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RESEARCH ARTICLE

Improved methods for quantifying potential nutrient interception by riparian buffers

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Abstract Efforts to quantify the effects of riparian buffers on watershed nutrient discharges have been confounded by a commonly used analysis, which estimates buffer potential as the percentage of forest or wetland within a fixed distance of streams. Effective landscape metrics must instead be developed based on a clear conceptual model and quantified at the appropriate spatial scale. We develop new metrics for riparian buffers in two stages of increasing functional specificity to ask: (1) Which riparian metrics are more distinct from measures of whole watershed land cover? (2) Do functional riparian metrics provide different information than fixed-distance metrics? (3) How do these patterns vary within and among different physiographic settings? Using publicly available geographic data, we studied 503 watersheds in four different physiographic provinces of the Chesapeake Bay Drainage. In addition to traditional fixed-distance measures, we calculated mean buffer width, gap frequency, and measures of variation in buffer width using both ''unconstrained'' metrics and ''flow-path'' metrics constrained by surface topography. There were distinct patterns of relationship between watershed and near-stream land cover in each physiographic province and strong correlations with watershed land cover confounded fixed-distance metrics. Flow-path metrics were more independent of watershed land cover than either fixed-distance or unconstrained measures, but both functional metrics provided greater detail, interpretability, and flexibility than the fixed-distance approach. Potential applications of the new metrics include exploring the potential for land cover patterns to influence water quality, accounting for buffers in statistical nutrient models, quantifying spatial patterns for process-based modeling, and targeting management actions such as buffer restoration.

Keywords Riparian buffers · Landscape metrics · Land cover · Nutrient filters · Topographic analysis

Introduction

Riparian areas can have an ecological importance that greatly exceeds their areal proportion in the landscape, thus they are often cited as a classic example of the importance of landscape pattern to ecosystem processes and landscape function (Naiman and Decamps 1997; Turner et al. 2001). Intact riparian areas can impart many benefits to aquatic systems through a variety of ecosystem functions (e.g., shading,

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carbon sources, bank stability; Gregory et al. 1991), but this paper is primarily concerned with their ability to intercept materials discharged from disturbed upslope landscapes. The nutrient filtering capacity of riparian areas has received much attention due to its potential to mitigate eutrophication in receiving waters and downstream estuaries (Gilliam 1994; Lowrance et al. 1997). In this paper, riparian buffers are defined as areas of relatively undisturbed forest and wetland vegetation adjacent to a stream channel with the potential to intercept nutrients moving from upslope sources to aquatic ecosystems.

A number of riparian transect studies have documented substantial nutrient filtering along hydrologic flow paths (Peterjohn and Correll 1984; Lowrance et al. 1985; Jacobs and Gilliam 1985; Cooper 1990; Jordan et al. 1993), yet other studies have described more variable results (Osborne and Kovacic 1993; Phillips et al. 1993; Altman and Parizek 1995; Hill 1996; Correll et al. 1997; Vidon and Hill 2004). In whole watershed analyses, evaluations of riparian effects have been mixed, showing strong (Weller et al. 1996; Baker et al. 2001; Johnson et al. 1997; Norton and Fisher 2000; Jones et al. 2001) or weak (Omernik et al. 1981; Osborne and Wiley 1988) riparian effects. Quantifying or even just demonstrating a riparian effect on nutrient discharges across a river network, among watersheds, or across regional landscapes is still a challenge.

There is an inherent mismatch between the scales at which riparian buffers have been studied in the field and represented in whole-watershed analyses. Riparian-buffer nutrient retention has been studied in the field by measuring changes in nutrient concentration along hydrologic flow pathways and then relating nutrient retention to the specific characteristics of the study site, such as riparian buffer width, soil properties, water table fluctuations, vegetation structure, or other features (e.g., Jordan et al. 1993). In contrast to detailed field observations of specific transects, evaluations of buffer effects in whole watersheds or across even larger extents have typically involved statistical analyses in which nutrient discharges from whole watersheds are related to geographic properties, such as land cover. The extent of riparian buffering in a watershed is usually represented by the percentage of forested area within a fixed distance of streams (e.g., Omernik et al. 1981; Osborne and Wiley 1988; Hunsaker et al. 1992; Hunsaker and Levine 1995; Johnson et al. 1997; Shuft et al. 1999; Jones et al. 2001), a measure we will refer to here as a ‘‘fixed-distance’’ metric.

Fixed-distance metrics pose both conceptual and interpretive problems for investigators concerned with nutrient retention in riparian buffers. To function as a buffer for material discharge, a riparian system must be *in between* the stream and some nutrient source area, such as agricultural lands. The proportion of forest and/or wetland within a fixed distance of a stream provides only vague information about the arrangement of buffer ecosystems along flow paths. Riparian forests, by definition, occur near streams. However, there is no guarantee that all forests within a fixed distance of streams function as riparian buffers or that all riparian filters fall within any specified distance of streams (Fig. 1). Thus, at any location within a river network, riparian forests may be narrower or wider along a source-to-stream transect than the fixed-distance zone, and the variation in forest width among many such transects has strong implications for their aggregate filtering potential in a watershed.

Because fixed-distance metrics almost always include areas that are *irrelevant* to buffering, they cannot resolve several spatial patterns important for understanding riparian nutrient retention: forests with and without upslope sources, upstream-downstream patterns of whole-watershed land cover, differences between stream banks, or combinations of these patterns (Fig. 2). When quantified across stream networks at broad spatial scales and then employed in statistical models, fixed-distance metrics imply that proximity exactly equals function, a poor assumption given the problems described above. According to Li and Wu (2004), the limitations and ambiguities inherent in such poorly chosen indices can lead to improper use and misinterpretation of landscape patterns.

To more effectively observe and quantify nutrient capture by riparian buffers across whole watersheds, we must develop landscape metrics that are based on a clear conceptual model and quantified at an appropriate spatial scale. There are three critical concepts that must be considered: connectivity, retention, and aggregation. *Connectivity*, an implied characteristic of all functioning riparian buffers, describes the location and magnitude of source areas connected to specific riparian buffers by surface or subsurface transport

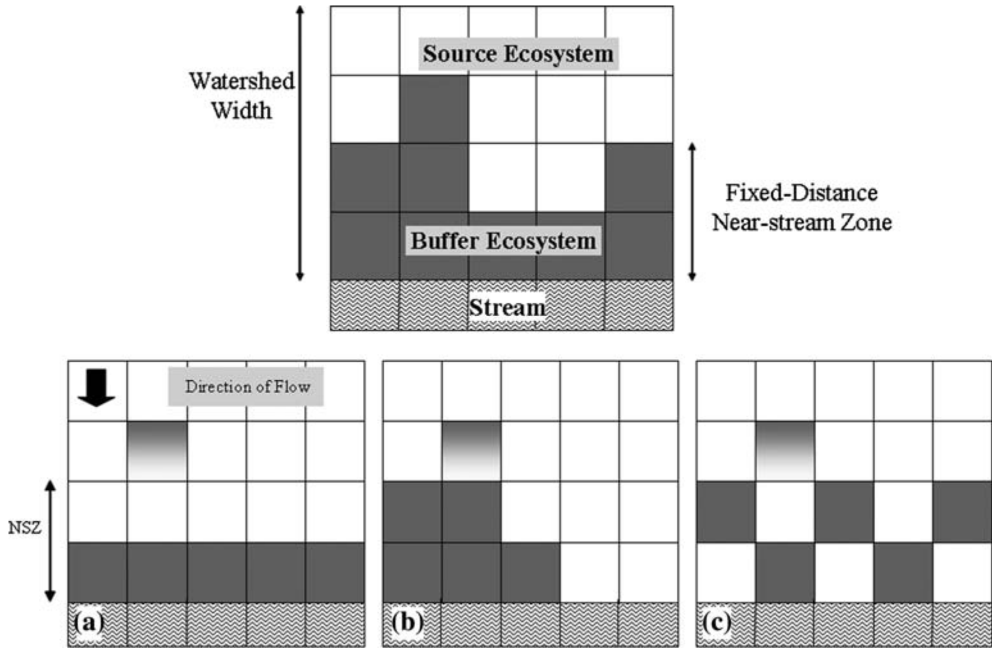

Fig. 1 Hypothetical landscapes illustrating how fixed-distance metrics fail to account for buffer distributions along stream channels. In each example **a**–**c**, the proportion of fixed-distance buffer is the same, yet each has a distinct pattern of buffer widths and gaps. The shaded cell represents forest outside of the fixed-distance zone. In **b** a fixed distance would underestimate buffer potential by ignoring the shaded cell. In **c** a fixed distance would overestimate buffer potential by including disjunct (non-contiguous) cells

pathways. *Retention* describes the ability of a specific buffer to absorb nutrients. Retention is determined by rates of uptake or nutrient transformation. If these rates are similar throughout a riparian buffer, then retention along a flow path can be estimated from buffer width. However, retention may also be affected by site-specific soil, hydrology, and vegetation (Groffman et al. 1992; Osborne and Kovacic 1993; Hill 1996; Gold et al. 2001). Source connectivity and buffer retention can be integrated to estimate the nutrient delivery to streams for a specific flow pathway, but estimates of nutrient delivery for an entire watershed require one further step: *aggregation* of the path-specific connectivity-retention characteristics across all flow paths that enter the stream network.

