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PLACEMENT OF RIPARIAN FOREST BUFFERS TO IMPROVE WATER QUALITY

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ABSTRACT

Riparian forest buffers can improve stream water quality, provided they intercept and remove contaminants from surface runoff and/or shallow groundwater. Soils, topography, hydrology, and surficial geology determine the capability of forest buffers to intercept and treat these flows. This paper describes landscape analysis techniques for identifying and mapping locations where forest buffers can effectively improve water quality. One technique employs soil survey and climate information to rate soil map units for how effectively a buffer would treat runoff. Results can be used to compare map units for relative effectiveness of buffer installations to improve water quality and, accordingly, to prioritize locations to support buffer establishment. Within watersheds, another technique uses topographic and stream-flow information to help identify specific locations where buffers are more likely to intercept water moving towards streams. For example, a wetness index, an indicator of potential soil saturation based on terrain, identifies where buffers can readily intercept surface runoff and/or shallow groundwater flows. Maps based on this index can be useful for site-specific buffer placement at farm and small-watershed scales. A case study utilizing this technique shows that riparian forests likely have the greatest potential to improve water quality along first-order streams, rather than larger streams. Some locations are better than others for improving water quality using riparian forest buffers. These landscape analysis techniques use public data and produce results that are broadly applicable to identify priority areas for riparian buffers. The information can guide projects and programs at scales ranging from farm-scale planning to regional policy implementation.

Keywords: Conservation practices, soil survey, terrain analyses, nonpoint pollution, conservation planning.

INTRODUCTION

Establishment of riparian buffers has been encouraged and financially supported by agricultural policies, partly because riparian vegetation has the potential to improve water quality. Many field-scale studies have shown buffers can improve water quality, and this literature is well reviewed (e.g., Dosskey 2001; Fennessy and Cronk 1997). Yet at watershed scales, where public concern about water quality is focused, the water quality impacts of conservation practices (such as buffers) are difficult to establish, and efforts are underway to document benefits from practices supported by public funds (Mausbach and Dedrick 2004). This will be difficult, largely because the efficacy of riparian buffers in controlling non-point pollution depends on location. A number of soil and landscape processes influence the movement of water across or beneath riparian zones towards a stream or river, and these processes all vary in time and space. Riparian forest buffers are installed to modify these processes in a way that can improve water quality, most typically by slowing water movement, encouraging infiltration, increasing nutrient uptake and storage, increasing transpiration, and promoting denitrification in the shallow subsurface. However, opportunities to alter these processes through management are not the same everywhere.

If buffers should be installed where they will have the greatest impact on water quality, then managers need techniques to help them identify these locations. The idea of targeting conservation practices to optimize their effectiveness is not new, and has been discussed in the literature for at least 20 years (Maas et al. 1985). Although examples in the research literature are rare, these types of assessments have been successfully applied at scales ranging from national (Johansson and Randall 2003) to individual landscapes (Bren 1998). However, methods to prioritize locations for buffer establishment using publicly available data across broad areas are still needed. In this paper, we present two techniques for using soil survey and digital terrain data to identify priority locations for establishment of riparian forest buffers.

SOIL SURVEY TECHNIQUE

National Soil Survey data contain information on soil types and topography that are important controls on a buffer’s capacity to filter pollutants from agricultural runoff. Soil surveys also map the locations of different soil types across agricultural landscapes. This technique uses a simple model to rate each soil type for the capacity of buffer vegetation to reduce pollutant load in surface runoff. Then, a soil map is used to locate the soil types where buffers will perform relatively better.

Method

A two-step model was developed for sediment trapping by buffers: (1) An equation for computing an initial value for a soil map unit based on soil characteristics and slope, and (2) a second equation to convert that initial value into sediment trapping efficiency of a buffer in that soil map unit.

The first equation obtains a sediment index (SI), and is based on information provided by a soil survey and utilizes parts of the Revised Universal Soil Loss Equation (RUSLE; Renard et al. 1997):

$$SI = D_{50} \,/\, R\ K\ L\ S \qquad (1)$$

where D_{50} is the median particle diameter of the surface soil, and R , K, L and S are rainfall and runoff erosivity, soil erodibility, slope length, and slope steepness factors from RUSLE, respectively. The value for D_{50} is assigned based on texture of the surface soil according to Table 1; R is obtained from the map in Figure 2-1 of Renard et al. (1997); K is obtained from tables in the county soil survey; L and S are computed according to Renard et al. (1997) for a 200 m field length using the mean of the slope range given for the map unit in the soil survey.

