This article was downloaded by: [DigiTop - USDA's Digital Desktop Library]
On: 30 May 2014, At: 12:31
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK

Communications in Soil Science and Plant Analysis

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/lcss20

Removal of Vegetative Clippings Reduces Dissolved Phosphorus Loss in Runoff

James Ippolito[a], Ross Spackman[b], James Entry[c] & Robert Sojka[a]

[a] U.S. Department of Agriculture-Agricultural Research Service, Northwest Irrigation and Soils Research Laboratory, Kimberly, Idaho, USA

[b] Water Resource Management, College of Southern Idaho, Twin Falls, Idaho, USA

[c] Nutrigrown LLC, Columbia, Maryland, USA

Accepted author version posted online: 14 Apr 2014.Published online: 28 May 2014.

To cite this article: James Ippolito, Ross Spackman, James Entry & Robert Sojka (2014) Removal of Vegetative Clippings Reduces Dissolved Phosphorus Loss in Runoff, Communications in Soil Science and Plant Analysis, 45:11, 1555-1564, DOI: 10.1080/00103624.2013.875202

To link to this article: http://dx.doi.org/10.1080/00103624.2013.875202

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the “Content”) contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms &

Communications in Soil Science and Plant Analysis, 45:1555–1564, 2014

ISSN: 0010-3624 print / 1532-2416 online
DOI: 10.1080/00103624.2013.875202

Taylor & Francis
Taylor & Francis Group

Removal of Vegetative Clippings Reduces Dissolved Phosphorus Loss in Runoff

JAMES IPPOLITO,[1] ROSS SPACKMAN,[2] JAMES ENTRY,[3]
AND ROBERT SOJKA[1]

[1]U.S. Department of Agriculture–Agricultural Research Service, Northwest Irrigation and Soils Research Laboratory, Kimberly, Idaho, USA
[2]Water Resource Management, College of Southern Idaho, Twin Falls, Idaho, USA
[3]Nutrigrown LLC, Columbia, Maryland, USA

Rainfall simulation was used to study the vegetative filter strip (VFS) conditions under which losses of total dissolved phosphorus (TDP) and dissolved reactive phosphorus (DRP) leaching occur. Boxes containing silt loam soil were planted with ryegrass and cut at two different intervals prior to simulated rainfall 14 days apart. Grass clippings were either removed or retained. During the second simulated rainfall, runoff TDP and DRP were greater for treatments cut the day before irrigation with clippings retained as compared to treatments cut the same day as irrigation with clippings retained. Removing clippings yielded the lowest mean TDP and DRP concentrations. Increasing the senesced vegetative surface area for contact with water, and the amount of time for leaching to occur, resulted in the greatest DRP loss. The VFS management implications should consider clipping removal or no or reduced mowing during the growing season followed by end-of-season removal to reduce DRP leaching losses.

Keywords Eutrophication, grass, phosphorus, rainfall simulator, vegetative filter strip

Introduction

The primary pathway for phosphorus (P) loss from agricultural soils is through surface runoff (Vadas, Kleinman, and Sharpley 2004; Sharpley et al. 2002). Phosphorus-enriched surface waters may lead to accelerated downstream eutrophication, a major concern in the United States (Vaughan et al. 2007; USEPA 2001). To prevent eutrophication, it is suggested that total P [as phosphate (PO_4)] not exceed 0.05 mg L^{-1} at the point where a stream enters a lake or reservoir and not exceed 0.10 mg L^{-1} in streams that do not directly discharge into a lake or reservoir (Mueller and Helsel 1999). However, stream enrichment typically occurs from waters containing and releasing P from both particulate and soluble P. Thus, methods that reduce agricultural system sediment and soluble P losses can help alleviate environmental degradation.

Techniques that control erosion and detain sediment have been shown to significantly decrease particulate P transfers (Sojka and Lentz 1996; Sojka et al. 2005; Chardon et al.

