Spatial patterns of sediment and phosphorus in a riparian buffer in western Iowa

M.D. Tomer, T.B. Moorman, J.L. Kovar, D.E. James, and M.R. Burkart

Abstract: Riparian buffers prevent sediment and phosphorus (P) from reaching streams but their accumulation in buffers is seldom measured. This study's objectives were to determine accumulations of sediment and phosphorus in a multi-species riparian buffer and characterize spatial-temporal patterns of phosphorus in soil water and groundwater. The buffer was planted in 2000, below a steep-sloping field in row-crop production under no-tillage management in Iowa's Loess Hills. Topographic surveys were conducted in 2002, after the buffer was fully established, and again in 2005. Mapped differences in elevation showed sediment accretion was associated with concentrated flow pathways and lateral flow along the buffer-crop margin. About 32% of the buffer's outer switchgrass (*Panicum virgatum* L.) zone had sediment accumulations exceeding 4 cm (1.6 in), which totaled 14.5 Mg ha^{-1} (over three years) contributing area, or 4.8 Mg ha^{-1} yr^{-1} (2.1 t ac^{-1} yr^{-1}). Among five soil plots, total phosphorus in accreted sediment varied from 7 to 55 g m^{-2} (0.02 to 0.18 oz ft^{-2}) totaling 9.6 kg P ha^{-1} (8.5 lb P ac^{-1}) contributing area. Phosphorus concentrations in soil water were greatest beneath the switchgrass, compared to the crop and the buffer's inner vegetation zones ($p < 0.05$). Concentrations in soil water and groundwater were also greater where sediment accumulated, presumably due to increased infiltration of runoff. Sediment and phosphorus trapping occurred despite no-tillage management on the contributing hillslope and relatively dry conditions during the study. This emphasizes the importance of installing multiple, complementary conservation practices in sensitive environments. Considering seasonal risks of runoff when selecting buffer species and anticipated runoff patterns when designing buffer areas could reduce subsurface phosphorus losses through riparian areas.

Key words: agricultural runoff—conservation practice assessment—conservation targeting—phosphorus—riparian buffer—sediment

Riparian buffers are an important conservation practice widely used to protect water quality in a variety of environments (Dosskey 2001; Fennessy and Cronk 1997; Hill 1996). In agricultural landscapes, riparian buffers have the capacity to trap and remove a variety of contaminants including sediment, nutrients, pesticides, and pathogens (Barfield et al. 1998; Lee et al. 2003; Reungsang et al. 2001). However, the episodic timing of runoff events that transport runoff and contaminants from fields into buffers makes assessment of buffer performance difficult. Much of the published literature on buffer effectiveness is based on observations of few runoff events (Dosskey et al. 2002; Helmers et al. 2005), and cumulative assessments of buffer performance are rare. Exceptions include Daniels and Gilliam (1996) who reported 45% to 61% sediment trapping efficiency through two growing seasons in North Carolina, and Sheridan et al. (1999), who found 67% to 90% sediment trapping efficiency through four growing seasons in Georgia.

The effectiveness of buffers for removing sediment and associated contaminants is also difficult to measure because contaminant-transport pathways are spatially variable for flows both across the land surface (Dosskey et al. 2002) and beneath it (Simpkins et al. 2002). Many studies have used borders (or made similar attempts) to encourage uniform flow across research plots (Helmers et al. 2005). Yet, convergence of overland flow pathways is pervasive in buffers (Dosskey et al. 2002). This has been demonstrated even in a buffer that was mechanically graded for uniform distribution of surface irrigation water (Helmers et al. 2005). Moreover, the direction of tillage and row-cropping in the contributing field influences the proportion of a buffer that receives runoff (Dosskey et al. 2002).

Evaluations of phosphorus removal within buffers are typically focused on overland flow, which can readily be slowed to allow infiltration in a grass buffer unless the flows are concentrated into channels. Recent plot-scale research has shown buffers can remove large proportions of total phosphorus loads (or flow-averaged concentrations) in runoff. Removal efficiencies for total phosphorus of 78% to 91% were reported in Iowa (Lee et al. 2003), of 78% to 100% in Illinois (Schoonover et al. 2005), of 27% to 97% in Scandanavia (Uusi-Kamppa et al. 2000), and of 56% to 67% in Georgia (Lowrance and Sheridan 2005). Sediment trapping is generally regarded as the chief mechanism for phosphorus retention in buffers (Dosskey 2001). However, subsurface transport of phosphorus has been documented (e.g., Fortune et al. 2005; King et al. 2006) and ecologically significant concentrations of dissolved phosphorus in groundwater have been reported in the US Midwest (Burkart et al. 2004). There is little information about riparian-buffer effects on phosphorus in the subsurface.

Opportunities to map sediment accumulations in a riparian buffer are rare. Observed changes in the volume and sediment concentration of runoff passing through a buffer are typically used to estimate sediment trapping. Terrain analyses can indicate where sediment is most likely to become trapped in a buffer at a variety of scales (e.g., Helmers et al. 2005; Tomer et al. 2003). Yet, actual spatial patterns of sediment accumulation over time are seldom measured. The primary objective

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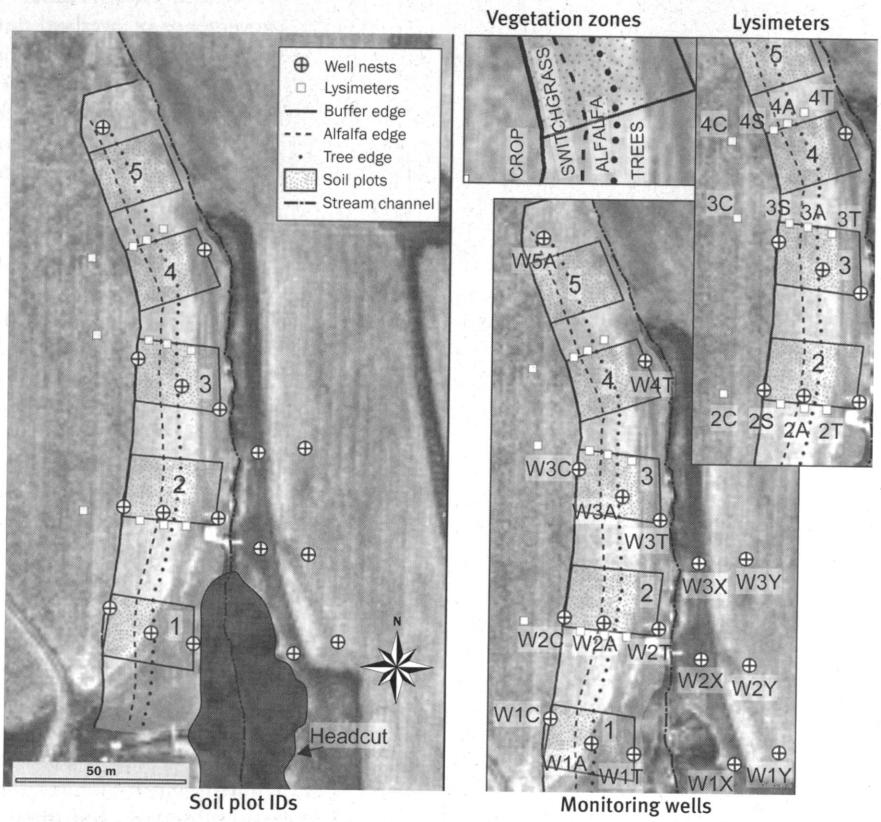
Figure 1