Table 1. Values for D_{50} used for calculating the sediment index (from Muñoz-Carpena and Parsons 2000).

Soil Texture Class	**D_{50} (mm)**
Clay	0.023
Silty clay	0.024
Sandy clay	0.066
Silty clay loam	0.025
Clay loam	0.018
Sandy clay loam	0.091
Silt	0.019
Silt Loam	0.027
Loam	0.035
Very fine sandy loam	0.035
Fine sandy loam	0.080
Sandy loam	0.098
Coarse sandy loam	0.160
Loamy very fine sand	0.090
Loamy fine sand	0.120
Loamy sand	0.135
Loamy coarse sand	0.180
Very fine sand	0.140
Fine sand	0.160
Sand	0.170
Coarse sand	0.200

The next equation uses the SI value to estimate Sediment Trapping Efficiency (STE, or percent of input load deposited in a buffer), a key output variable from the Vegetative Filter Strip Model (VFSMOD; Muñoz-Carpena and Parsons 2000). The VFSMOD model is a mechanistic, field-scale, single-event model that is based on the hydraulics of flow and of sediment transport and deposition. A regression was set up by calculating SI and STE for combinations of soil types, slopes, rainfall amounts representing a wide range of cultivated lands in the eastern US (Figure 1). In calculating both variables, standard conditions were assumed that include buffer design (12 m width with grass groundcover) and field conditions (200 m slope length; contour tillage with moderate residue; 2-yr frequency, 24-hr rainfall event for that location; wet antecedent soil conditions). The regression results were:

$$\text{STE} = 84.6\,(1.17 - \exp^{(-1320\ \text{Sediment Index})}) \qquad (2)$$

The excellent regression results ($R^2 = 0.94$) occur because both SI and STE account for the major variables that determine buffer effectiveness for trapping sediment in surface runoff. In general, effectiveness of a buffer depends on the magnitude of the runoff load and the capability of the buffer zone to promote deposition (Dosskey 2001; Helmers et al. 2002). Factors that produce larger runoff loads, such as higher rainfall, higher soil erodibility, and steeper slopes will reduce buffer effectiveness. Conversely, coarser-textured soils promote greater buffer effectiveness by infiltrating more rainfall and runoff, thereby reducing erosion and sediment transport capacity, and by producing larger sediment particles that are readily deposited. This regression equation allows soil survey information to be converted to STE, a mechanistic yet intuitive variable that can be used to interpret a buffer's capacity to trap sediment according to soil map unit, while holding slope length and event frequency constant.

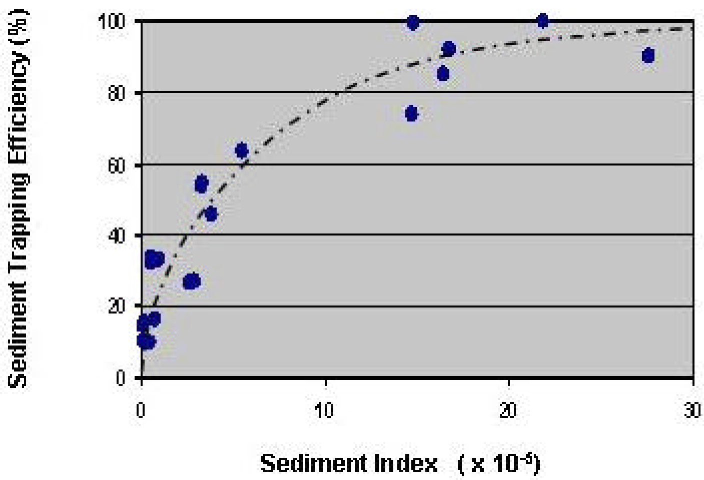

Figure 1. Comparison of sediment index values and corresponding values for sediment trapping efficiency (percent of input load deposited in the buffer) estimated using VFSMOD (Muñoz-Carpena and Parsons 2000). The fitted curve is given by Eq. 2.