Received 11 January 2013; accepted 14 May 2013.

Address correspondence to James Ippolito, U.S. Department of Agriculture–Agricultural Research Service, Northwest Irrigation and Soils Research Laboratory, 3793 N. 3600E, Kimberly, Idaho, 83341, USA. E-mail: jim.ippolito@ars.usda.gov

2011; Ippolito, Barbarick, and Elliott 2011; Penn et al. 2011). One erosion control technique is the use of vegetative filter strips (VFS), areas of vegetation planted adjacent to and maintained to minimize sediment entering surface water. Water flows through the plant material at reduced velocity, sediment is trapped, and water and nutrient infiltration is increased (Fiener and Auerswald 2005). The outflow carries less sediment and nutrients, and thus water quality is improved. Vegetated filter strips have been used to control sediment in urban runoff (Deletic 2005) and studied for their effectiveness in removing sediment, phosphorus (P), and nitrogen (N) from agricultural irrigation returns (Lee, Isenhart, and Schultz 2003; Tate et al. 2000). Dunn et al. (2011) showed that total suspended solids losses were reduced by 64% when using VFS. Blanco-Canqui et al. (2004) observed a 72% reduction in sediment loss when using a VFS; providing an additional vegetative barrier before the VFS further reduced sediment loss to 91%. The authors also showed that VFS could reduce particulate P loss by almost 95%.

Although VFS are effective in removing particulate P, their efficacy to remove dissolved P (DP) has been less consistent, and surface waters may still receive appreciable DP at concentrations supporting eutrophic conditions. Significant DP loss can occur through leaching from agricultural fields such as those dominated by sandy soil (Novak et al. 2000), organic soil (Porter and Sanchez 1992), and artificial drainage (Heckrath et al. 1995). Phosphorus can also resolubilize from trapped sediment within the VFS (Sharpley, Ahuja, and Menzel 1981).

Vegetative filter strip P losses may also be a function of vegetation age (Sharpley 1981; Turner and Haygarth 2000), soil–plant fertility status (Bromfield and Jones 1972; Nash and Halliwell 1999), senescent or plant clippings left in place (Nash and Murdoch 1997), and live clipped vegetation (Mundy et al. 2003). Sharpley (1981) showed that as plants aged from 42 to 84 days, P from plant leachate caused a 20–60% increase in surface runoff P. Furthermore, Nash and Halliwell (1999) and Bromfield and Jones (1972) suggested that, because more water-soluble P may be present in plants grown under highly fertile conditions, plant P losses may be more important than in unfertile soils. Slow-moving water across organic residues (e.g., clipped vegetation) has been shown to potentially be a major source of runoff P (Nash and Murdoch 1997). Mundy et al. (2003) showed that a perennial pasture cut to shorter heights led to greater runoff dissolved reactive P (DRP) losses as compared to higher plant heights. The authors suggested that this was due to increased live plant structural damage.

While this research illustrates the importance of P loss from vegetation, most VFS P transport research has focused on particulate removal and nutrient infiltration. Thus, a need exists to further understand the role vegetation plays as a P source when plant cutting or mowing occurs. Previous in-field irrigation research suggested that grassed [orchard grass (*Dactylis glomerta* L.)] fields contributed to offsite P movement (Spackman 2006). The current research focused controlled efforts on understanding field observations. Thus, the research objectives were to (i) determine if cutting grass prior to simulated rainfall resulted in release of DRP and total dissolved P (TDP) and (ii) compare DRP and TDP runoff results where the vegetation is removed after cutting with results where vegetation is retained.