Weller et al. (1998) analyzed a conceptual landscape simulation model to explore how the distribution of buffer width among flow pathways interacted with unit-buffer retention to yield an aggregate nutrient discharge from an entire landscape. They investigated which measures of buffer distribution were the best predictors of landscape-level nutrient discharge across a range of buffer retentions. They found mean buffer width was the most effective metric in landscapes with relatively leaky buffers, gap frequency was most effective in landscapes with relatively retentive buffers, and measures of the variability in buffer width were most effective in landscapes of moderate (or highly variable) buffer retention. These results need to be evaluated in real watersheds.

In this paper, we develop new metrics for riparian buffers that integrate the three concepts of connectivity, retention, and aggregation to provide a spatial framework for testing the predictions from hypothetical landscapes (Weller et al. 1998) in real watersheds. We calculate and evaluate the new metrics in tributary watersheds of the Chesapeake Bay drainage and begin to address the conceptual and interpretive problems inherent in current fixed-distance metrics. Because croplands are a major source of stream nutrients in Chesapeake watersheds (Jordan et al. 1997a, b, 2003; Liu et al. 2000), we focus on describing the connectivity of cropland to streams through riparian buffers. We develop the new riparian metrics in two stages of increasing functional specificity to address three fundamental questions: (1) Which riparian metrics are more distinct from measures of whole watershed land cover? (2) Do functional riparian metrics provide dif-

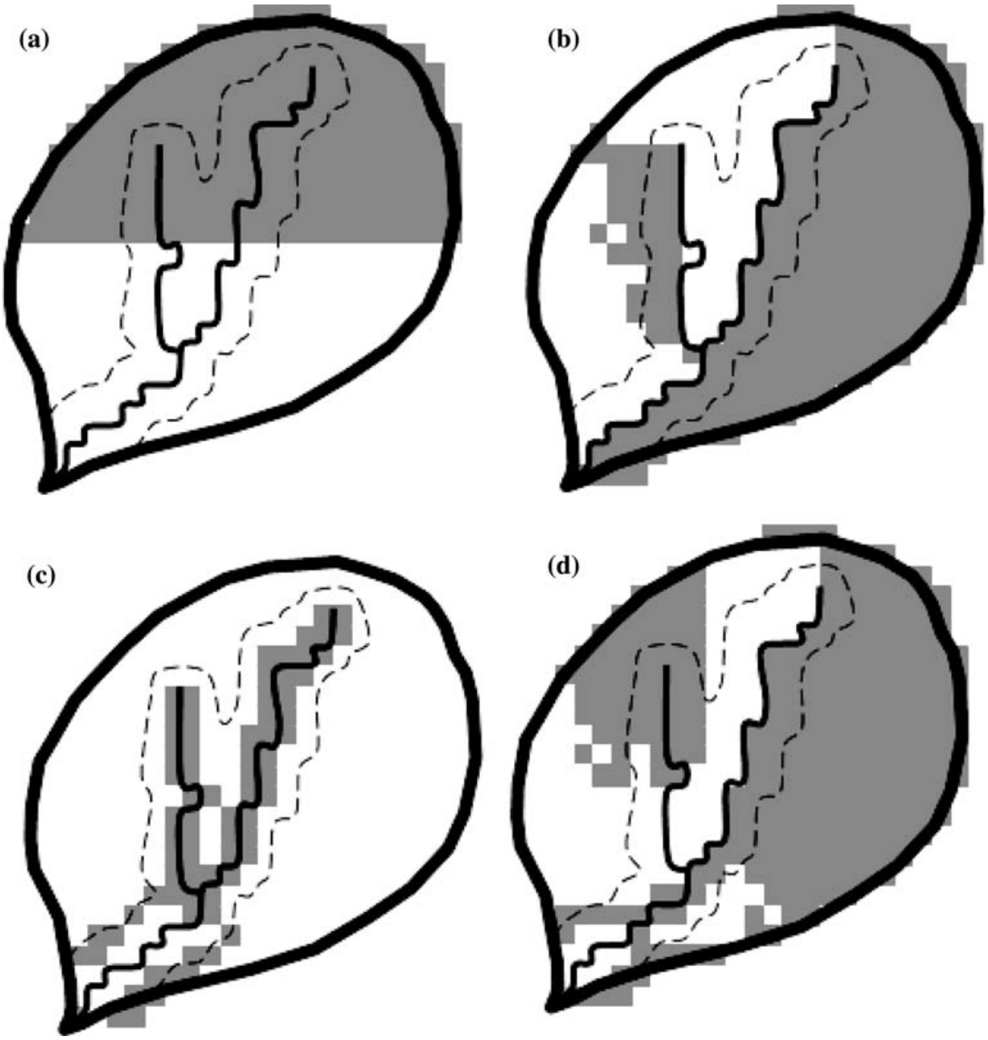

Fig. 2 Set of hypothetical watersheds with the same proportion of forests and wetlands (for-wet) within a fixed distance of the stream, but with different nutrient filtering potentials. The fixed-distance metric fails to account for **a** longitudinal patterns of land cover, **b** different buffer patterns on two stream banks, **c** contiguous versus disjunct near-stream for-wet, and **d** combinations of different patterns

ferent information than fixed-distance metrics? (3) How do these patterns vary within and among different physiographic settings?

Methods

Study watersheds

We studied 503 watersheds selected for their contrasting physiography, differing proportions of land cover, range of population densities, and lack of sewage outfalls. The watersheds were located in 14 clusters distributed across four major physiographic provinces (Langland et al. 1995) of the 166,000 km^2 Chesapeake Bay Drainage (Fig. 3): Coastal Plain (143 watersheds), Piedmont (172), Appalachian Mountain (including Blue Ridge and Great Valley; 109), and Appalachian Plateau (65). Watershed size ranged from 5.5 to 48,010 ha. Liu et al. (2000) provide detailed descriptions of land cover, physiography, and water chemistry.