Application

This technique is used by computing one value for sediment trapping efficiency for each soil-survey map unit in the area of interest using Equations 1 and 2. A difference between soil map units reflects inherent soil, slope, and rainfall conditions that affect sediment trapping by a buffer. These results can be used to base different recommendations for management in each soil map unit.

For example, two soil map units in a small watershed in northwestern Missouri (Figure 2), "Grundy Silt Loam, 2-5% slopes" and "Shelby Loam, 9-14% slopes" have estimated sediment-trapping efficiencies of 62% and 29%, respectively. The higher value for the Grundy soil is mainly because lower slopes produce smaller runoff loads and promote greater sediment deposition than steeper slopes of the Shelby soil. Based on these results, a manager may recommend sooner buffer installation and greater buffer width (than the 12-m standard) on the Shelby soil because, it is a greater source of sediment and a wider buffer will be needed to achieve the same percentage level of effectiveness as a 12-m buffer the Grundy soil. Optimal sites for other practices such as filter strips could be defined using these maps as well. The soil map covering this watershed (Figure 2) will help locate Shelby soils and others with relatively low sediment-trapping efficiencies.

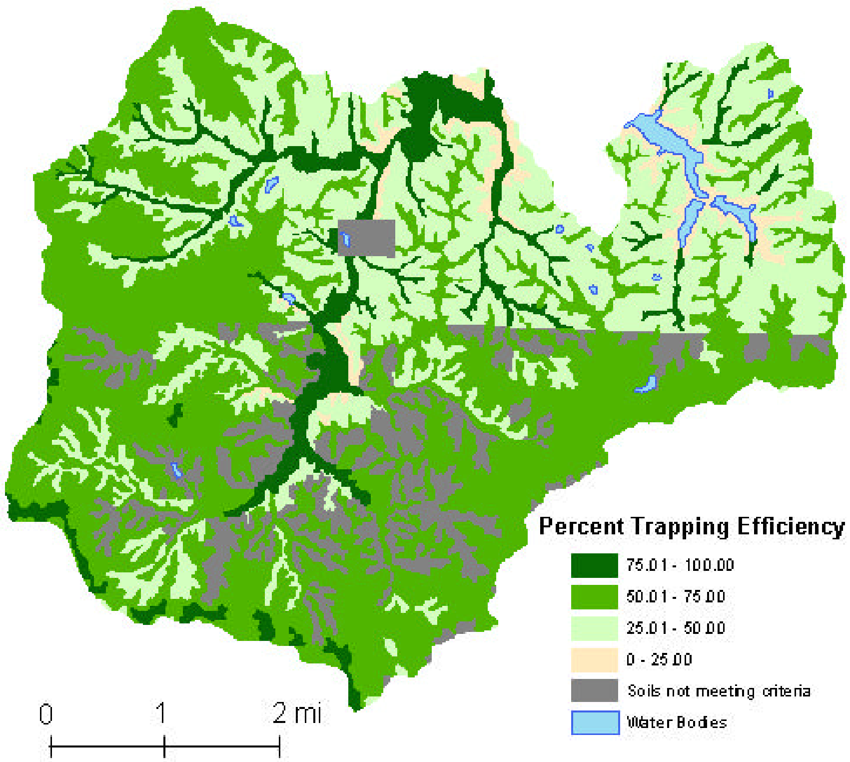

Figure 2. Sediment trapping efficiency of buffers under standard conditions for soil map units in the Cameron-Grindstone watershed (~ 25 sq. mi) in northwestern Missouri.

TERRAIN ANALYSIS TECHNIQUE

The National Elevation Database (USGS, 2004) is a 30-m raster topographic map for the entire US. These digital elevation model (DEM) data are derived from digitized quadrangle maps, which are typically at 1:24000 scale, similar to soil survey maps. USGS (2004) provide metadata on map sources, and Tomer et al. (2003) summarize source-map implications for data quality. Digital terrain analyses (Moore et al. 1991) can be applied to determine a range of landform parameters such as slope, aspect, upslope contributing area, and others that are defined below. Mapping these parameters provides images that reveal pathways of water movement and areas of water accumulation on the landscape. These maps can be classified and interpreted to identify priority sites for riparian buffers. Figure 3 depicts the key concepts in applying the techniques. These analyses have been applied to identify priority stream reaches (Burkart et al. 2004), and specific riparian zones for field-level planning (Tomer et al. 2003).