Materials and Methods

Box Construction

Sixteen wooden boxes were constructed based upon dimensions outlined in the National Phosphorus Research Project (NPRP) indoor runoff box protocol (National Phosphorus

Research Project 2001). Boxes were 1 m long, 20 cm wide, and 5 cm deep with back walls 2.5 cm higher than the soil surface. Nine 5-mm drainage holes were located in the base at the upper, middle, and lower locations as described by the NPRP (National Phosphorus Research Project 2001). A collection trough was attached to the bottom end of each box at a slope to channel runoff through a tube then into a collection container. A plastic shield covering each trough excluded rainfall that had not run through the box (Kleinman et al. 2002). All boxes were placed in a greenhouse.

Soil

One cm of sand was placed in the bottom of each box. Air-dried Portneuf silt loam soil (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid) with 17% sand, 60% silt, and 23% clay as determined by the hydrometer method (Gee and Bauder 1986) was placed in the boxes. The Portneuf series plays an important role for crop production, occupying approximately 117,000 ha in southern Idaho (USDA-NRCS 2008). The soil was removed from the top 7.5 cm of a field near Kimberly Idaho, mixed, passed through a 19-mm sieve, and solarized under plastic inside a greenhouse for 5 days to reduce soil pathogens prior to use. The soil electrical conductivity (EC) and pH from a saturated paste extract was 1.0 dS m^{-1} (Rhoades 1996) and 7.8 (Thomas 1996), respectively. The total carbon (C) content (Nelson and Sommers 1996) was 1.7%. The calcium carbonate equivalent (Allison and Moodie 1965) was 6.8%. Organic C content was 1.0% as determined by difference between total and inorganic C content. The Olsen extractable P concentration was approximately 18 mg kg^{-1} as determined by using 0.5 M sodium bicarbonate ($NaHCO_3$; Olsen et al. 1954).

Grass Preparation

Annual ryegrass seeds were planted in plastic trays containing about 1 cm of a commercial potting mix. After growing 6 to 8 cm, the grass mat was transplanted into the boxes. This provided a uniform stand of grass, which rooted into the soil well. This process deviated from the NPRP but was necessary to assure uniform stand establishment among the boxes. No fertilizer was applied.

Experimental Design

Grass within the boxes was grown inside a greenhouse for about 60 days in a completely randomized design with four replicates. Grass blade length was maintained at 5 to 9 cm. Trimming was done with scissors weekly and all clippings were removed. After 2 months, four treatments were imposed which included (1) uncut grass, blade length 9 cm (Control), (2) grass cut to 5 cm on the day of rainfall simulator irrigation with clippings removed (Removed), (3) grass cut to 5 cm on the day of rainfall simulator irrigation with clippings retained within the box (Retained), and (4) grass cut to 5 cm, 24 h before rainfall simulator irrigation with clippings retained within the box (Cut-24). Each treatment was replicated four times. After the simulated rainfall, the grass clippings were removed from treatments that had residue retained. Maintenance watering, with no runoff, and grass clipping with full removal from all treatments were performed until the second rainfall event 14 days later.

Rainfall Simulator

The rainfall simulator applied water through an oscillating sprinkler similar to one described by Meyer and Harmon (1979). A Veejet nozzle (8070; Hesco, Inc., Niles, Ill., USA) was mounted 3 m above the soil surface. Well water [electrical conductivity (EC) = 0.73 dS m^{-1}; pH = 7.2] was used at a nozzle pressure of 76 kPa, providing a median drop size of 1.2 mm in diameter. Irrigation rate was verified prior to the study as ranging from 82 to 112 mm h^{-1}; the average irrigation was 96 mm h^{-1}. These rates were similar to sprinkler designs that apply an instantaneous application of 102 to 127 mm h^{-1} (Evans and Sneed 1996).

Sampling and Analysis

Four boxes, one from each treatment, were laterally placed on a 1% sloped stand. Position was randomized, and each box was oriented in the same direction with 2.5 cm separation between boxes. The nozzle sprayed into a bypass tray before oscillation started and between sample collections so the pressure could be stabilized. Sample collection did not begin until water runoff was observed from each box. Runoff water was diverted into covered containers through tubing attached to each box trough. After runoff began, samples were collected from intervals of 0 to 5, 5 to 10, 10 to 15, and 15 to 30 min. From these samples, a subsample was collected for analysis and the sample remainder was discarded. Rainfall was halted after 30 min.