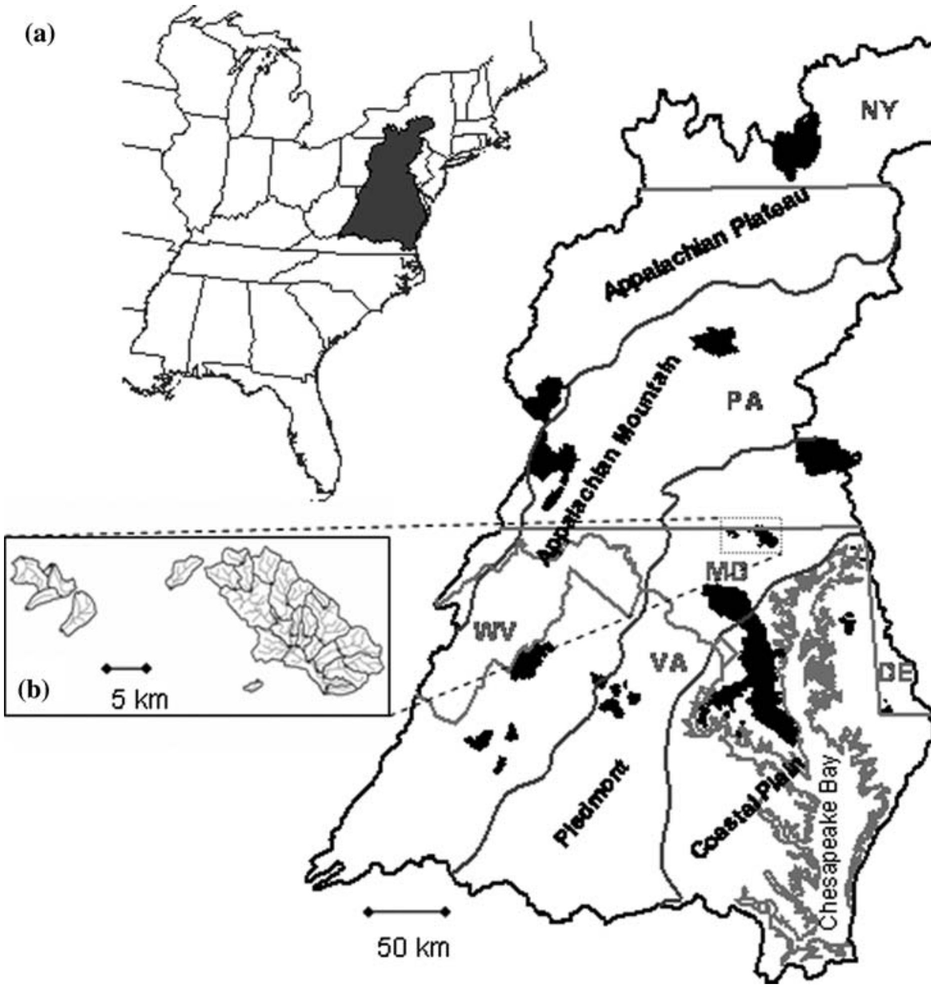

Fig. 3 Map of Chesapeake Basin showing location of study watershed clusters. Insets show the extent of the basin across the eastern U.S. **a** and the distribution of watersheds in a single cluster **b**

Geographic data sources

We analyzed publicly available geographic data sets for elevation, stream channels, and land cover using the Arc/Info (ESRI, Inc) geographic information system (GIS). Land cover information was derived from the National Land Cover Dataset (NLCD) (Vogelmann et al. 1998a, 1998b; USEPA 2000). Elevation information was obtained from USGS 1:24,000 topographic maps and digital elevation models (DEM; National Elevation Dataset; http://ned.usgs.gov). We also used 1:24,000 digital-line-graph (DLG) stream maps derived from the same USGS 7.5-min quadrangles (http://nhd.usgs.gov). Watershed outlets were located in the GIS by manually digitizing sampling points marked on 7.5-min quadrangle maps. Watershed boundaries were initially manually interpreted and digitized into a GIS dataset from contour lines and streams on paper topographic maps and from county ditch maps (Liu et al. 2000). These manual boundaries were later modified to match the DEM with the normalized excavation method for automatic watershed delineation using elevation and stream maps (Baker et al. 2006). Watershed boundaries, land cover, and stream maps were converted to rasters at the pixel resolution of the DEM so that all digital datasets were represented on a common grid. Stream rasters were also thinned to the width of a single pixel, and the DEM was modified within 100 m of stream channels using the normalized-excavation version of AGREE (Baker et al. 2006). AGREE excavates channels using stream maps, then raises or lowers the elevation values of DEM surfaces near streams so that discrepancies between topographic flow lines and stream maps do not create the appearance of parallel channels (Hellweger 1997).

Metric calculation: fixed distance

Riparian buffer metrics were generated in three levels of increasing functional detail: fixed distance, unconstrained, and flow path. We present the general logic here and provide additional technical details in the Appendix A. In the traditional fixed-distance method, we quantified the percent forest and wetland (for-wet) land cover within 100 m of mapped stream channels in each watershed. This distance is a common compromise in many published land-cover analyses to allow for poor resolution or minor registry differences among land cover, elevation, and stream maps (e.g., Osborne and Wiley 1988; Richards et al. 1996; Johnson et al. 1997; Norton and Fisher 2000) and because considering smaller distances (30–100 m) apparently makes little difference in the resulting land cover estimates obtained using 30-m data (Roth et al. 1996).

Metric calculation: unconstrained

In the ''unconstrained'' method, we first identified for-wet cover that was contiguous with mapped stream channels. Forest or wetland patches had to be connected to stream channels by an unbroken chain of for-wet pixels in order to be considered contiguous. This step removed isolated patches of forest or wetland that occurred within a fixed distance of streams but were separated from stream channels by other types of land cover. It also allowed for a variable-width buffer by including contiguous for-wet areas that fell outside of the fixed-distance zone.

Buffer width was then estimated for each stream pixel (or each approximately 30-m stream reach) as the shortest distance to any source (cropland) pixel across the contiguous for-wet buffer. For example, using the primary map in Fig. 1, buffer width would be calculated as 2, 1.2, 1, 1, and 1.2 cell widths, respectively from left to right. In these measures, distance is computed between cell centroids, so a diagonal cell traverse combined with a vertical or horizontal traverse led to a value of 1.2 cell widths, whereas two consecutive diagonal traverses would lead to a value of 1.4 cell widths (for technical details see Appendix A). Dividing across the 5 columns leads to an average of 1.28 cell widths. One potentially undesirable consequence of the unconstrained method was that, in extreme cases, a single pixel of source area in an otherwise forested watershed could influence buffer width estimates throughout the stream network. Thus, if the purpose of the buffer measurement was to aid in the estimate of watershed nutrient discharges, the unconstrained metrics could yield misleading results.

Stream channels in our study area are rarely as wide as 30 m, so rasterizing vector stream maps to 30-m pixels could introduce significant error into our calculations by obscuring the area closest to the stream channel. Therefore, unless channels were shown as water in the land cover map, we also included land cover overlain by stream pixels in our analysis by assuming that the channel fell in the middle of the pixel. This adjustment would probably be unnecessary with higher-resolution data. For each stream pixel, the minimum width value in the surrounding eight cells was used to assign a width value for that portion of the channel. If a stream pixel was underlain by for-wet cover, the value of one-half the cell size was added to its minimum buffer width.

Buffer gaps were interpreted as stream pixels that did not contain for-wet. We quantified the number and percent (gap frequency) of unbuffered stream pixels (buffer width = 0) in each watershed. For each watershed, we aggregated individual buffer widths (stream pixels with minimum buffer width>0) by calculating the mean, evenness (see Weller et al. 1998), and coefficient of variation.

Metric calculation: flow path

In the ''flow-path'' method, we used the DEM identify a surface transport pathway following the steepest descent from each source (cropland) pixel to a stream using commercially available topographic analysis techniques (e.g., Jenson and Domingue 1988) as implemented in ArcInfo. We then isolated for-wet cover contiguous with the stream along each flow pathway and quantified the for-wet width. For each source pixel, we assessed whether a buffer gap existed (no contiguous for-wet along the flow path), and if not, augmented buffer width estimates by one half the cell size to account for for-wet cover underlying the stream pixel. For each watershed, we derived aggregated metrics by calculating percent buffer gaps as well as mean, evenness, and coefficient of variation in buffer width across all source cells.

Unlike the unconstrained method, the flow-path method provided a unique buffer-width measure for each source cell and only for source cells. For example, consider the 11 source cells in the primary map of Fig. 1. Using flow-path metrics (assuming flow pathways are confined to columns), each source cell is assigned the width of buffer cells between it and the stream, or [(2*2)+(1*3)+(3*1)+(3*1)+(2*2)]/11, respectively from left to right (see Appendix A). Thus, the mean flow-path buffer width would be 1.54 cell widths, whereas the mean unconstrained buffer width would be 1.28 cell widths.

Flow-path characterization enabled two additional calculations: mean inverse buffer width and adjusted cropland proportion. Inverse buffer width could represent a decrease in the unit effect of cropland area with transport distance through a buffer that would be consistent with published observations of strong declines in nutrient concentrations along transects (e.g., Lowrance et al. 1997). We calculated inverse buffer width as $1/(w+1)$ for each cropland cell and averaged this calculation across all cropland cells. The mean inverse buffer width is considered an additional riparian metric that should be independent of watershed land cover proportion. We calculated adjusted cropland proportions by summing the inverse buffer width across all cropland cells and then dividing by drainage area. Adjusted cropland proportion is an estimate of watershed cropland adjusted downward to represent how much riparian buffers along flow paths might reduce nutrient delivery to the stream. This adjustment is essentially an inverse distance weighting (see King et al. 2005), where distance is measured as the width of contiguous for-wet cover that must be traversed to reach a stream.