Left: Map of riparian buffer showing soil plots (labeled 1 through 5), monitoring installations, and large gully headcut below the buffer. Right: Three cut-out maps showing labels for vegetation zones, lysimeter IDs, and monitoring wells.



Notes: IDs associate installations with soil plot (typically in transects) and with vegetation zone (C = crop, S = switchgrass, A = alfalfa/brome, T = trees). X and Y = wells on nonbuffered side of the stream.

of this study was to map and thereby quantify sediment accumulation in a riparian buffer by comparing two sequential topographic surveys. Additional objectives were to quantify phosphorus stored in the trapped sediment and to identify spatial-temporal patterns of phosphorus in soil water and in shallow groundwater following the establishment of a multi-species riparian buffer.

Materials and Methods

Site Description. The research was conducted at the Deep Loess Research Station near Treynor, Iowa, in watershed 1, with 27.6 ha (68.2 ac) of runoff-contributing area (Kramer et al. 1999). Soils were developed in deep (10 to 25 m [33 to 83 ft]) uniform loess and loess-derived alluvium (Karlen et al. 1999). Based on a first-order soil survey (Charles Fisher, unpublished data, 1970), soils are primarily Typic Hapludolls (Monona series), Typic Udorthents (Ida and Dow series), and Cumulic Hapludolls (Napier and Kennebec series) (Soil Survey Staff 2003). Land use in the watershed is well documented, with a research history dating back to the 1960s (Karlen et al. 1999). This watershed was managed in continuous corn and conventional, full-width tillage from 1963 through 1995. Soil erosion is a major soil-resource issue in Iowa's Loess Hills, and documenting erosion and runoff under conventional tillage in this watershed was a focus of research during this time (Kramer et al. 1999; Tomer et al. 2005). The consequent impacts of long-term conventional tillage on soil-landscape relationships have also been described (Cambardella et al. 2004; Moorman et al. 2004; Tomer et al. 2006).

In 1996, a corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.) rotation was initiated with no-tillage management. There were light rotary cultivations to control weed seedlings in emerged crops in 2001 through 2003, but these did not reduce residue cover and were the only operations that disturbed the soil surface other than seeding and fertilizing. There were split applications of commercial nitrogen fertilizer to corn, with formulations varied among years, at application rates determined based on monitoring of available soil nitrogen and realistic yield goals. Fertilizer applications banded at seeding included phosphorus rates that replaced crop uptake (20 to 25 kg ha^{-1} [about 20 lb ac^{-1}]) through the year 2000. There were no manure applications.

In autumn 2000, a multi-species riparian buffer was planted along the west side of the watershed's stream, above a large headcut (figure 1) that defined the stream origin (Thomas et al. 2004). The buffer area was level, below the foot of the adjoining slope, with its soil mapped as the Kennebec Series with 0% to 2% slopes. The multispecies buffer was composed of three strips of vegetation, including switchgrass (*Panicum virgatum* L.) at the crop-field edge (5 m [16.4 ft] wide), a brome and alfalfa mix (*Bromus inermis* L. and *Medicago sativa* L.) in the intermediate position (5 m [16.4 ft] wide), and four rows of poplar (*Populus deltoides*) with one row of walnut trees (*Juglans nigra* L.) planted in the center. The poplars were transplanted rooted cuttings and were 20 to 30 cm (8 to 12 in) high. Timothy (*Phleum pratense* L.) was sown as an understory ground cover beneath the trees. The tree zone of the buffer was 15 m (49 ft) wide. The contributing area of cropland upslope of the buffer was 2.8 ha (6.9 ac), and the total area of the buffer was 0.44 ha (1.1 ac), including 0.13 ha of switchgrass, 0.08 ha in alfalfa-brome, and 0.23 ha in trees (0.3, 0.2, and 0.6 ac, respectively). The buffer was not harvested, although the switchgrass zone of the buffer was mowed during the first year (2001) to help control weed competition with this slow-establishing species. Also, the alfalfa-brome mix was re-seeded in spring 2002, and all planted species became successfully established with essentially full ground cover that year. Kelly et al. (2007) provided biomass data for the experiment.

Sampling and Measurements. Five plots were established in the buffer (figure 1), where soil samples were collected by vegetation zone in May 2001 and July 2005. Soil samples were collected from 0 to 5, 5 to 15, and 15 to 30 cm depth intervals (0 to 2, 2 to 6, and 6 to 12 in). Within each vegetation zone and plot, eight cores were taken with a 3.7 cm (1.48 in) diameter hand probe

to 30 cm depth, segregated by depth interval, and bulked for analysis. Samples were analyzed for available phosphorus using an exchange-resin method (Abrams and Jarrell 1992). For samples collected in 2005, total soil phosphorus was determined following the method of McGrath and Cunliffe (1985), through sample digestion with concentrated HCl/HNO_3, followed by measurement using a plasma spectrometer.