Two samples were prepared for each time interval. Water for DRP analysis was passed through a 0.45-μm membrane filter, preserved with a 1% boric acid solution, and refrigerated until analyzed using the molybdate blue method (Murphy and Riley 1962). Total dissolved P was determined using inductively coupled plasma–optical emission spectrometry (ICP-OES) on filtered water.

Statistical Analysis

Residuals were normally distributed with constant variance as determined by Proc Univariate in the Statistical Analysis Software (SAS) program (SAS Institute Inc. 2008; Cary, N.C.). SAS was then used to conduct the GLM analysis, which showed that all interactions for parameters were significant for irrigation time (day 1 vs. day 14) by individual treatments (Control, Retained, Removed, Cut-24) at $P \leq 0.05$. Therefore, differences between individual treatment means, and differences between TDP and DRP for all treatments combined, were compared between irrigation times (day 1 vs. day 14). Differences across collection intervals (5 to 30 min), for each treatment from days 1 and 14, were also compared using a t-test. Significant differences reported ($P \leq 0.05$) were determined by the least squares means test.

Results and Discussion

No treatment differences were found for TDP and DRP in the first rainfall (day 1; Table 1) likely due to no appreciable mineralization or release of plant-borne P. However, during the second rainfall event (day 14) Cut-24 leached the greatest concentrations of TDP (0.95 mg L^{-1}) as compared to all other treatments, and DRP (0.74 mg L^{-1}) compared to all treatments except Retained. The lowest DRP concentration was for Removed at 0.39 mg L^{-1}. These results suggest that plant clipping left on the soil surface can contribute

Table 1

Treatment means (n = 4) for total dissolved P (TDP) and dissolved reactive P (DRP) in runoff compared by day in which irrigation occurred

	TDP (mg L^{-1})		DRP (mg L^{-1})	
Treatment	Day 1	Day 14	Day 1	Day 14
Control	0.82 (0.07) a A	0.69 (0.08) b A	0.55 (0.07) a A	0.54 (0.06) bc A
Retained	1.01 (0.07) a A	0.74 (0.07) b B	0.70 (0.05) a A	0.59 (0.07) ab A
Removed	0.90 (0.14) a A	0.56 (0.05) b B	0.59 (0.12) a A	0.39 (0.05) c A
Cut-24	1.11 (0.22) a A	0.95 (0.06) a A	0.68 (0.06) a A	0.74 (0.05) a A

Notes. Different lowercase letters within P form across treatments for either day 1 or day 14 indicate significant difference at $P < 0.05$. Different uppercase letters indicates significant treatment difference ($P < 0.05$) between day 1 and day 14 for either TDP or DRP. Values inside parentheses indicate one standard error of the mean.

to greater leachate P losses as compared to clippings removed; this result is exacerbated when clippings remain for at least 24 h prior to an irrigation event. The present finding differs from those of Bierman et al. (2010), who found no significant difference in runoff TP or DRP between returned versus removed turfgrass (*Poa pratensis* L.) clippings. However, the findings of Bechmann et al. (2005) showed that freezing and thawing of plant material (i.e., plant cell disruption, much like clipping plant material) increased water-extractable P in runoff. Fiener and Auerswald (2009) found that VFS DP losses increased after freezing periods, suggesting that these grassed areas may be a source of DP. Plants growing in soils containing low P fertility can increase the amount of soluble P transported in leachate by 15 to 95% (Sharpley 1981), as water-soluble P in plants have been shown to be 60 to 83% of the TP in plants (Bromfield and Jones 1972). Based on our results, timing of clipping can further exacerbate P leaching losses.