Metric comparisons

To interpret riparian metric patterns among and within physiographic provinces, it was necessary first to understand more general land cover differences. We described distributions of cropland (source) and for-wet (buffer) land-cover proportions among watersheds in different physiographic provinces in three ways: gross proportions, proportions within a fixed distance from streams, and fixed-distance cover as a fraction of watershed-wide cover. We tested the independence of all three riparian metric calculations relative to watershed-wide land cover using Pearson product–moment correlation. To assess whether different metrics provided similar or distinct information, we examined correlations between fixed-distance and functional riparian metrics, then regressed fixed-distance metrics against both unconstrained and flow-path estimates. To evaluate the potential for conceptual problems in fixed-distance analyses that might confound riparian interpretation, we evaluated groups of watersheds where fixed-distance metric values were similar and examined the range of differences in functional metrics. We also regressed watershed-wide cropland proportions against both mean inverse buffer width and adjusted cropland proportions to evaluate the potential for more detailed spatial modeling to improve nutrient discharge predictions in different provinces.

Results

Among-province land cover differences

The distribution of watershed cropland proportions in our sample varied with physiographic province (Fig. 4). Piedmont watersheds had the greatest median cropland proportion (10.8%) and the second greatest mean (10.0%), whereas Coastal Plain watersheds had a smaller median (6.9%) but a greater mean (12.7%) due six watersheds with cropland proportions in excess of the Piedmont maximum (39.4%; Fig. 4a). Watersheds in both provinces had markedly greater amounts of cropland than watersheds in the Appalachian Mountains and Plateau (Fig. 4a). Percent cropland within a 100-m fixed-distance from the stream was greater

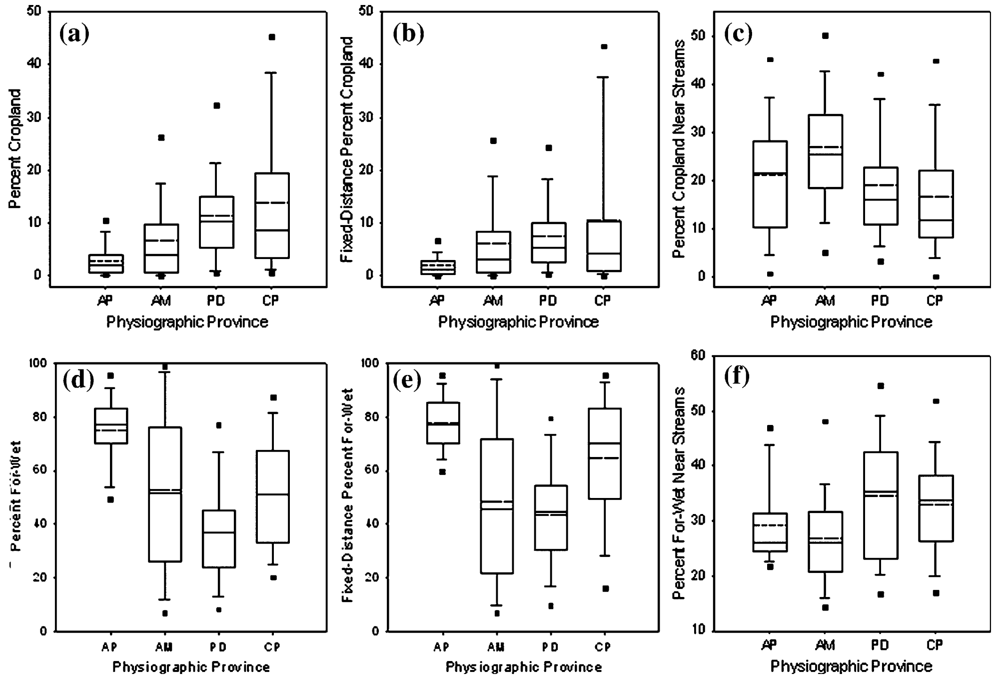

Fig. 4 Boxplots depicting patterns of watershed **a** and **d**, fixed-distance **b** and **e**, and the fraction of watershed land cover occurring near a stream **c** and **f** for cropland and forest-wetland across Appalachian Plateau (AP), Appalachian Mountain (AM), Piedmont (PD), and Coastal Plain (CP) physiographic provinces. Boxes delimit the 25th and 75th percentiles, whiskers the 10th and 90th, and dots the 5th and 95th. Dashed lines indicate the mean value in each province and solid lines indicate the median

in the Piedmont than in Coastal Plain and Appalachian Mountain watersheds, and the distribution of cropland percentages across provinces (Fig. 4b) was similar to watershed-scale patterns (Fig. 4a). In contrast, a markedly greater fraction of watershed cropland occurred within 100 m of streams in the Appalachian provinces than in either the Piedmont or Coastal Plain (Fig. 4c). Thus, although less cropland occurred in Appalachian Plateau and Mountain watersheds, it was more likely to be located close to a stream than in watersheds of either the Piedmont or Coastal Plain.

Watersheds in the Appalachian Plateau had the greatest percent for-wet cover and Piedmont watersheds the least (Fig. 4d). For-wet distributions using fixed-distance proportions near streams (Fig. 4e) were similar and showed similar rank orders to whole-watershed proportions (Fig. 4d), except that Piedmont and Appalachian Mountain watersheds had similar low percent fixed-distance for-wet cover. Fractions of watershed for-wet cover occurring within 100 m of a stream were lower in the two Appalachian provinces than in either the Piedmont or the Coastal Plain (Fig. 4f).

Among provinces, patterns of for-wet cover showed markedly different interactions with agricultural land use. For example, watersheds with 10% cropland in the Appalachian Mountains had between 6% and 60% for-wet within 100 m of streams, whereas Coastal Plain watersheds with 10% cropland had between 40% and 90% for-wet within 100 m of streams. On the other hand, Appalachian Mountain and Piedmont watersheds had somewhat similar distributions of for-wet cover within 100 m of streams (Fig. 4e) even though watershed-scale land cover (Figs. 4a and d) and the propensity for cropland to be located near a stream were more distinct (Fig. 4c). Therefore, even though both provinces had similar amounts of fixed-distance for-wet (Fig. 4e), a pixel of for-wet in Piedmont watersheds was much more likely to be near a stream than in the Appalachian Mountains (Fig. 4f).

Table 1 Correlations among whole-watershed cropland, forest-wetland cover proportions, and riparian metrics across the Chesapeake Basin (CB, n=503), as well as within Appalachian Plateau (AP, n=65), Appalachian Mountain (AM, n=113), Piedmont (PD, n=174), and Coastal Plain (CP, n=151) physiographic provinces

Landscape (riparian) metric	Cropland (%)						Forest-wetland (%)				
		Physiographic province						Physiographic province			
	CB	AP	AM	PD	CP		CB	AP	AM	PD	CP
Whole-watershed											
Forest-wetland %	−0.58	**−0.78**	−0.60	−0.66	−0.58	Cropland	−0.58	**−0.78**	−0.60	−0.66	−0.58
Adjusted % cropland	**0.88**	**0.89**	**0.98**	**0.97**	**0.86**		−0.60	−0.69	−0.64	−0.66	−0.54
Fixed-distance											
Fixed-distance cropland %	**0.90**	0.68	**0.96**	**0.79**	**0.92**		−0.48	−0.42	−0.53	−0.55	−0.54
Fixed-distance for-wet %	−0.49	−0.54	−0.54	−0.59	−0.61		**0.90**	**0.84**	**0.97**	**0.90**	**0.88**
Unconstrained											
Mean width	−0.35	−0.57	−0.37	−0.33	−0.47		0.65	**0.77**	**0.75**	**0.75**	**0.77**
% Gaps	0.40	0.50	0.52	0.53	0.50		**−0.87**	**−0.79**	**−0.97**	**−0.87**	**−0.85**
Evenness	−0.38	−0.43	−0.56	−0.46	−0.51		**0.75**	**0.71**	**0.86**	0.67	**0.76**
C.V. width	0.30	0.26	0.62	0.41	0.41		−0.64	−0.51	**−0.74**	−0.65	**−0.77**
Flowpath											
Mean width	−0.25	−0.30	−0.24	−0.42	−0.38		0.50	0.33	0.44	0.65	0.55
% Gaps	0.29	0.21	0.44	0.49	0.55		−0.56	−0.27	**−0.74**	−0.61	−0.53
Evenness	−0.05	0.17	−0.12	−0.19	−0.20		0.30	−0.20	0.40	0.39	0.24
C.V. width	−0.25	n.s.	0.55	0.48	0.45		−0.41	n.s.	−0.53	−0.46	−0.41