Seventeen piezometric monitoring wells (shown in figure 1) were installed prior to buffer installation as described by Tomer and Burkart (2003) and sampled as described below. Wells labeled W5A and W2T (figure 1) were installed during 1996; all others were installed during 1999. These installations were multi-depth piezometer nests with 60 cm (2 ft) screened intervals. However, here we only report results from the shallowest piezometers (monitoring wells) that were screened to intercept the water table, in order to best indicate any responses of shallow groundwater phosphorus concentrations to buffer installation. Herein, these wells are identified according to the closest soil plot (see figure 1). In spring 2001, pairs of ceramic-suction-cup soil-water samplers were installed within each vegetation type, including the crop, at a 1.5 m (5 ft) depth along transects near the edge of soil plots 2, 3, and 4 (figure 1). This installation depth was about 0.5 to 1.0 m (1.6 to 3.3 ft) above the water table.

Water samples were collected from the wells on a quarterly basis and from the suction lysimeters on a monthly basis, except when lysimeters could not yield sufficient water volumes for analysis (during dry or frozen soil conditions). When sampling groundwater, at least 1.5 well-volumes of water were purged prior to sample collection. Water samples were filtered at the time of field collection through a 0.45 μm filter and analyzed for dissolved P concentration using a flow injection analysis technique (O'Dell 1993) with a minimum quantitation limit of 0.01 mg L^{-1} (0.01 ppm).

Detailed topographic surveys of the switchgrass zone of the buffer were conducted in August 2002 and September 2005 using a Trimble 4700 real-time kinematic survey-grade global positioning system (GPS) with an onsite reference base station. Elevations were obtained using real-time kinematic methods, with about one observation recorded per square meter in both surveys. Check runs were used during the surveys to ensure consistent accuracies, which were within 2 cm (0.8 in) horizontal and vertical (maximum error). Prior to the first survey, a local network of benchmarks was established using historic USDA benchmarks in the watershed and a series of concrete filled pipes installed in the buffer area. The concrete pipes were set to 3 m (10 ft) depth to be below frost depth and included a diameter increase at 1.5 m (5 ft) to minimize settling. These concrete benchmarks were surveyed using fast-static GPS methods and post-processing to achieve 5 mm (0.2 in) horizontal and vertical accuracies. At the second (2005) survey, relative elevations of the buffer benchmarks were verified with a double-run auto-level survey to be within 0.9 mm (0.035 in) of their original elevation.

These surveys were focused in the switchgrass zone of the buffer adjacent to the cropland, where sediment trapping was expected to be greatest. Switchgrass often takes two years to establish a full ground cover, and the first survey coincided with the time of establishment of essentially full cover of the planted species throughout the buffer. The time interval between the surveys, therefore, includes the three years of the study when sediment trapping in the switchgrass would have been most effective. The GPS survey of the buffer in 2005 included the contributing hillslope, from which a 2 m (7 ft) grid digital elevation model (DEM) was constructed to evaluate slope distributions and overland flow pathways, as discussed below.

Data Analysis. Topographic data obtained from the two surveys were converted to a 0.5 m (1.6 ft) grid elevation model by direct triangulation of the survey points, through a triangulated irregular network to grid conversion in ArcGIS 9.1 (ESRI 2006). This method of interpolation minimized edge errors and smoothing of the original survey data, which occur with other methods such Kriging or trend-surface analysis. It was particularly important to avoid edge errors given the narrow width of the survey area. Elevation differences between the 2002 and 2005 surveys of the buffer were calculated by overlay and subtraction of the two grids. These differences, an indicator of sediment accretion and its spatial pattern in the buffer, were compared to the distribution of runoff flow pathways from the upslope cropland toward the buffer. These pathways were identified using terrain analysis. The 2 m (7 ft) grid DEM of the hillslope above the buffer was used to produce maps of specific contributing area (A_s) and slope using terrain analysis methods described by Tarboton (1997). A map of A_s revealed pathways of concentrated runoff from the hillslope to the buffer, which were visually compared patterns of sediment accumulation.

Sediment accretion was converted from volume to mass using a bulk density of 1.24 Mg m^{-3} reported for surface soils in this watershed (Tomer et al. 2006), with a standard deviation (sd) of 0.10 Mg m^{-3}. This is near the value of 1.28 Mg m^{-3} (sd = 0.11) reported by Rachman et al. (2004), who also found a bulk density of 1.22 Mg m^{-3} (sd = 0.14) within switchgrass hedges located immediately south of the contributing hillslope to the buffer. Soil samples collected in the buffer for this study (as described above) had an average bulk density of 1.33 Mg m^{-3}, but several large values, presumed due sampling error, created a larger standard deviation for this estimate.

To place the estimate of total sediment trapped in context, the sediment discharge record from the watershed was summarized. Sediment discharged was measured through runoff-event sampling at a weir placed across the stream about 100 m (330 ft) downgradient from the buffer. This event-monitoring scheme was described by Kramer et al. (1999) and continued through 2004. We only considered the sediment record subsequent to 1975, when 6.0 ha (14.8 ac) of the watershed had grass filter strips installed. Sediment discharge from that area was then monitored separately, and we subtracted that discharge to ensure consistency of the record. Runoff volumes and sediment mass losses were summed for each runoff event, including estimates of sediment loss from events in 2005. This watershed sediment record is not a direct validation of the sediment accumulation estimates for the buffer but does provide independent data to place the estimates in context.

Soil phosphorus accumulations were calculated for each plot by multiplying average sediment accretion by total soil phosphorus concentration (0 to 5 cm [0 to 2 in]) in the switchgrass zone. Conversion to total mass again assumed a bulk density of 1.24 Mg m^{-3}. Dissolved phosphorus concentrations in soil water collected from the suction-cup

lysimeters were compared among vegetation zones and soil plots by applying multi-factor analysis of variance to the results across all dates. A log transform was applied to dissolved phosphorus data to meet normality assumptions. Differences among vegetation zones were tested using type–3 sums of squares, after removing date and plot (transect location) effects, and means were compared using Duncan's multiple range test. These analyses were conducted using SAS/ANALYST (SAS Institute 1999). Analysis of groundwater phosphorus concentration data was based on plots of temporal and topographic patterns found in groundwater east (unbuffered) and west (buffered) of the stream. This approach provided better insight than comparisons among vegetation zones.