Total dissolved P in the Removed and Retained treatments decreased from the first to second rainfall event, while all other treatment means remained constant (Table 1), even though plants were 2 weeks older. Although P concentrations did not significantly increase with time, Sharpley (1981) showed that as plants age the amount of soluble P in runoff could increase by about 20 to 60%. Plant age, particularly at the flowering stage, has been shown to increase DP losses (Fiener and Auerswald 2009). The concept of plant aging is that crops accumulate P in aboveground tissue, some of which may become available to runoff (Bechmann et al. 2005). Plants in the current study may not have been as mature as those found in the Sharpley (1981) or Fiener and Auerswald (2009) studies, and thus increases in TDP and DRP leaching losses associated with plant age were not observed.

Average TDP and DRP concentrations combined across all treatments were significantly greater ($P < 0.05$), by 18% and 10%, respectively, for the first irrigation than the second (Figure 1). Dissolved P and particle-bound P were likely lost from the boxes in greater concentrations during the first irrigation because water had not been applied with the same intensity to the grass boxes during the establishment phase as under rainfall simulation. Tate et al. (2000) reported that first year effectiveness of VFS is subject to prior area management such as fertilizer application or animal grazing and it takes time to leach soil reserves of soluble nutrients accumulated in the soil or from vegetation. The authors postulated that filter strip effectiveness should increase over time. Mundy et al. (2003) reported that increased structural damage to grass through mowing or grazing increased the

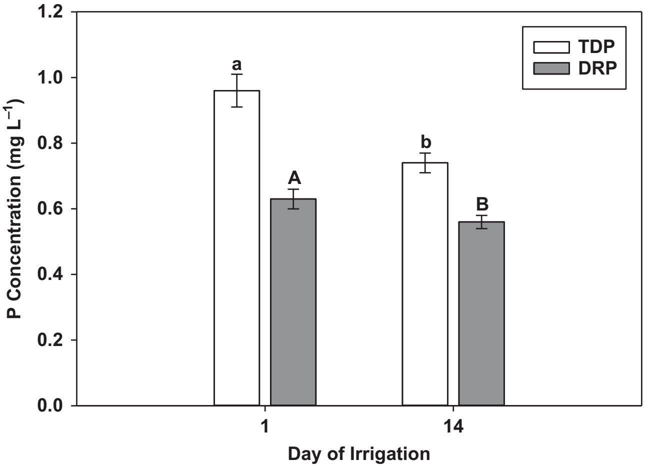

Figure 1. Comparison of total dissolved P (TDP) and dissolved reactive P (DRP) combined means (n = 16) of all treatments for day 1 and day 14 rainfall events. Different lower- or uppercase letters for TDP or DRP, respectively, between day 1 and day 14 indicate significant difference at $P < 0.05$. Error bars represent the standard error of the mean.

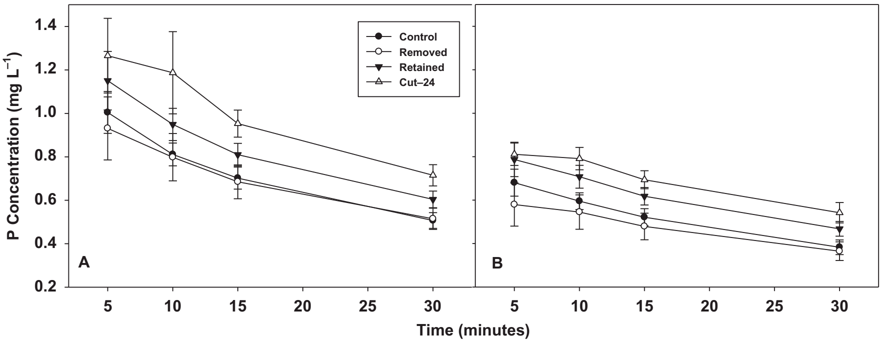

Figure 2. (A) Total dissolved P (TDP) and (B) dissolved reactive P (DRP) mean (n = 4) concentrations compared by treatment and time. Error bars represent the standard error of the mean.

concentration of nutrients in runoff and that it was most severe following the first irrigation following defoliation.