Methods

Stream-reach analyses were conducted for Silver and Keg Creek watersheds (western Iowa), and analyses of riparian locations at greater resolution were conducted in Tipton Creek (north-central Iowa). Slope (tan ß) and specific catchment area (A_s,) were used to calculate hydrologic indices (see Figure 3 and Moore et al. 1991). As is the upslope area that can possibly contribute surface runoff to a grid-cell, per width of flow (m^2 m^{-1}). Flow directions between adjacent cells were determined using the D- method (Tarboton, 1997) with software by D.G. Tarboton (http://www.engineering.usu.edu/dtarb/). The method proportions the upslope contributing area from each cell to two adjacent cells that define the direction of steepest descent (see Tarboton 1997). The terrain parameters were classified along each stream segment, according to stream order (Strahler 1969).

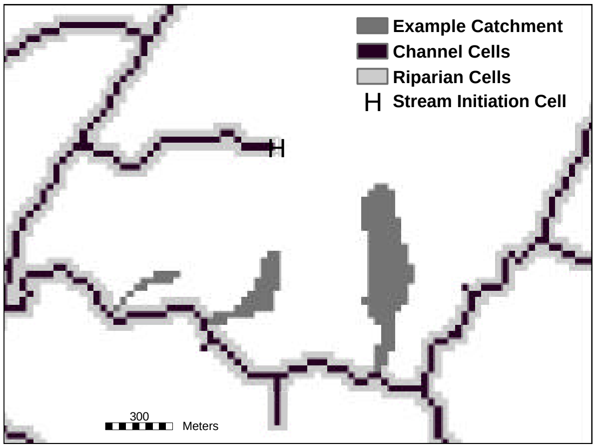

Figure 3. Examples of riparian catchments, channel cells, and riparian cells using 30-m cells in part of Keg and Silver Creek basins (Burkart et al. 2004).

Terrain parameters are defined and interpreted as follows. The discharge index (äq) indicates the proportional contribution of a riparian reach to the total stream discharge. This influence is estimated using contributing area ratios; i.e., äq is the ratio (per mille) of the riparian-cell catchment area to the catchment area of the stream.

$$\text{äq} = A_{rc}/A_c * 1{,}000 \qquad (3)$$

Simply interpreted, larger values of this index occur where riparian forest buffers are likely to *measurably* impact water quality in the stream.

The wetness index (W) is defined as:

$$W = \ln (A_s/\tan \hat{a}) \qquad (4)$$

Moore et al. (1991) derived this parameter to map areas most prone to soil saturation during rainfall events. Flat areas with large upslope contributing areas are associated with large W values. Buffers in these areas can remove contaminants from shallow groundwater, and/or filter surface runoff. Filtering of surface runoff can occur where slows and infiltrates in flat areas below hillslopes. Also, flat riparian areas tend to have shallow groundwater. In both situations, permanent vegetation (including trees) can benefit water quality. In some instances, however, shallow ground water approaches the surface and limits infiltration of runoff, therefore benefits for surface *and* subsurface flows may not accrue at all locations with large W values.

A sediment transport index (ô) can be used to locate riparian cells where deposition or erosion is likely (Moore et al. 1991):

$$ô = (A_s/22.13)^{.6} * (\sin â/0.0896)^{1.3} \quad (5)$$

where â is the slope of the riparian cell (in degrees). Small ô values occur in riparian areas where overland flow velocities are reduced and sediment can accumulate. The largest ô values represent erodible conditions and may indicate a need for protective measures such as streambank stabilization.

Application

Results of the stream-reach analyses in Silver and Keg Creeks clearly indicate that riparian buffers placed along first-order streams have the greatest potential to improve water quality. Discharge index (äq) values show that buffers along first-order streams provide significantly ($p < .05$) greater opportunities to produce a measurable affect on water quality in adjacent streams than do those along higher-order streams (Figure 4). Statistical comparisons show significant differences between all stream orders.

