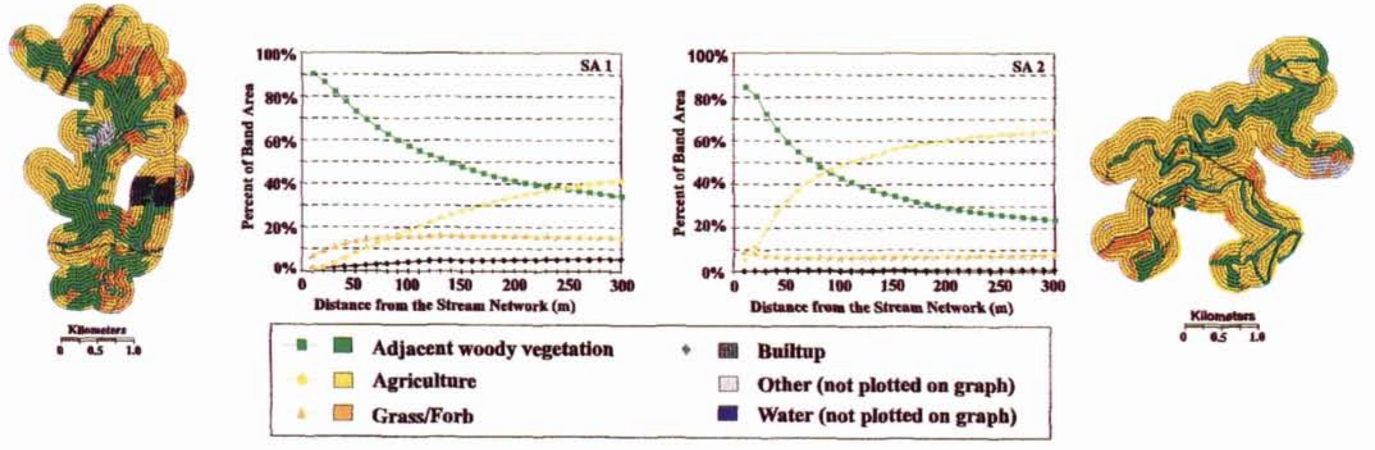


Plate 1. Comparison of the distribution of SA land cover as a function of distance from the stream network using incremental banding.

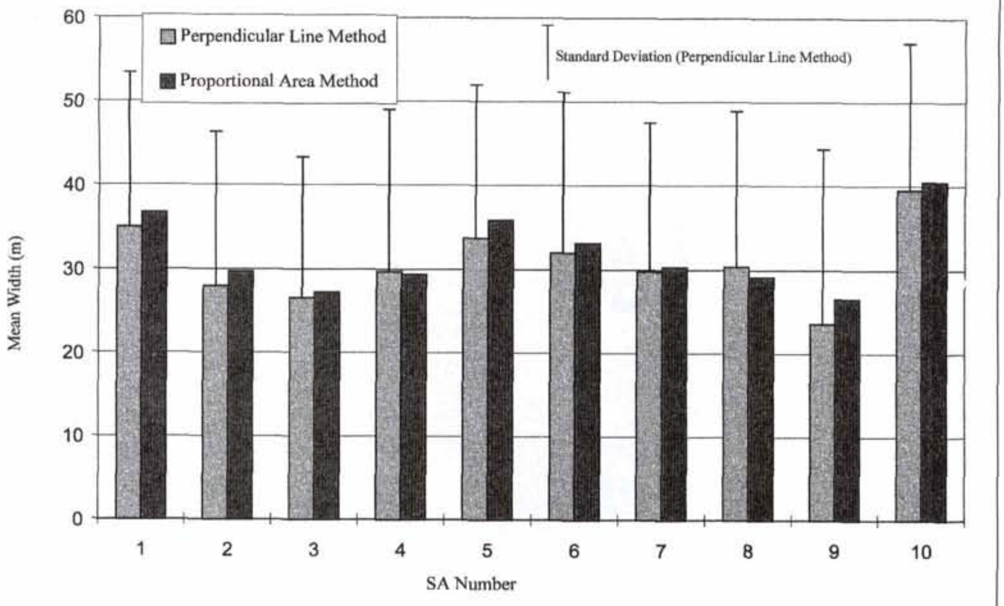


Figure 8. Comparison of the perpendicular line and proportional area methods for estimating the width of adjacent woody vegetation along the stream network.