Total dissolved P and DRP concentrations significantly decreased across collection intervals (5 to 30 min; Figures 2A and B), for each treatment, when data were averaged over irrigation events. The percentage decreases in TDP and DRP from 5 to 30 min were (1) Control, 49% and 44%, (2) Retained, 48% and 41%, (3) Removed, 45% and 38%, and (4) Cut-24, 37% and 29%. The TDP decrease was more evident than the DRP decrease probably due to greater soil erosion and particulate P removal near the beginning of the rainfall (at 5 min). Lentz and Lehrsch (2010) demonstrated that sediment and DP concentrations in furrow runoff peaked shortly after initial runoff occurred and declined afterward. Our findings were also similar to those of Austin, Prendergast, and Collins (1996), who found that 80% of the TP lost from irrigated pastures occurred in the first runoff event.

Treatments in which grass was cut with vegetation retained on the soil surface (i.e., Retained and Cut-24) had greater TDP and DRP concentrations in runoff compared to the Control or Removed treatments at almost all sampling intervals (Figures 2A and B). This supports the contention that damaged or cut vegetation is more prone to cellular P loss as compared to intact vegetation. Mundy et al. (2003) found that TP concentration in runoff almost doubled when plants were cut at 47 versus 155 mm height, likely due to plant P leakage. McDowell, Nash, and Robertson (2007) studied the effects of grazing on P loss, stating that a significant proportion of P mobilized following grazing could come directly from plant P stores or from disrupted cells, xylem, and phloem exposed to irrigation water. In our box study, leaving clippings in place instead of removing them further increased P concentration in runoff, likely due to P leakage from the clippings themselves. In addition, the Cut-24 treatment had greater TDP and DRP concentrations in runoff compared to the Retained treatment at almost all time intervals. This suggests that plant susceptibility to P leakage continues over at least a 24-h period. Therefore, increasing the vegetative (living and freshly clipped) surface area that contacts runoff water results in a greater runoff P concentration. Furthermore, if irrigation of grass containing clippings is delayed for 24 h, the runoff P concentration is further increased.

Conclusions

Foliar leaching losses of P were quantified according timing and length of clipped vegetation (ryegrass). Total dissolved P and DRP concentrations associated with foliar leaching were greater during the first versus second rainfall, consistent with previous research. Removing clippings from the grass stand produced the lowest concentration in runoff, whereas treatments that retained clippings produced the greatest TDP and DRP concentrations. Of the treatments that retained clippings, clipping the plants 24 hours prior to rainfall produced greater TDP and DRP runoff concentrations than clipping the plants on the day of irrigation. Damaged vegetation (e.g., cutting, mowing, grazing) is more prone to cellular P loss when the severed ends of stubble and clippings are both subjected to rainfall. This finding is consistent with other research that indicated more P leakage from damaged plant cells and greater concentrations in runoff leaving the site. Only ryegrass was used in this experiment; other vegetation may produce different results. Thus, vegetation selection may also be an important criterion when implementing VFS into an ecosystem management plan. Further management implications should consider clipping removal from VFS or for pasture management, or perhaps eliminating or reducing mowing, to reduce DP leaching losses.

Acknowledgments

We gratefully acknowledge the logistical and advisory support from the Nortwest Irrigation and Soils Research Laboratory of the U.S. Department of Agriculture–Agricultural Research Service in Kimberly, Idaho, the University of Idaho, and Jason Elsworth over the course of the full series of projects that culminated in this study.

Funding

We acknowledge funding support from the Nortwest Irrigation and Soils Research Laboratory of the U.S. Department of Agriculture–Agricultural Research Service.