All correlations shown are significant (P<0.05). Strong correlations (>|0.7|) are shown in bold type

Table 2 Correlations of functional riparian metrics with fixed-distance percent forest-wetland in watersheds of the Chesapeake Basin (CB), and in Appalachian Plateau (AP), Appalachian Mountain (AM), Piedmont (PD), and Coastal Plain (CP) physiographic provinces

Riparian metric	CB (503)	Physiographic province			
		AP (65)	AM (113)	PD (174)	CP (151)
Unconstrained					
Mean width	0.55	**0.81**	**0.78**	**0.71**	**0.72**
Gap frequency	**−0.98**	**−0.97**	**−0.99**	**−0.98**	**−0.96**
Evenness	**0.86**	**0.92**	**0.87**	**0.81**	**0.89**
C.V. width	**−0.75**	**−0.79**	**−0.73**	**−0.78**	**−0.88**
Flow-path					
Mean width	0.60	0.43	0.46	**0.71**	0.64
Gap frequency	**−0.75**	−0.43	**−0.79**	**−0.73**	**−0.70**
Evenness	0.50	n.s.	0.46	0.55	0.44
C.V. width	−0.57	−0.20	−0.56	−0.58	−0.57
Mean inverse buffer width	**−0.73**	−0.46	**−0.72**	−0.65	**−0.74**
Adjusted % cropland	−0.66	−0.57	−0.60	−0.69	**−0.73**

All correlations shown are significant (P<0.05). Strong correlations ($|r|$>0.7) are shown in bold type

Metric independence

Among all watersheds, cropland proportions were strongly correlated (r=0.90) with fixed-distance percent cropland (Table 1). Fixed-distance percent for-wet was similarly correlated with watershed for-wet (r=0.90) and showed a more moderate negative correlation with watershed-wide percent cropland (r=−0.49). Functional metrics were not strongly correlated with watershed-wide cropland ($|r|$<0.45) with the expected exception of adjusted percent cropland, but some unconstrained metrics (gap frequency, evenness) were strongly correlated with watershed for-wet. A similar pattern existed within each province (Table 1), although Appalachian Mountain and Coastal Plain watersheds showed stronger correlations between watershed and fixed-distance cropland cover, as well as unconstrained

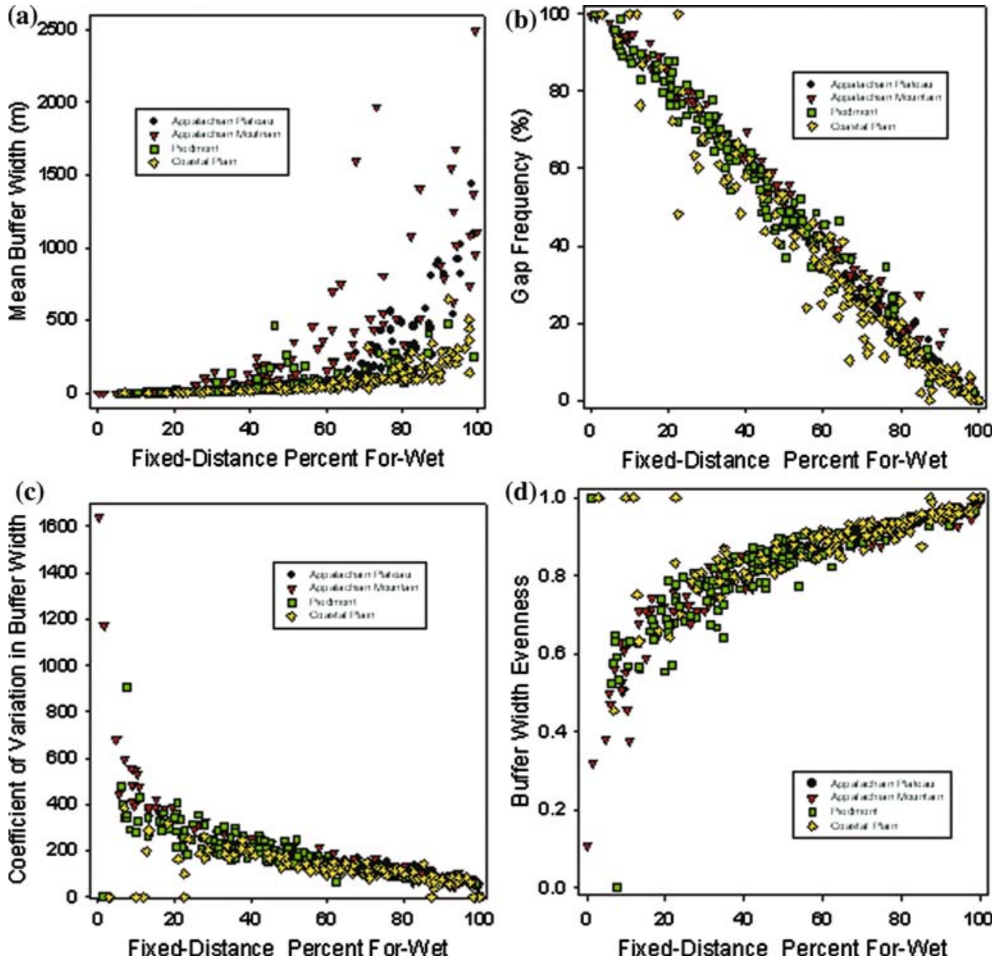

Fig. 5 Scatterplots showing the relationship of fixed-distance percent forest-wetland cover to unconstrained measures of **a** mean buffer width, **b** percent gaps, **c** coefficient of variation in buffer width, and **d** width evenness across physiographic provinces of the Chesapeake Basin

metrics. In every case, flow-path metrics were more independent of watershed cropland than fixed-distance measures and, in most cases, than unconstrained metrics.

Comparing functional and fixed-distance metrics

The relationships between fixed-distance metrics and functional metrics are described by a correlation matrix (Table 2) and scatter-plots (Figs. 5 and 6). Because fixed-distance metrics were so highly correlated with whole-watershed land cover, riparian metrics that are independent of fixed-distance measures are desirable for their ability to provide distinct information in land cover analysis. Across watersheds in the Chesapeake Basin, fixed-distance percent for-wet was strongly and negatively correlated ($r=-0.98$) with unconstrained measures of gap frequency (Table 2, Fig. 5b), followed in strength by negative relationships with increasing variability (or decreasing evenness, Figs. 5c and d) in unconstrained buffer width. Variation measures for unconstrained buffer width (C.V. and evenness) were non-linearly related to fixed-distance percent for-wet (Figs. 5c and d). In contrast, fixed-distance percent for-wet showed only moderate positive correlations with unconstrained mean buffer width (Fig. 5a). A similar pattern of correlations occurred among watersheds of any single physiographic province with one notable difference (Table 2):