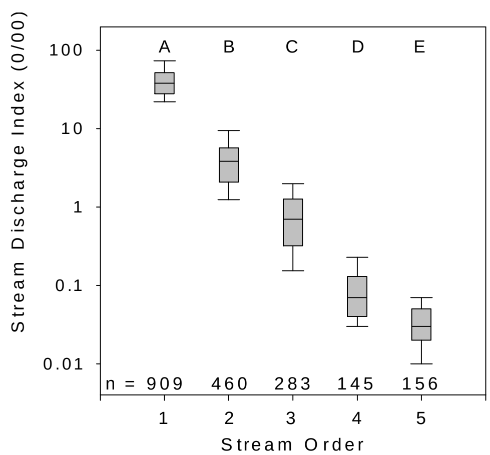

Figure 4. Mean discharge index (äq) values for 30-m riparian cells along stream segments in Keg and Silver Creek basins (Burkart et al. 2004).

Riparian-cells along first-order streams also had significantly larger values of A_s and W ($p < 0.05$) than those of larger streams (Figure 5) in Keg and Silver Creeks. Thus, interception of contaminants in groundwater and/or surface runoff will be most effective along first-order streams. The distributions of ô values (Figure 5) show a discontinuous increase with stream order. That is, riparian cells along stream orders one through three have significantly smaller values ($p < 0.05$) than stream orders four and five. Therefore, in these watersheds, riparian areas along smaller streams provide more deposition sites. Critical sites for erosion protection in riparian areas are indicated along the larger streams with large ô values (Figure 5).

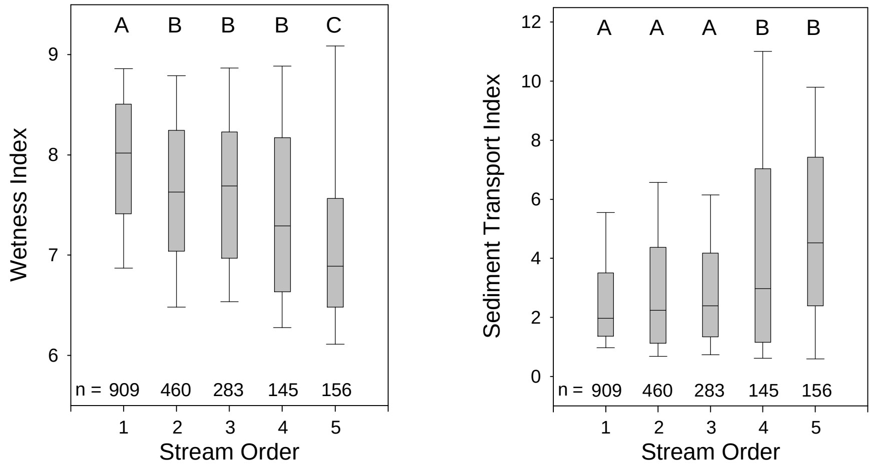

Figure 5. Mean values for wetness index (W, left figure), and sediment transport index (ô, right figure), for 30-m riparian cells along stream segments in Keg and Silver Creek basins in western Iowa (Burkart et al. 2004).

The wetness index can also be used to identify specific riparian zones where runoff or shallow groundwater flows can be intercepted (Figure 6). Similar maps for ô also highlighted locations with steep, actively eroding banks. These interpretations were confirmed through a field review with local conservation planners (Tomer et al. 2003).