References

Allison, L. E., and C. D. Moodie. 1965. Carbonate. In *Methods of soil analysis, part 1*, ed. C. A. Black, 1379–1396. Madison, Wisc.: American Society of Agronomy.

Austin, N. R., J. B. Prendergast, and M. D. Collins. 1996. Phosphorus losses in irrigation runoff from fertilized pasture. *Journal of Environmental Quality* 25:63–68.

Bechmann, M. E., P. J. A. Kleinman, A. N. Sharpley, and L. S. Saporito. 2005. Freeze–thaw effects on phosphorus loss in runoff from manured and catch-cropped soils. *Journal of Environmental Quality* 34:2301–2309.

Bierman, P. M., B. P. Horgan, C. J. Rosen, A. B. Hollman, and P. H. Pagliari. 2010. Phosphorus runoff from turfgrass as affected by phosphorus fertilization and clipping management. *Journal of Environmental Quality* 39:282–292.

Blanco-Canqui, H., C. J. Gantzer, S. H. Anderson, and E. E. Alberts. 2004. Grass barriers for reduced concentrated flow induced soil and nutrient loss. *Soil Science Society of America Journal* 68:1963–1972.

Bromfield, S. M., and O. L. Jones. 1972. The initial leaching of hayed-off pasture plants in relation to the recycling of phosphorus. *Australian Journal of Agricultural Research* 23:811–824.

Chardon, W. J., J. E. Groenenberg, E. J. M. Temminghoff, and G. F. Koopmans. 2011. Use of reactive materials to bind phosphorus. *Journal of Environmental Quality* 41:636–646.

Deletic, A. 2005. Sediment transport in urban runoff over grassed areas. *Journal of Hydrology* 301:108–122.

Dunn, A. M., G. Julien, W. R. Ernst, A. Cook, K. G. Doe, and P. M. Jackman. 2011. Evaluation of buffer zone effectiveness in mitigating the risks associated with agricultural runoff in Prince Edward Island. *Science of the Total Environment* 409:868–882.

Evans, R., and R. E. Sneed. 1996. *Selection and management of efficient center-pivot and linear move irrigation systems* (North Carolina Cooperative Extension Service Publication EBAE-91-151). Available at http://www.bae.ncsu.edu/programs/extension/evans/ebae-91-151.html

Fiener, P., and K. Auerswald. 2005. Measurement and modeling of concentrated runoff in grassed waterways. *Journal of Hydrology* 301:198–215.

Fiener, P., and K. Auerswald. 2009. Effects of hydrodynamically rough grassed waterways on dissolved reactive phosphorus loads coming from agricultural watersheds. *Journal of Environmental Quality* 38:548–559.

Gee, G. W., and J. W. Bauder. 1986. In *Methods of soil analysis, part 1: Physical and mineralogical methods*, ed. A. Klute, 383–411. Madison, Wisc.: American Society of Agronomy.

Heckrath, G., P. C. Brookes, P. R. Poulton, and K. W. T. Goulding. 1995. Phosphorus leaching from soils containing different phosphorus concentrations in the Broadbalk experiment. *Journal of Environmental Quality* 24:904–910.

Ippolito, J. A., K. A. Barbarick, and H. A. Elliott. 2011. Drinking water treatment residuals: A review of recent uses. *Journal of Environmental Quality* 40:1–12.

Kleinman, P. J. A., A. N. Sharpley, B. G. Moyer, and G. F. Elwinger. 2002. Effect of mineral and manure phosphorus sources on runoff phosphorus. *Journal of Environmental Quality* 31:2026–2033.

Lee, K. H., T. M. Isenhart, and R. C. Schultz. 2003. Sediment and nutrient removal in an established multi-species riparian buffer. *Journal of Soil and Water Conservation* 58:1–8.

Lentz, R. D., and G. A. Lehrsch. 2010. Nutrients in runoff from a furrow-irrigated field after incorporating inorganic fertilizer or manure. *Journal of Environmental Quality* 39:1402–1415.