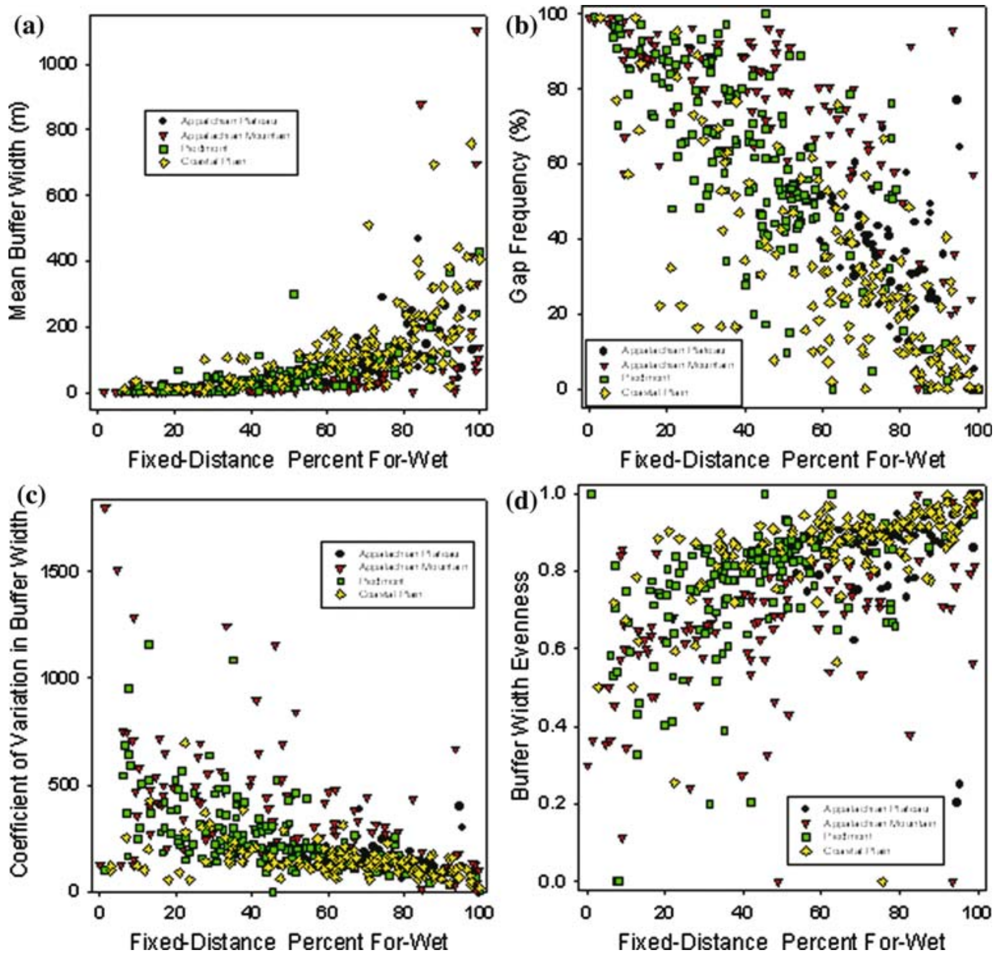

Fig. 6 Scatterplots showing the relationship of fixed-distance percent forest-wetland cover to flow-path measures of **a** mean buffer width, **b** percent gaps, **c** coefficient of variation in buffer width, and **d** width evenness across physiographic provinces of the Chesapeake Basin

unconstrained measures of buffer width were more strongly correlated with fixed-distance percent for-wet within any physiographic province than among all provinces. This relationship was distinct within each province (Fig. 5a), so, the strength of the overall correlation was weakened by strong differences among physiographic provinces.

Flow-path measures of buffer width also showed moderate, positive correlation with fixed-distance percent for-wet, and this pattern was also attributable to both distinct relationships among physiographic provinces and non-linear relationships within provinces (Table 2, Fig. 6a). Mean buffer widths were always small when the percent of fixed-distance for-wet was low, but mean buffer widths varied greatly at higher fixed-distance proportions. Flow-path mean buffer width was most strongly correlated with fixed-distance percent for-wet in the Piedmont and Coastal Plain, and more weakly correlated within Appalachian provinces due to tremendous variability in mean buffer width at high fixed-distance proportions. Flow-path buffer gaps were strongly and negatively correlated with percent near-stream for-wet cover, yet showed lower correlation and much greater variation in correlation among provinces (Table 2, Fig. 6b) than did the unconstrained version (Table 2, Fig. 5b). Measures of variability in flow-path buffer width were also weakly and inconsistently correlated with near-stream percent for-wet. Once again, these relationships were characterized by province-specific patterns of decreasing variation with increasing fixed-distance proportions (Fig. 6c and d). In each case, poor correlation with fixed-distance for-wet cover implied that distinct and heretofore unknown information was generated by the flow-path metric.

Discussion

Constraints on riparian land cover

Broad-scale land cover patterns can result from climatic, topographic, hydrologic, and historical constraints on land use practices, so describing differences in land-use patterns among provinces provides an important context for interpreting riparian metrics. For example, more cropland occurs near streams in Appalachian Mountain watersheds because these locations have the lowest slopes and most tillable soils. In the Coastal Plain, steeply incised stream banks or poorly drained floodplains are common, making it more difficult to farm along streams. Such floodplain wetlands can be the last bastions of natural land cover in highly agricultural watersheds (Norton and Fisher 2000). Therefore, in contrast with Appalachian Mountains where forest clearing and cropland occur near streams, Coastal Plain watersheds had the smallest fraction of their cropland and (along with Piedmont watersheds) the greatest fraction of their for-wet cover located within 100 m of stream channels. Distinct spatial relationships between sources and sinks lead to different patterns of buffer potential. Opportunities for effective riparian buffering should be greater in the Coastal Plain, and this is consistent with lower observed nutrient yield per unit cropland in the Coastal Plain when compared with Appalachian Mountain watersheds (Liu et al. 2000).

Despite similar patterns of near-stream forest and wetland cover, broad-scale land cover patterns can be quite distinct and expectations of buffer performance based solely on fixed-distance metrics can be quite wrong. Just because watersheds have more near-stream forest than others does not necessarily mean they are as well-buffered. Given the distinct relationships between watershed and near-stream land cover within and among provinces, patterns measured with fixed-distance metrics may reflect physiographic constraints on regional land cover patterns rather than the potential for riparian areas to act as nutrient sinks.

In our study, fixed-distance metrics were strongly correlated with whole-watershed land cover because *any* large, representative, areal sample tends to reflect broader landscape patterns, especially across physiographic provinces (e.g., King et al. 2005). In this context, fixed-distance metrics can not tell us much about nutrient flux that is not already captured by watershed proportions. Although the spatial patterns implied by fixed-distance metrics (i.e., having forest or wetland land cover near a stream) are necessary characteristics of riparian buffers, such metrics do not accurately represent riparian effects in statistical models. In a broad-scale, cross-province study in the Mid-Atlantic, Jones et al. (2001) documented strong, negative correlations between percent fixed-distance forest and the percent of both fixed-distance (−0.88) as well as watershed-wide (−0.94) agriculture. When any one of these parameters are selected during a step-wise procedure to predict nutrient discharge, it is difficult to determine whether variation in nutrient concentrations is being predicted by whole watershed agriculture, proximal (near stream) agriculture, a lack of riparian buffers, or some combination of the three. These confounding correlations can obscure causal relationships and influence the performance and interpretation of fixed-distance buffer metrics in univariate or multivariate statistical models.

New riparian metrics: the flow-path advantage

We have developed two levels of new metrics for characterizing riparian buffering of upslope nutrient sources. Our metrics are derived from a conceptual understanding of riparian processes. Both unconstrained and flow-path metrics were based on an explicit, transect-scale conceptual model and three concepts critical for characterizing riparian buffers. Concept 1: functional buffers are defined by their hydrologic *connectivity* and must be explicitly linked to both an upslope source and a down-slope stream. Therefore, only buffers connected to source and stream are relevant for nutrient transport and other land cover, including other forests or wetlands, should be excluded from metric calculations. The definition of connectivity we use here refers to nutrient transport and is distinct from the longitudinal network connectivity usually associated with species movement along riparian corridors (Gregeory et al.

1991; Naiman and Decamps 1997). Concept 2: active riparian buffers are characterized by their nutrient *retention*. In this analysis, we assumed that retention was a function of buffer width and that active riparian buffers were more likely to occur when buffers were contiguous with stream channels. Concept 3: there needs to be an explicit *aggregation* step that describes how transect-scale understanding of riparian buffers is scaled to represent whole-watershed processes.