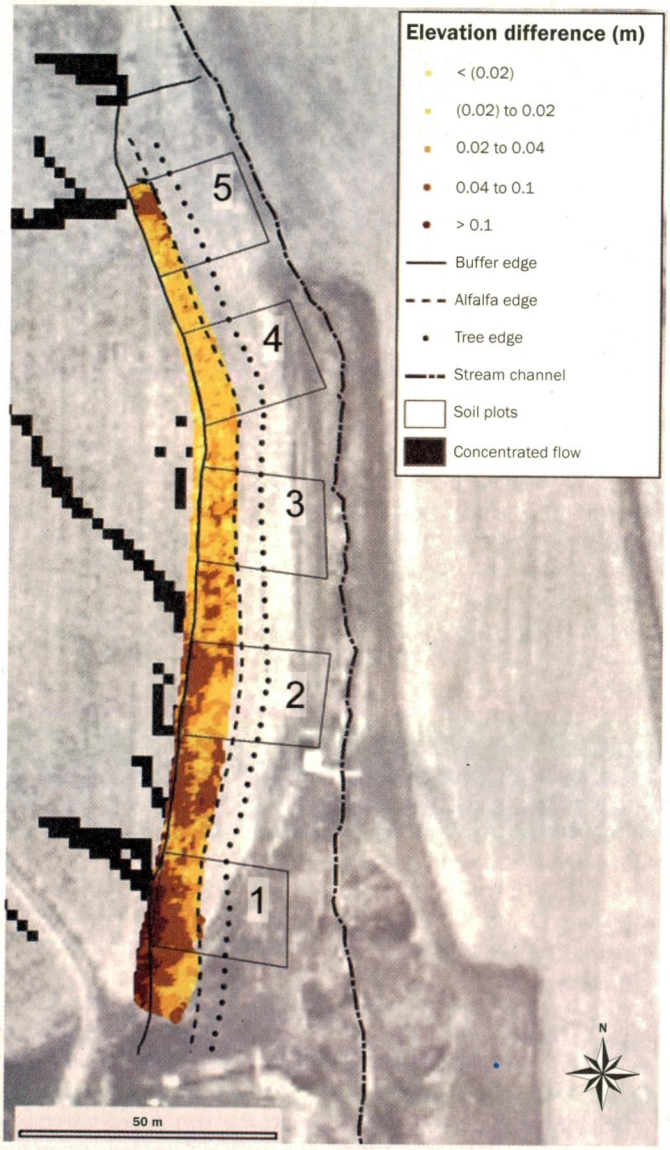
Results and Discussion

Hillslope Survey. The topographic survey of the hillslope above the buffer, conducted in 2005, showed the contributing area was 2.8 ha (6.9 ac). Only 26% of the slopes had less than a 5% grade, when measured in the direction of steepest descent (Tarboton 1997). A third of the area had 5% to 9% slopes, 24% had 9% to 14% slopes, and 18% had 14% to 20% slopes. Given the erodibility of the silt-loam textured soils, the distribution of slopes emphasizes the susceptibility of this landscape to runoff and erosion. The total buffer area of 0.44 ha (1.1 ac) resulted in a buffer/cropland area ratio of about 0.16. This ratio is within the range reported for a variety of other buffer studies (Dosskey et al. 2002).

Sediment Accretion. Surface elevations measured in 2002 and 2005 within the switchgrass zone of the buffer (total area of 1,300 m^2 [14,000 ft^2]) differed between –0.07 and +0.21 m (–0.23 and +0.69 ft) (figure 2). An elevation increase of 0.02 m (0.8 in) was the modal value of the elevation differences (figure 3), and the average elevation increased by 0.035 m (1.4 in) between 2002 and 2005. Values near zero (±0.02 m) occupied about 39% of the area and dominated the area around plots 3 and 4. We regard these near-zero values to indicate little, if any, erosion or deposition. Negative values less than –0.02 m, indicating that a decrease in surface elevation occurred, occupied only 2% of the surveyed buffer area. These decreases mostly occurred along the outer edge of the buffer near plots 3 and 4 and may have resulted from erosion by laterally flowing runoff along the edge of the buffer (figure 2) and/or possibly wheel-traffic compaction at the edge of the cultivated area associated with normal farming operations. However, there was no obvious wheel rutting, and traffic across the buffer during the experiment was limited to that required for research activities.

Figure 2

Map showing the spatial distribution elevation differences in the switchgrass zone of the buffer, indicative of sediment accretion.



Note: Concentrated flow pathways from the adjacent hillslope are shown in black; the shaded grid cells have specific contributing areas greater than 75 m^2 m^{-1}.

Elevation increases exceeding 0.02 m (0.8 in) occupied most (59%) of the switchgrass-planted buffer area. We attribute these increases largely to sediment accretion with minimal litter accumulation (perhaps 1 to 2 mm [0.04 to 0.08 in]), and no significant transport of crop residue from the field into the buffer was observed. Less than half of the values >0.02 m (27% of the total) showed elevation increases between 0.02 and 0.04 m (0.80 to 1.6 in), indicating moderate deposition occurred. However, about one third of the survey area (32%) showed elevation increases exceeding 0.04 m, and 6% showed sediment accretion of >0.1 m (3.9 in). Because re-surveying of the benchmarks within the buffer in 2005 involved excavating up to about 10 cm (3.9 in) of

Figure 3
Histogram of elevation differences between 2002 and 2005, with vertical dashed lines demarking classes shown in the map in figure 2.