connectivity of adjacent woody vegetation (includes our nine forest classes and shrub/scrub class) for our ten SAs. In summary, the longitudinal extent, number of gaps, mean gap length, and maximum gap length for the ten SAs ranges from 72 to 92 percent, 0.9 to 3.4 gaps/km of stream network banks, 44 to 143 m, and 186 to 808 m, respectively. Although connectivity is considered a key attribute in assessing riparian functioning (Barton *et al.*, 1985; Petersen, 1992; Forman, 1997), the definition of what constitutes a gap is not straightforward and remains an important research question. The level of classification used and how the vegetation classes are aggregated for summary purposes should be fundamentally related to the riparian function(s) under consideration. For example, although a number of short gaps in adjacent woody vegetation may have little effect on stream temperature, they may be significant conduits for the transport of upland nutrients, sediment, and pollutants directly to the stream (Forman, 1997). On the other hand, gaps in forested vegetation approaching one km have been demonstrated to have significant effects on stream temperature and trout distribution (Barton *et al.*, 1985). By retaining our minimum gap length (i.e., 5 m) and calculating gaps between closed canopy forest patches (includes our closed canopy coniferous, deciduous, and mixed forest classes), the results listed in Table 3 would have changed dramatically. For example, with this lower level of aggregation (i.e.,. closed canopy forest), the longitudinal extent, number of gaps, mean gap length, and maximum gap length for the ten SAs ranges from 41 to 76 percent, 1.2 to 3.7 gaps/km of stream network banks, 88 to 376 m, and 269 to 2,297 m, respectively. Although the overall direction from this type of aggregation is expected, this example illustrates the magnitude of the changes and potential implications that aggregation can have on assessing stream ecological condition. Finally, because connectivity and width of riparian vegetation are related, both attributes should be considered simultaneously for an ecologically based definition of a gap. The incremental banding approach shows promise for addressing both dimensions simultaneously, because a mean gap length can be calculated from the stream network outward by averaging the non-woody adjacent lengths along the 10-m incremental bands.

The 10-m incremental banding approach appears to have potential beyond its use in delineating an appropriate distance from the stream network to be sampled. Incremental banding provides an efficient method for estimating the areal distribution of land cover as a function of distance from the

TABLE 3. COMPLETENESS (I.E., LONGITUDINAL EXTENT AND CONNECTIVITY) OF ADJACENT WOODY VEGETATION FOR THE TEN SAS.

SA No	Total length of Stream Network Banks (km)	Longitudinal Extent (% of total stream network banks occupied)	Number of Gaps (number/km of stream network banks)	Mean (std. dev.) Gap Length (m)	Maximum Gap Length (m)
1	26.994	92.2	1.8	43.7 (46.2)	212
2	28.158	87.2	0.9	143.0 (230.4)	808
3	11.512	89.4	1.4	76.2 (69.0)	186
4	17.504	77.6	2.3	95.8 (129.6)	455
5	16.268	91.9	1.5	55.2 (63.3)	225
6	22.410	87.4	1.7	73.9 (98.6)	435
7	39.512	89.2	1.4	77.0 (102.8)	665
8	10.212	84.5	2.4	65.6 (103.7)	404
9	28.090	71.5	3.4	83.1 (124.7)	522
10	6.390	87.6	1.4	88.1 (67.5)	254