Many landscape studies use metrics or indices that can be calculated with simple GIS operations (e.g., fixed-distance buffers) or with widely available software (e.g., FRAGSTATS; McGarigal and Marks 1995; Gergel et al. 2002; Griffith 2002). To further understand pattern-process linkages, we need to continue to develop indices based on landscape attributes that more directly influence a specific process of interest (Weller et al. 1998; Liu et al. 2000; Tischendorf 2001; Li and Wu 2004). Here we developed indices explicitly focused on factors relevant to nutrient transport from nutrient source areas through buffers to streams. The broad range of mean buffer width possible at moderate to high fixed-distance proportions documents the imprecision of traditional fixed-distance measures and illustrates why functional metrics provide more information beyond watershed land cover proportions than do fixed-distance estimates. Both sets of functional metrics provide implicit information about land cover arrangement through identification of contiguous buffers and defining their connection to source areas and stream channels. Both also allow explicit analysis of within-watershed variability. The key difference between the unconstrained and flow-path metrics was the use of surface topography in the flow-path versions to more precisely define connectivity and contiguity.

Like field studies that characterize processes along individual transects (e.g., Jordan et al. 1993), flow-path connectivity was defined explicitly at the transect scale to match conceptual models and characterize the material retention afforded by specific buffers. By aggregating individual flow paths across a broader landscape, our approach provides a method for correctly scaling empirical transect observations to whole watersheds. This is far more appropriate for material transport models than an estimate of proximal land cover made across whole river networks by fixed-distance metrics and helps meet widespread calls for the development of scaling rules (Turner et al. 1989; Cullinan and Thomas 1992).

Given the constraints imposed by our conceptualization—hydrologic connectivity of source areas and buffers and ignoring land cover not directly involved in nutrient transport—flow-path metrics showed much smaller correlations with both watershed and fixed-distance land cover than did unconstrained measures. One consequence of this relative independence is that flow-path measures should be more useful for watershed-specific estimates of buffer condition in multivariate models because they are statistically distinct from measures of watershed land cover. On the other hand, the riparian metrics described here (with the exception of adjusted proportions) should be poor statistical predictors of observed nutrient concentrations *by themselves* since they are unrelated to factors that determine the amount of solute (cropland or source area) or the amount of water available for solution (watershed size).

Using buffer metrics in combination with other important variables to create a modified estimate of ''adjusted'' source proportion (Fig. 7) is an additional approach that holds promise for improving spatial predictions of nutrient discharge. Although multi-regional studies using fixed-distance metrics are confounded by the correlation of fixed-distance proportions with watershed-wide land cover, more explicit functional metrics may actually indicate regional variation by capturing province-specific land cover patterns. We expect that better methods of riparian characterization will provide insight into patterns of land cover arrangement and improved whole-watershed predictions of nutrient discharge. In such predictions, the ability to evaluate explicit riparian measures prior to engaging in intensive, process-based modeling may prove extremely useful.

Limitations and potential improvements

Although our unconstrained approach was functionally motivated, it resulted in measures that were statistically indistinguishable from both watershed and fixed-distance land cover. The number of unconstrained buffer width measurements within a

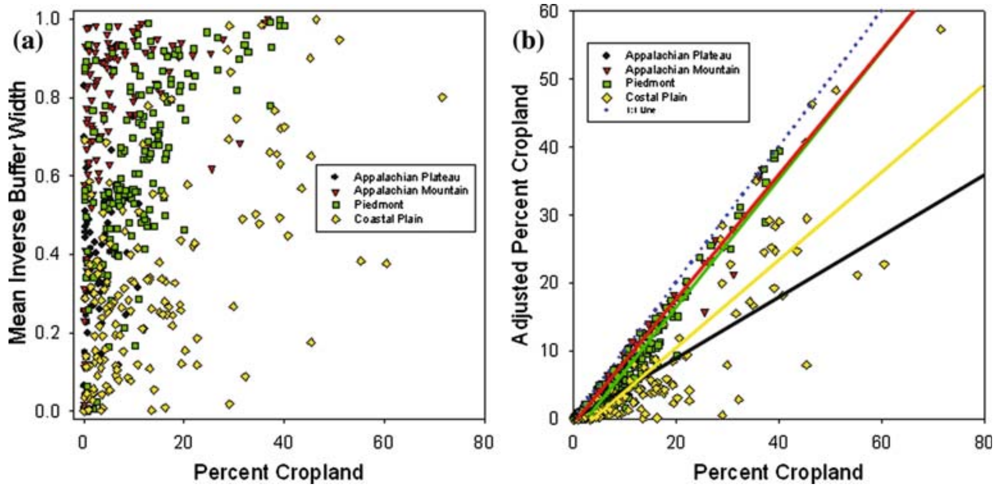

Fig. 7 Scatterplots showing the relationship of percent cropland to mean inverse buffer width **a** and adjusted percent cropland **b**. In **b** points falling on or near a 1:1 line indicate little potential improvement for buffer characterization to enhance nutrient predictions based solely on cropland proportions

given watershed was highly dependent upon the amount of near-stream for-wet cover. In part, this was because our definition of contiguity resulted in near-stream proportions of ''buffer'' that accounted for 99% of the variation in fixed-distance for-wet both among and within regions. Despite these correlations, the unconstrained approach allowed calculation of mean width, gap frequency, and other parameters described by Weller et al. (1998), so such metrics might yet be useful for analysis of other ecological processes (such as animal movement or seed dispersal) when landscape connectivity is multidirectional rather than hydrologic or when specific transport pathways are unclear. Also, this approach more precisely captures forest and wetland land cover patches that are contiguous with stream channels and not limited to a particular fixed-distance zone. However, flow-path metrics remain the best option for nutrient transport studies.

The flow-path metrics described here represent a significant improvement over both fixed-distance and unconstrained measures, but they do not represent an exhaustive analysis. Our approach was developed with the implicit recognition that, due to the limitations of existing spatial data and our understanding of relevant processes, increased functional specificity did not necessarily guarantee increased predictive accuracy. We used surface topography and a relatively imprecise topographic analysis to define flow pathways. It would certainly be better to have more information on subsurface flow paths and this area merits further research at the landscape scale. In the meantime, flow paths based on surface topography should give better results than fixed-distance approaches, which include no flow path information at all. Future improvements might include more realistic algorithms for predicting surface water flow (e.g., Tarboton 1997) or including constraints on subsurface flux (e.g., Baker et al. 2003).

We have also presumed uniform buffer transmissivity and used buffer width to describe total material retention along each pathway. Further characterization of local site conditions using soil properties, landscape position, or wetland maps might well allow more precise estimation of active buffers (Russel et al. 1997; Norton and Fisher 2000; Baker et al. 2001; Rosenblatt et al. 2001). Although vegetation type and age may also influence buffer retention, such information is not always interpretable from land cover data (Marceau et al. 1994).

Our basic approach is a framework for spatial analysis that will also work with finer-scale topographic and land cover data, so high-resolution maps or aerial photos may yield more accurate results. The metrics described here were developed using readily available data from public sources, including the 30-m NLCD. This relatively coarse land cover information may miss narrow patches of forest and wetlands that typically occur along streams in fragmented landscapes, thus the metrics may not describe important effects of smaller buffers. Recent analysis by Hollenhorst et al. (2006) using a fixed-distance approach indicates that 30-m NLCD data does miss many forested patches along streams and may greatly overestimate near-stream agricultural activity compared to interpretation of aerial photos. Similarly, for any riparian metric, the universe of interaction between a stream and surrounding land cover is influenced by the density of mapped streams. Thus, stream-map resolution may affect riparian metrics and explain some inconsistencies among published studies (Baker et al. *in review*).

Even though flow-path metrics are more independent of watershed patterns than fixed-distance measures, they remain sensitive to regional patterns of land use, especially land use near stream channels. This sensitivity is apparent from among-province differences in the range of metric values relative to fixed-distance proportions (Fig. 6) and has several implications for riparian studies. Constraints on among-watershed land-cover variation may impair our ability to detect riparian effects in statistical models (Gergel 2005). Just as the idea of buffer effects makes little sense in a completely forested watershed, watersheds with intensive cropland or development concentrated along stream channels can limit buffer potential at the watershed scale. For example, the relationship of watershed cropland to mean inverse buffer width or adjusted cropland proportion indicates whether buffer distributions suggest filtering potentials large enough to meaningfully influence statistical predictions of nutrient discharge (Table 1, Fig. 7). Appalachian Mountain watersheds in particular appear to be consistently poorly buffered (i.e., mean inverse buffer width approaches 1.0 at low proportions of cropland so adjusted percent cropland roughly equals percent cropland across all watersheds). In contrast, Piedmont, Appalachian Plateau, and Coastal Plain watersheds showed more variability with low cropland proportions, and adjusted percent cropland was much less than percent cropland for many watersheds. At cropland proportions greater than 20%, only Coastal Plain watersheds showed potential buffer reductions across enough watersheds sufficient to substantially alter adjusted percent cropland (Fig. 7b). Therefore, statistical predictions using some form of buffer characterization have the potential to alter and even improve predictions of nutrient discharge in these Coastal Plain watersheds.