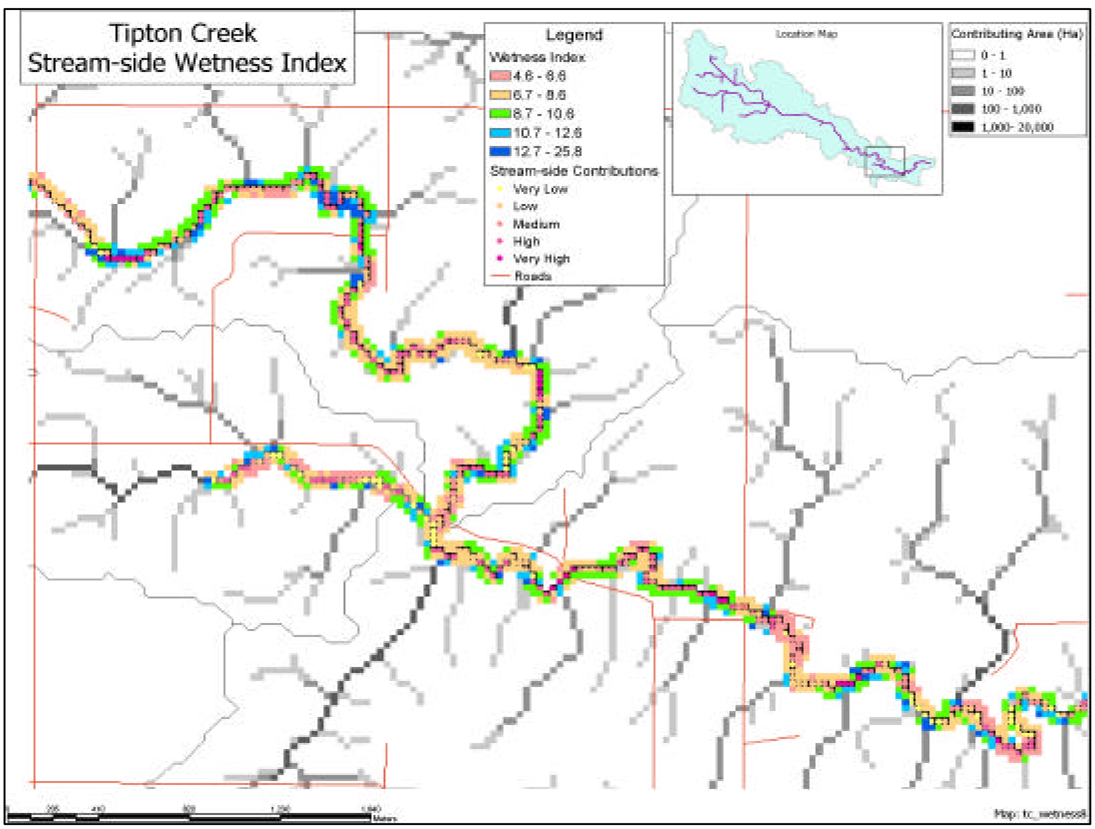

Figure 6. Map of riparian-cell wetness index values for a part of Tipton Creek (Tomer et al. 2003). Riparian areas with green and blue shading indicate where opportunities to intercept surface runoff and shallow groundwater with buffer vegetation are greatest.

Similar advantages and limitations apply to both types of methods. Both provide a standardized basis for comparing locations across watersheds, states, and regions in the eastern US soil survey map units can be one hectare or less, and individual DEM grid-cells represent 0.09 ha. Therefore, both techniques are capable of providing detailed spatial resolution. Optimal locations for installing buffers can be located easily by displaying computed results in maps. Calculations and mapping for large areas are readily accomplished using digitized databases for soil survey (USDA-NRCS 1994) and topography (USGS 2004) in a geographic information system (GIS). Both data sources are freely available to the public. The methods can also be applied at multiple scales, by varying the soil survey data source (i.e., STATSGO or SSURGO), or shifting the focus from individual riparian zones to stream reaches for DEM analyses.

Because simplifying assumptions are used in both methods, the techniques should be used only as a general guide for locating buffers. The soil survey method applies only to controlling sediment runoff from cultivated cropland. For terrain-modeling results, field review is needed to determine whether surface runoff or groundwater may be most influenced by buffers at specific locations (Tomer et al. 2003). This difference has implications for buffer design and species selection. Results are probably best used as a screening tool for planners to target locations where water-quality benefits are likely to accrue, and avoid locations where benefits are likely to be minimal.

CONCLUSIONS

Two ways of identifying priority locations for establishing riparian forest buffers for water quality improvement have been presented. Both soil survey and terrain data originate from maps created at similar scales (about 1:24,000). Therefore, it may be possible to use these two methods in concert to further enhance buffer planning. The soil survey method identifies where soil properties will best support buffer functioning where runoff can be intercepted. The terrain analysis method identifies where runoff can be intercepted. A combination of these two methods may help planners identify specific locations where buffers can achieve the maximum water-quality impact. Initial work has shown that soil survey and terrain analyses can provide consistent interpretations for conservation planning (Tomer and James 2004). Conclusions from work to date are:

1. Soil survey data can be used to identify locations where buffers are capable of trapping pollutants from surface runoff.
2. Terrain analyses can show where buffers will intercept more runoff. In general, better opportunities to intercept runoff and/or baseflow occur along first order streams than along larger streams.
3. Detailed maps of riparian zones can indicate specific locations best suited for buffers, and can be applied to field-scale planning.
4. Both the soil survey and terrain analysis techniques can be applied at varying scales. General availability of data also allows application in most areas in the US.

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