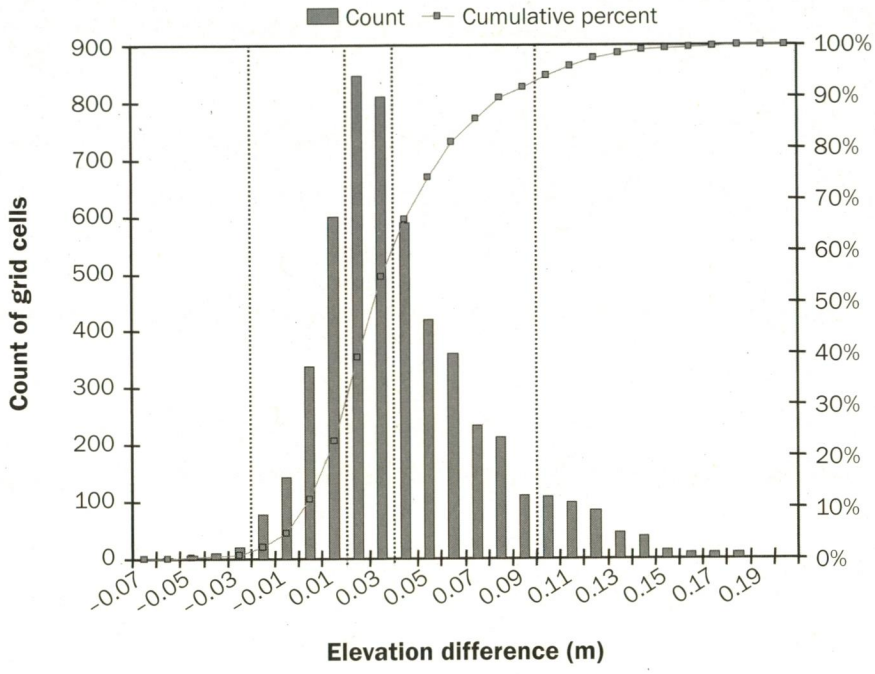
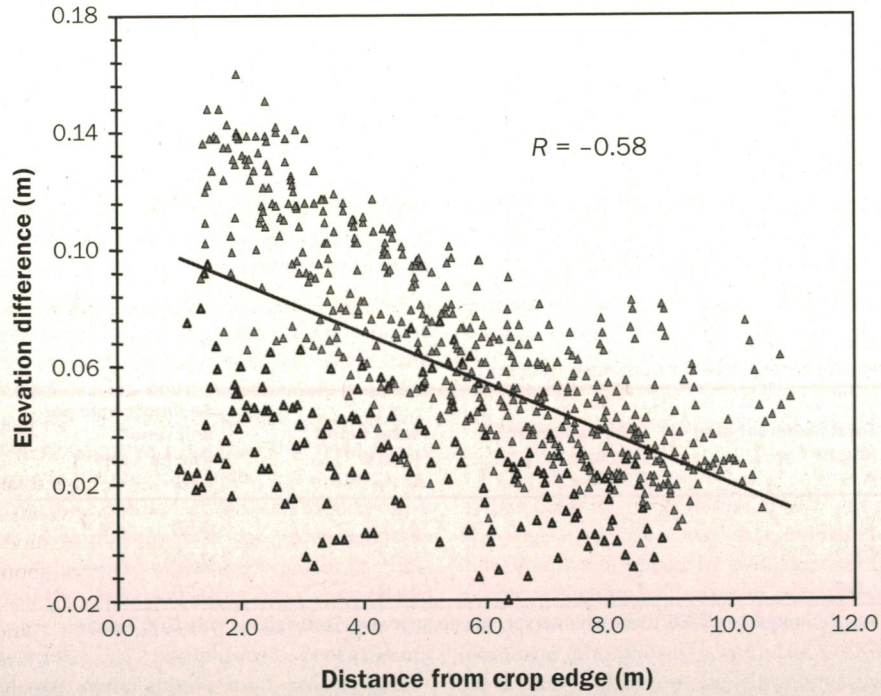


Figure 4
Elevation differences between 2002 and 2005 decreased with increasing distance from crop edge in plot 1 ($p < 0.0001$), as plotted here.



Note: Correlation coefficients for all plots are given in table 1.

sediment to expose the benchmarks, which were all confirmed to be within 0.9 mm (0.035 in) of their original elevation in 2002, accumulation of trapped sediment is assumed to be responsible for the increases in surface elevation.

A map of changes in elevation between 2002 and 2005 (figure 2) also shows concentrated flow pathways from the contributing hillslope (specific contributing area [S_c] greater than 75 m^2 m^{-1} [250 ft^2 ft^{-1}]). Based on these flow pathways, most sediment accumulation would be anticipated in/around plots 1, 2, and 5 (figure 2) as the elevation differences show. The pattern of sediment accumulation around plots 1 and 2 also suggests some lateral flow of runoff along the edge of the buffer occurred and transported sediment along the buffer edge to the southern end of the buffer. Visual field observations after runoff events also support this interpretation. The pattern of sediment accumulation also shows that accretion decreased from the edge of the buffer towards the stream in plots 1 and 2 but not in the other plots (table 1, figure 4). This provides further evidence that elevation increases found around plots 1 and 2 are due to accretion of sediment delivered with runoff from the cropped hillslope.

Summing all elevation differences results in a volume difference of +45.53 m^3 (1,607 ft^3), or about 56.5 Mg (62.3 t) assuming 1.24 Mg m^{-3} density. Including only elevation increases greater than 0.02 m (0.07 ft) in the summation, the volume difference is 43.3 m^3 (1,528 ft^3). To obtain a conservative estimate of sediment trapping, we summed only the grid cells with >0.04 m (>0.13 ft) elevation increase. This third of the survey area trapped an estimated 32.7 m^3 (1,154 ft^3) (40.6 Mg [44.7 t]) of sediment, or 14.5 Mg ha^{-1} (6.50 t ac^{-1}) of contributing area (or 4.8 Mg ha^{-1} yr^{-1} [2.1 t ac^{-1} yr^{-1}]). This figure represents those areas where the elevation increase exceeds the maximum expected error from the surveys, as described below. We use this conservative value in subsequent discussion of total sediment accretion across the switchgrass zone of the buffer. The sediment accumulation was at least 40% of "tolerable" soil loss as defined by the USDA Natural Resources Conservation Service (NRCS). Therefore, optimal erosion control on row-cropped hillslopes in the Loess Hills region may require complementary, edge-of-field conservation practices, such as buffers, in addition to good residue management.

Table 1
Correlation coefficients *(R)* between sediment accretion (elevation difference) and distance from buffer edge in five soil plots.

	Soil plot 1	Soil plot 2	Soil plot 3	Soil plot 4	Soil plot 5
R	-0.58	-0.50	0.10	0.22	0.14

Note: Large negative values indicate greatest sediment accretion at the crop edge of the buffer in plots 1 and 2 (plot 1 data are graphed in figure 4).

Note that an exact error analysis of the sediment accretion is not possible because we did not exactly duplicate the points surveyed in 2002 for the 2005 survey (due to time constraints). However, if the standard error of a grid cell's elevation is 1.0 cm (0.4 in [half the maximum measurement error of the survey]), then the elevation difference between the surveys, for an individual grid cell, has a standard error of 1.4 cm ($[1^2 + 1^2]^{0.5}$). Therefore, our conservative figure only sums elevations that exceed zero by at least 2.9 standard deviations. Also, the average sediment accretion of 3.5 cm (1.4 in) was 2.5 standard deviations greater than zero. Note that if the standard error of the elevation increase is divided by the root of the number of independent observations to obtain the standard error of the mean, that error is only a few percent, even if the number of independent observations is a fraction of the 5,200 grid cells. However, conversion of volume to mass increases that standard error by 8% to 11%, based on the bulk density information given above.