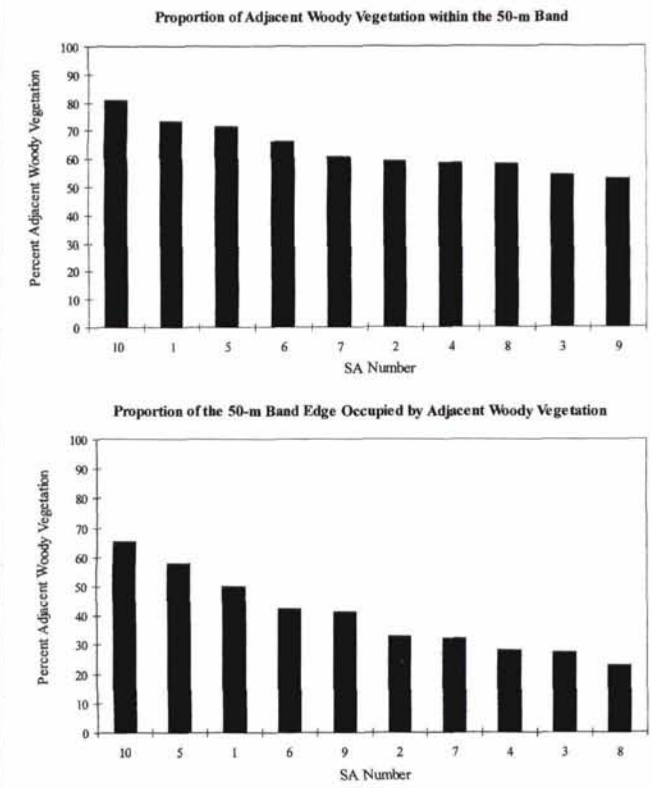


Figure 9. Proportional area and edge dispersion of adjacent woody vegetation at the 50-m band for the ten SAs.

stream network, as well as a method for estimating the dispersion of the edge of adjacent woody vegetation along the stream network. Because of gaps in adjacent woody vegetation, edge dispersion is not a surrogate for width. However, this landscape metric offers an advantage over the other metrics presented because it combines the elements of lateral and longitudinal dimensions of adjacent woody vegetation along the stream network. As shown in Figure 9, the relative ranking of the ten SAs is not the same when comparing the proportional area and edge dispersion of adjacent woody vegetation within the 50-m band. Differences in edge dispersion among the ten SAs are greater and may prove useful in future research seeking to quantify relationships between landscape metrics and indicators of stream ecological condition. Combining metrics such as proportional area and edge dispersion to form indices of stream ecological condition may provide even more discrimination among the SAs.

Detailed land cover digitized as GIS coverages provides considerable flexibility for the calculation of landscape metrics to characterize various structural attributes of riparian corridors important to stream ecological condition. A particularly useful feature of the methods developed in this study is the ability to generate landscape metrics at any level in a classification hierarchy and at multiple lateral and/or longitudinal spatial scales along a stream network. Relationships between conceptually based structural attributes of riparian corridors and stream ecological condition are not well established. We believe that the incremental banding approach of characterizing riparian-stream networks provides maximum flexibility for partitioning land cover to explore and test empirical relationships among functionally important structural attributes of riparian corridors, adjacent land-use composition and pattern, and indicators of stream ecological condition that are derived from field sampling data, such as fish and macroinvertebrate assemblages, in-stream physical habitat, and water chemistry.

Acknowledgments

The authors thank Lynda Corkum and Denis White for critical reviews of the manuscript, Scott Leibowitz and Phil Larsen for helpful suggestions during the planning and analytical phases of the pilot study, Frances Beck for technical editing of the manuscript, and Francie Faure for GIS support. The research described in this document has been funded by the U.S. Environmental Protection Agency, Western Ecology Division in Corvallis, Oregon through Contract 68-C6-0005 to Dynamac Corporation. It has been subjected to the Agency's peer and administrative review and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

References

Anderson, J.R., E.E. Hardy, J.T. Roach, and R.E. Witmer, 1976. *A Land Use and Land Cover Classification System for Use with Remote Sensor Data*, Geological Survey Professional Paper 964, U.S. Government Printing Office for the U.S. Department of the Interior, Geological Survey, Washington, D.C., 28 p.

Baker, J.P., D.H. Landers, H.L. Lee II, P.L. Ringold, R.R. Sumner, P.J. Wigington, Jr., R.S. Bennett, E.M. Preston, W.E. Frick, A.C. Sigleo, D.T. Specht, and D.R. Young, 1995. *Ecosystem Management Research in the Pacific Northwest: Five-Year Research Strategy*. EPA/600/R-95/069, U.S. Environmental Protection Agency, Washington, D.C., 251 p.

Barton, D.R., W.D. Taylor, and R.M. Biette, 1985. Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams, *N. Am. J. Fish. Manage.*, 5:364–378.

Beschta, R.L., R.E. Bilby, G.W. Brown, L.B. Holtby, and T.D. Hofstra, 1987. Stream temperature and aquatic habitat: Fisheries and forestry interactions, *Streamside Management: Forestry and Fishery Interactions* (E.O. Salo and T.W. Cundy, editors), College of Forest Resources, University of Washington, Seattle, Washington, pp. 191–232.

Brinson, M.M., B.L. Swift, R.C. Plantico, and J.S. Barclay, 1981. *Riparian Ecosystems: Their Ecology and Status*, FWS/OBS-81/17, U.S. Department of the Interior, Fish and Wildlife Service, Kearneysville, West Virginia, 155 p.