We have presented a series of novel metrics for describing the function of riparian buffers in material transport. These functional metrics provide greater detail, interpretability, and flexibility in a clearer conceptual framework than do traditional, fixed-distance measures. Potential applications include exploring the potential for land cover patterns to influence water quality, accounting for buffers in statistical nutrient models, organizing spatial information for process-based modeling, and targeting management action. Until empirical observation can consistently link patterns of streamside buffers to significant reductions in nutrient concentrations across whole watersheds, demonstrating the utility of riparian filtering as a strategy for basin-scale nutrient reductions remains an elusive goal. Only by applying more appropriate analytical tools will we be able to assess buffer effectiveness across broad regions.

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Appendix A: technical methods for metric calculation

The unconstrained method

1. *Contiguous For-Wet Cover*: We isolated for-wet cover contiguous with mapped stream channels using least-cost-path analysis and the ArcInfo *costallocation* function. Least-cost-path analysis involves distance calculations between an originating cell(s) and focal cell(s) where distance is defined as the product of geographic distance and some impedance described by a ''cost surface''.

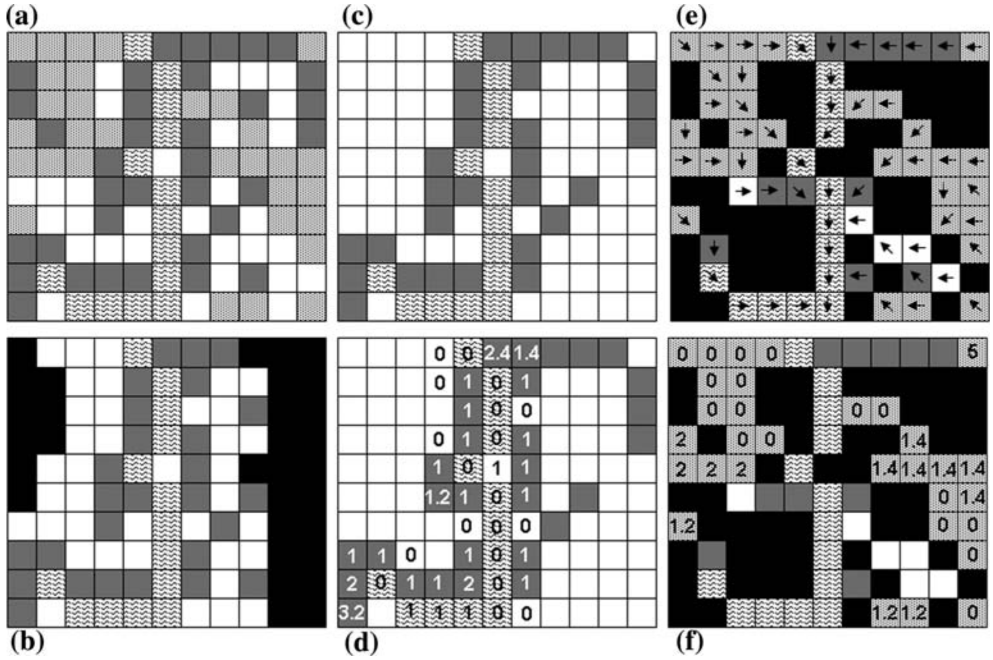

Fig. A.1 Hypothetical maps showing the results of different riparian metric calculations from **a** a 30-m NLCD landscape with source areas (black speckle) and buffers (gray) distributed along a stream channel (waves), **b** buffers within 100 m of streams, **c** contiguous buffers using the unconstrained method, **d** buffer widths for each pixel adjacent to the stream channel (numbers adjacent to stream in units of cell width) and the minimum buffer width for each 30-m reach (black numbers in stream cells), **e** isolated flow paths from source areas to stream showing contiguous buffers and flow direction (arrows), and **f** flow path buffer widths for each source pixel in units of cell width

A cost-allocation function adds cells to the originating raster as they are traversed while computing distance. In this calculation, stream pixels were used as the originating cells, for-wet cells were given an impedance value of one, and all other types of land cover functioned as a barrier (No Data) to allocation (Fig. A.1c). Any pixels ''allocated'' to the originating cells in the output raster were contiguous with the stream raster, but not necessarily the stream channel (see optional correction below).

2. *Buffer Width*: Width was estimated as the shortest distance (least-cost-path using the ArcInfo *costdistance* function) from any cropland pixel to a stream channel. In this analysis, cropland cells were the origin of the cost-distance measure, for-wet cells were assigned an impedance value of one, stream cells were assigned No Data (a barrier to measurement), and all other land cover was assigned an impedance value of zero. The output raster populated all cells in the watershed with a buffer distance value except for stream pixels, which contained No Data (Fig. A.1d). We assigned stream pixels a distance value larger than the buffer maximum, then evaluated the minimum buffer width around each stream pixel using a *focalmin* function and a 3-by-3 cell neighborhood. The output raster contained the minimum buffer width to each particular stream cell within that stream pixel (Fig. A.1d). These results were isolated using an analysis mask.
3. *Optional Correction for Coarse Resolution Data*: Because the 30-m NLCD data was coarse enough to miss many stream channels, we felt it was important to evaluate land cover underlying the stream raster. This analysis would probably not be necessary with higher-resolution data because the location of streams would be better captured by land cover pixels. Using the stream raster as an analysis mask, we identified stream pixels underlain by forest or wetland cover using a conditional statement (the *con* function). All other stream pixels were assigned a buffer width of zero. For stream pixels underlain by for-wet cover, the value

of the minimum buffer with was augmented by one-half the cell size (15 m). The resulting raster was used to compute all buffer statistics.

The flow path method

1. *Flow Path Isolation*: The pathways between all cropland cells and the stream were isolated after the DEM was used to create a flow direction (*flowdirection* in ArcInfo) surface for the watershed. We used a weighted *flowaccumulation* function where each cropland cell contained a value of one and all other cells contained zero. By adding the weight raster values to the resulting flow accumulation surface, we created a raster where all non-zero values were involved in at least one source transport pathway. The zero values of this raster were converted to No Data and used to mask out all other land areas within the watershed (Fig. A.1e).
2. *Contiguous For-Wet Cover*: The following paragraph applies only to the optional correction for coarse resolution data. Using a series of eight nested conditional statements (the *con* function), we assessed the eight-directional *flowdirection* surface and evaluated land cover within the cell immediately downslope from each pixel using the ArcInfo *neighborhood notation* functionality. The output raster contained a value of one if the downslope pixel contained for-wet cover and a zero otherwise. We then used an analysis mask to assign a value of 1 to all cells not immediately adjacent to a stream pixel. The result was then multiplied by a binary for-wet cover raster to create a for-wet cover map where the value of for-wet pixels adjacent to the stream was adjusted to reflect whether the downslope stream pixel was underlain by for-wet cover.

   We created two *flowlength* maps from the stream upslope along the *flowdirection* surface. The first *flowlength* calculation was weighted so that only for-wet pixels (or adjusted for-wet) were measured; the second *flowlength* calculation used the entire watershed. If the two *flowlength* maps contained equivalent values, they indicated contiguous for-wet cover along a flow path (Fig. A.1f); this comparison was accomplished using the *con* function.
3. *Buffer Width*: We measured buffer width using a third *flowlength* calculation where length was measured downstream and weighted by the contiguous for-wet raster. Because the analysis was masked to include only flow paths originating at a cropland cell, the downstream *flowlength* measure assigned a buffer width to each cropland pixel (Fig. A.1f), which we augmented by one half the cell size to account for for-wet cover underneath the stream pixel. In this calculation, there were two diagonal measures that could result in decimal values (or multiples of these values) of buffer width. A diagonal cell traverse combined with a vertical or horizontal traverse led to a value of 1.2 cell widths, whereas two consecutive diagonal traverses led to a value of 1.4 cell widths (Fig. A.1f). We used a mask of all cropland cells to isolate width values for calculation of metric statistics.

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