To put the estimates of sediment accumulation in the buffer in context, we summarized the watershed's stream-discharge sediment record. Between 1975 and 1995, when the watershed was conventionally tilled, annual sediment losses were 20.7 Mg ha^{-1} (9.2 t ac^{-1}), or 0.50 Mg ha^{-1} mm^{-1} (5.7 t ac^{-1} in^{-1}) of runoff (Kramer et al. 1999). Implementation of no-tillage led to decreased sediment losses from 1996 through 2001 (table 2), although four of the five largest runoff events recorded after 1975 occurred during this period, each exceeding 50 mm (2.0 in) runoff. Despite a substantial increase in annual runoff volume during these years, sediment production decreased by about a third on a runoff-weighted basis (table 2).

The watershed's runoff and sediment losses from 2002 through 2005 included data from 42 runoff-hydrograph events, which only delivered a total 51 mm (2.0 in) of runoff. Of this total, 47 mm (15.8 mm yr^{-1}) was discharged during the period between the elevation surveys (see table 2). This was a droughty period, and obviously, climate variation limits our ability to assess combined effects of no-tillage and buffer practices on sediment yield by comparing time periods. Garbrecht et al. (2006) discuss this issue in detail. The watershed's sediment yield value for 2002 to 2005 (table 2) includes measurements through 2004 and estimates from 13 events during 2005 that totaled 8 mm (0.3 in) of runoff, assuming the sediment-loss rate observed for 2002 to 2004 (0.28 Mg ha^{-1} mm^{-1} [3.2 t ac^{-1} in^{-1}]).

Gully headcutting and soil erosion are major resource problems in the Loess Hills region (Prior 1991). Expansion of the headcut gully in this watershed was an important source of sediment losses from this watershed and was described by a regression model with an R^2 of 0.96 (Thomas et al. 2004):

$$V = 11180 \times (1 - e^{-0.037t}), \quad (1)$$

where V is volume (m^3) of gully expansion and t is years since 1964. This model provides estimates of gully contributions (table 2), which comprised a major fraction of the watershed's total sediment loss but declined over time.

When totaled from August 2002 through September 2005, the watershed's estimated sediment loss (4.4 Mg ha^{-1} yr^{-1} [2.0 Mg t ac^{-1} yr^{-1}]) is similar to the buffer's estimated sediment accretion (4.8 Mg ha^{-1} yr^{-1} [2.2 Mg t ac^{-1} yr^{-1}]). This close match is clearly coincidental; comparison of these figures cannot account for headcut erosion, which was not measured after 2000, nor accumulated sediment that may have been deposited in the buffer's location had it not been planted. Nevertheless, the estimated sediment trapping obtained from the elevation differences appears reasonable in context with the watershed's sediment losses.

To further put these sediment accumulations in perspective, Gilley et al. (2000) conducted a rainfall simulation study of runoff and erosion in this watershed but found erosion losses from no till plots were 0.05 Mg ha^{-1} mm^{-1}, (0.6 t ac^{-1} in^{-1}) much less than the calculated rate of sediment accumulation in the buffer. Nearly 20% of the contributing slopes were greater than the 14% slope plots in Gilley et al. (2000) study. Yet, we believe that concentrated flow, rather than sheet-and-rill erosion, is the major process transporting sediment from the slopes in this watershed. Visual observations of gully formation on this slope, in areas indicated as concentrated flow pathways in figure 2, support this interpretation.

Table 2
Sediment losses from the watershed and the gully headcut during three time periods.

Period	Management	Total sediment load (Mg ha^{-1} yr^{-1}) A	Gully sediment (Mg ha^{-1} yr^{-1}) B	Total runoff (mm yr^{-1}) C	Sediment load per unit runoff (Mg ha^{-1} mm^{-1}) A/C
1975 to 1995	Conventional tillage	20.7	8.7	41.1	0.50
1995 to 2001	No tillage	28.2	5.3	85.7	0.33
2002 to 2005*	No tillage, established buffer	4.4	†	15.8	0.28

* Only includes runoff observed from August 2002 through September 2005 to match interval between surveys. Total sediment for 2005 was estimated (see text).

† Not measured.

Notes: Annual gully sediment is the average per year based on equation 1 (Thomas et al. 2005). Note that total sediment load (A) includes gully sediment (B) and that the final column can be calculated by dividing total sediment (A) by total runoff (C).

Phosphorus in Soil and Trapped Sediment. Plant-available (resin exchangeable) phosphorus concentrations tended to decrease 10% to 20% between soil samplings in 2001 and 2005, at all vegetation zones and depths (table 3). These changes were not statistically significant, but the trend could result from uptake and cycling of phosphorus by buffer vegetation, reported by Kelly et al. (2007). In 2005, total phosphorus concentrations found in the switchgrass zone at the soil surface (0 to 5 cm [0 to 2 in]) averaged 720 mg kg^{-1} and varied between 660 and 790 mg kg^{-1} (ppm) among the plots. The largest total phosphorus concentrations were found in plots 1 and 2 (757 and 790 mg kg^{-1}, respectively), where the sediment accretion by the switchgrass was also greatest (figure 2). Based on average sediment accretion and total phosphorus concentration found in the switchgrass zone of each plot, the amount of P trapped in accumulated sediment varied considerably, from 7 to 55 g P m^{-2} (0.02 to 0.17 oz ft^2; table 4). A conservative estimate of total phosphorus trapped in the switchgrass zone is obtained by taking 40.4 Mg (44.4 t) total sediment accumulation times the average of 662 g P Mg^{-1} (662 ppm) found at 5 to 15 cm (2 to 6 in) depth in the switchgrass zone of the buffer. We thereby estimate that the buffer trapped 26.7 kg (58.7 lb) of phosphorus from 2002 through 2005 or about 9.6 kg P ha^{-1} (8.6 lb ac^{-1}) of contributing area.