Castelle, A.J., A.W. Johnson, and C. Conolly, 1994. Wetland and stream buffer size requirements: A review, *J. Environ. Qual.*, 23: 878–882.

Cooper, J.R., J.W. Gilliam, R.B. Daniels, and W.P. Robarge, 1987. Riparian areas as filters for agricultural sediment, *Soil Science Society of America Journal*, 51:416–420.

Forman, R.T., 1997. *Land Mosaics: The Ecology of Landscapes and Regions*, Cambridge University Press, Cambridge, United Kingdom, 632 p.

Forman, R.T., and M. Godron, 1986. *Landscape Ecology*, John Wiley and Sons, New York, N.Y., 619 p.

Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Cummins, 1991. An ecosystem perspective of riparian zones, *BioScience*, 41:540–551.

Krummel, J.R., and M.I. Dyer, 1984. Consumers in agroecosystems: A landscape perspective, *Agricultural Ecosystems: Unifying Concepts* (R. Lowrance, B.R. Stinner, and G.J. House, editors), John Wiley & Sons, New York, N.Y., pp. 55–72.

Lillesand, T.M., and R.W. Kiefer, 1987. *Remote Sensing and Image Interpretation, Second Edition*, John Wiley and Sons, New York, N.Y., 721 p.

Lowrance, R., and G. Vellidis, 1995. A conceptual model for assessing ecological risk to water quality function of bottomland hardwood forests, *Environ. Manage.*, 19:239–258.

Malanson, G.P., 1993. *Riparian Landscapes*, Cambridge University Press, United Kingdom, 296 p.

McDade, M.H., F.J. Swanson, W.A. McKee, J.F. Franklin, and J. VanSickle, 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington, *Can. J. For. Res.*, 20:326–330.

Moser, T.J., P.J. Wigington, M.J. Schuft, P.R. Kaufmann, A.T. Herlihy, J. Van Sickle, and L.S. McAllister. 1997. *The Effect of Riparian Areas on the Ecological Condition of Small, Perennial Streams in Agricultural Landscapes of the Willamette Valley*, EPA/600/R-97/074, U.S. Environmental Protection Agency, National Health and Envrionmental Effects Laboratory, Western Ecology Division, Corvallis, Oregon, 64 p.

Naiman, R.J., 1992. New perspectives for watershed management: Balancing long-term sustainability with cumulative environmental change, *Watershed Management: Balancing Sustainability and Environmental Change* (R.J. Naiman, editor), Springer-Verlag, New York, N.Y., pp. 3–11.

Petersen, R.C., 1992. The RCE: A riparian, channel, and environmental inventory for small streams in the agricultural landscape, *Freshwater Biol.*, 27:295–306.

Roth, N.E., J.D. Allen, and D.L. Erickson, 1996. Landscape influences on stream biotic integrity assessed at multiple spatial scales, *Landscape Ecology*, 11:141–156.

Spence, B.C., G.A. Lomnicky, R.M. Hughes, and R.P. Novitzki, 1996. *An Ecosystem Approach to Salmonid Conservation*, TR-4501-96-6057, ManTech Environmental Research Services Corp., Corvallis, Oregon, 356 p. (available from the National Marine Fisheries Service, Portland, Oregon).

Stanford, J.A., and J.V. Ward, 1992. Management of aquatic resources in large catchments: recognizing interactions between ecosystem connectivity and environmental disturbance, *Watershed Management: Balancing Sustainability and Environmental Change* (R.J. Naiman, editor), Springer-Verlag, New York, N.Y., pp. 91–124.

Steedman, R.J., 1988. Modification and assessment of an index of biotic integrity to quantify stream quality in southern Ontario, *Can. J. Fish. Aquat. Sci.*, 45:492–501.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology, *Transactions of the American Geophysical Union*, 38:913–920.

Swanson, F.J., T.K. Kratz, N. Caine, and R.G. Woodmansee, 1988. Landform effects on ecosystem patterns and processes, *BioScience*, 38:92–98.

Van Deventer, J.S., 1990. *A Bibliography of Riparian Research and Management*, Idaho Riparian Cooperative, University of Idaho, Moscow, Idaho, 485 p.

Van Sickle, J., and S.V. Gregory, 1990. Modeling inputs of large woody debris to streams from falling trees, *Can. J. For. Res.*, 20: 1593–1601.

(Received 15 April 1998; accepted 29 October 1998; revised 10 November 1998)