Phosphorus in Soil Water. Phosphorus concentrations in soil water collected from suction-cup lysimeters (table 5) were greater beneath the switchgrass, compared to all other vegetation zones, and beneath areas where sediment accumulation was greatest (i.e., transect 2 compared to transects 3 and 4). These areas of the buffer would be expected to accumulate runoff from the adjacent slope, have greater infiltration, and have greater movement of soil water (and phosphorus) to depth. Interestingly, the water beneath the switchgrass had greater phosphorus concentrations than that beneath the crop ($p < 0.05$; see table 5). Switchgrass is a warm-season C4 grass that produces most of its biomass later in the growing season than the other vegetation types in the buffer. This difference in timing of growth and water uptake probably contributes to the difference in phosphorus concentrations because switchgrass is most actively growing after the time of crop canopy closure, when the crop attenuates runoff anyway.

Table 3
Resin-exchangeable soil phosphorus in 2001 and 2005 and total soil phosphorus in 2005 at three soil depths in each vegetation zone of the buffer.

Vegetation zone	Soil depth (cm)	Resin-exchangeable P (mg kg^{-1}) 2001	Resin-exchangeable P (mg kg^{-1}) 2005	Total P (mg kg^{-1}) 2005
Switchgrass	0 to 5	49 (9)	45 (10)	720 (52)
	5 to 15	31 (14)	25 (6)	662 (92)
	15 to 30	23 (12)	17 (6)	624 (74)
Alfalfa-brome	0 to 5	55 (15)	43 (15)	721 (81)
	5 to 15	31 (10)	25 (4)	665 (60)
	15 to 30	23 (9)	18 (5)	663 (93)
Trees	0 to 5	54 (11)	46 (17)	704 (109)
	5 to 15	30 (13)	23 (13)	657 (73)
	15 to 30	21 (12)	17 (11)	615 (53)

Notes: Results are mean values of five soil plots. Standard deviations are given in parentheses. No significant differences existed among years or vegetation zones at any soil depth.

Table 4
Estimates of phosphorus trapped by sediment accumulation in the switchgrass zone of the buffer based on mean sediment accumulation (elevation increase) and total soil phosphorus found at 0 to 5 cm in 2005.

Soil plot	Volume sediment accumulation (m^3 m^{-2})	Mass sediment accumulation (Mg m^{-2})	Total P at 0 to 5 cm depth (g Mg^{-1})	Mass P accumulation (g m^{-2})
1	0.059	0.073	757	55
2	0.040	0.049	790	39
3	0.016	0.020	693	14
4	0.008	0.010	702	7
5	0.029	0.036	660	24

Table 5
Phosphorus concentrations in water collected from suction-cup lysimeters shown as geometric mean values of all sampling dates for each vegetation zone and transect.

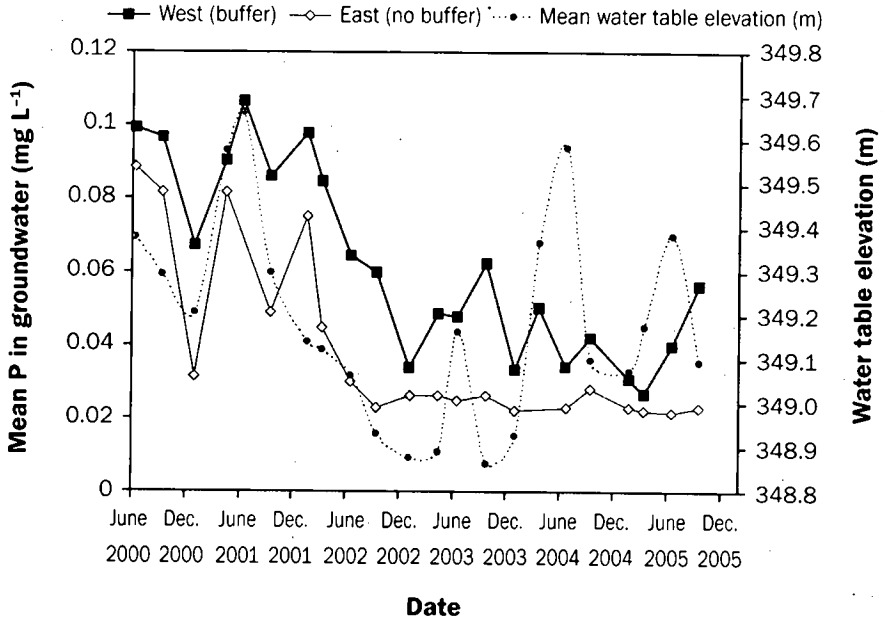
Vegetation zone	Transect 2 (mg L^{-1})	Transect 3 (mg L^{-1})	Transect 4 (mg L^{-1})	Vegetation zone mean (mg L^{-1})
Crop	0.03	0.05	0.04	0.04c
Switchgrass	0.15	0.06	0.05	0.09a
Alfalfa/brome	0.10	0.03	0.05	0.05b
Trees	0.07	0.02	0.03	0.03d
Transect mean	0.08a	0.03c	0.05b	

Notes: Transect locations are shown in figure 1. Letters not shared among transects and vegetation zones are significantly different at $p = 0.05$ based on Duncan's multiple range test.

Differences in phosphorus uptake among the vegetation zones may have contributed, but phosphorus uptake by switchgrass in this buffer was comparable to the other species zones through 2003 before poplar began to dominate phosphorus accumulation (Kelly et al. 2007). Therefore asynchronous timing of switchgrass growth with runoff from these watersheds, which peaks on average during mid-May (Tomer et al. 2005), is deemed the most important reason for differences in soil water phosphorus concentrations. Indeed, half the runoff observed from 2002 through 2005 occurred from mid-April through mid-June. The switchgrass cover would presumably trap sediment during this time but transpire little of the early-season runoff that infiltrates, enhancing deep percolation and phosphorus

Figure 5

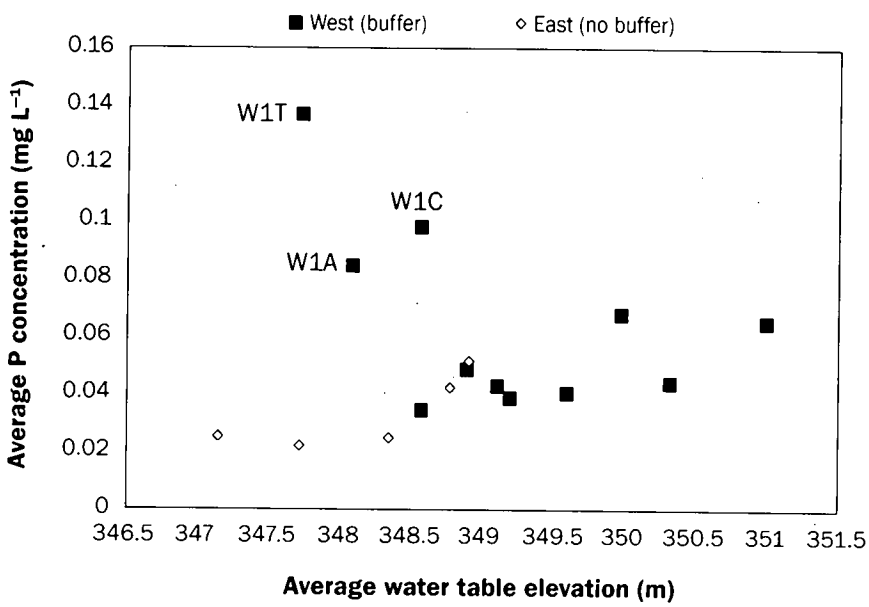
Temporal variation in dissolved phosphorus concentrations in groundwater on buffered and nonbuffered sides of the stream, compared with average water table elevations.



Note: Concentrations are plotted as geometric means for each date.

Figure 6

Groundwater phosphorus concentrations (geometric means across all dates) for each well, plotted against average water table elevation.



Notes: Symbols segregate west-side (buffered) and east-side (nonbuffered) wells. The largest phosphorus concentrations were in wells near the area of greatest sediment accumulation (labeled as in figure 1).

transport in this zone. Furthermore, the C4 photosynthetic metabolism of switchgrass is ecologically adapted to water and nutrients being in limited supply (Ehleringer and Monson 1993), which does not characterize the crop edge of a riparian buffer. Therefore, we speculate that this species' capacity to take up significant quantities of phosphorus throughout a riparian buffer's design life may be limited. The relatively long establishment period (two years in this instance) provides another reason to prefer a faster-establishing cool season grass at the buffer-crop edge.

Phosphorus in Groundwater. Effects of the buffer on phosphorus in groundwater were more difficult to interpret, partly because groundwater takes about 2.5 years to pass beneath the buffer (Tomer and Burkart 2003). We first compared groundwater on the west side of the stream to the east side. On the east side, well W2X (figure 1) was omitted due to large phosphorus concentrations that suggested possible channel water infiltration or well-seal failure. Temporal patterns were similar on both sides of the stream and showed a decline in concentration after 2001 (figure 5). Therefore the decline in groundwater phosphorus on the west side of the stream cannot be attributed to an effect of the buffer. The large concentrations during the first two years of monitoring may have resulted from recharge during very wet years in 1998 and 1999, when water table levels in the watershed peaked (unpublished data). However, water table levels were poorly correlated with P concentration ($p > 0.05$). After droughty years in 2001 to 2003, the water table recovered in 2004 and 2005, but any accordant responses in phosphorus concentrations were small and delayed (figure 5). Smaller phosphorus concentrations occurred on the east side of the stream, possibly due to shorter slope lengths and less contributing area (not shown), and/or lower water tables (figure 6) on that side of the stream.

The largest phosphorus concentrations in groundwater were found in the topographically lowest three wells on the west (buffered) side of the stream (figure 6). Again, these wells were located in the area where the greatest sediment accumulations occurred in the buffer, suggesting that enhanced infiltration and sediment trapping in the buffer could result in increased movement of phosphorus to groundwater. We note the geometric mean phosphorus concentration of these three wells (0.10 mg L^{-1}) exceeded

the US Environmental Protection Agency's suggested nutrient standard for streams (0.076 mg L^{-1}) in this region, whereas the mean of the other wells, apparently less influenced by infiltration and recharge of runoff, did not (0.04 mg L^{-1}).

Summary and Conclusions

A multispecies riparian buffer was positioned to intercept runoff and sediment from an adjacent 2.8 ha (6.9 ac) hillslope in Iowa's Loess Hills. Based on a comparison on two detailed topographic surveys, the switchgrass zone of the buffer, nearest the cropped area, trapped at least 14.5 Mg of sediment per ha (6.5 t ac^{-1}) contributing area during a three-year period. The use of sequential surveys to assess sediment trapping during multiple years identified patterns of sediment accumulation well matched to runoff pathways from the hillslope. The method also provided a plausible estimate of total sediment accretion, when considered in context with the available sediment record for the watershed. Results corroborate other studies showing that buffer inflows are spatially variable yet predictable. Despite the non-uniform nature of runoff pathways, the buffer appeared to trap sediment effectively.

The total sediment accretion of 4.8 Mg ha^{-1} yr^{-1} (2.1 t ac^{-1} yr^{-1}), being a conservative estimate, was at least 40% of 'tolerable' soil loss that has traditionally been promulgated by NRCS. Given the contributing hillslope was managed in no-tillage and that this accumulation occurred during a dry period with relatively little runoff, this suggests that multiple, complementary conservation practices may be needed to achieve optimal erosion control in sensitive environments such as Iowa's Loess Hills.

Phosphorus accumulated in the deposited sediment also showed considerable spatial variation, according to differences in sediment accumulation and soil concentration of total phosphorus. Among five soil plots, the largest total phosphorus concentrations in surface soils were found in the two plots that also had the largest sediment accretion. Therefore, in the outer switchgrass zone of the buffer, phosphorus accretion among five plots ranged from 7 to 55 g m^{-2} (0.02 to 0.17 oz ft^{-2}).

The variation in soil phosphorus accumulation has implications for phosphorus movement through buffers because water accumulates and infiltrates where sediment is deposited. Phosphorus concentrations in soil water from 1.5 m (5.0 ft) depth were greater beneath the switchgrass than beneath the crop, or beneath the brome/alfalfa or tree zones of the buffer. This probably results from a seasonal mismatch between runoff delivery and growth of switchgrass. While half of the watershed runoff was delivered from mid-April through mid-June, switchgrass is a warm season grass that exhibits most growth later in the season, and, therefore, may transpire little of the early season runoff that infiltrates within buffers. Phosphorus concentrations in soil water and in groundwater were also greatest in the topographically lowest area of the buffer, where most sediment accumulated. Buffer performance could be optimized by designs that position species to maximize plant uptake of water and nutrients in areas where runoff accumulates and that synchronize seasonalities of plant uptake and runoff.

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