McDowell, R. W., D. M. Nash, and F. Robertson. 2007. Sources of phosphorus lost from a grazed pasture receiving simulated rainfall. *Journal of Environmental Quality* 36:1281–1288.

Meyer, L. D., and W. C. Harmon. 1979. Multiple-intensity rainfall simulator for erosion research on row sideslopes. *Transactions of the American Society of Agricultural Engineers* 22:100–103.

Mueller, D. K., and D. R. Helsel. 1999. *Nutrients in the nation's waters: Too much of a good thing?* (U.S. Geological Survey Circular 1136). Washington, D.C.: National Water Quality Assessment Program. Available at: http://water.usgs.gov/nawqa/circ-1136.html

Mundy, G. N., K. J. Nexhip, N. R. Austin, and M. D. Collins. 2003. The influence of cutting and grazing on phosphorus and nitrogen in irrigation runoff from perennial pasture. *Australian Journal of Soil Research* 41:675–685.

Murphy, J., and J. P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta* 27:31–36.

Nash, D., and C. Murdoch. 1997. Phosphorus in runoff from a fertile dairy pasture. *Australian Journal of Soil Research* 35:419–429.

Nash, D. M., and D. J. Halliwell. 1999. Fertilisers and phosphorus loss from productive grazing systems. *Australian Journal of Soil Research* 37:403–429.

National Phosphorus Research Project. 2001. *National research project for simulated rainfall-surface runoff studies*. Raleigh: North Carolina State University. Available at http://www.sera17.ext.vt.edu/Documents/National_P_protocol.pdf

Nelson, D. W., and L. E. Sommers. 1996. Total carbon, organic carbon, and organic matter. In *Methods of soil analysis, part 3: Chemical methods*, ed. D. L. Sparks, 975–977. Madison, Wisc.: Soil Science Society of America.

Novak, J. M., D. W. Watts, P. G. Hunt, and K. C. Stone. 2000. Phosphorus movement through a coastal plain soil after a decade of intensive swine manure application. *Journal of Environmental Quality* 29:1310–1315.

Olsen, S. R., C. V. Cole, F. S. Watanabe, and L. A. Dean. 1954. *Estimation of available phosphorus in soils by extraction with sodium bicarbonate* (USDA Circular 939). Washington, D.C.: U.S. Government Printing Office.

Penn, C. J., J. M. McGrath, E. Rounds, G. Fox, and D. Heeren. 2011. Trapping phosphorus in runoff with a phosphorus removal structure. *Journal of Environmental Quality* 41:672–679.

Porter, P. S., and C. A. Sanchez. 1992. The effect of soil properties on phosphorus sorption by Everglades Histosols. *Soil Science* 154:387–398.

Rhoades, J. D. 1996. Salinity: Electrical conductivity and total dissolved solids. In *Methods of soil analysis, part 3: Chemical methods*, ed. D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnston, and M. E. Sumner, 417–435. Madison, Wisc.: Soil Science Society of America.

SAS Institute, Inc. 2008. *SAS/STAT user's guide, version 9.2*. Cary, N.C.: SAS Institute.

Sharpley, A. N. 1981. The contribution of phosphorus leached from crop canopy to losses in surface runoff. *Journal of Environmental Quality* 10:160–165.

Sharpley, A. N., L. R. Ahuja, and R. G. Menzel. 1981. The release of soil phosphorus to runoff in relation to the kinetics of desorption. *Journal of Environmental Quality* 10:386–391.

Sharpley, A. N., P. J. A. Kleinman, R. W. McDowell, M. Gitau, and R. B. Bryant. 2002. Modeling phosphorus transport in agricultural watersheds: Processes and possibilities. *Journal of Soil and Water Conservation* 57:425–439.

Sojka, R. E., and R. D. Lentz. 1996. Polyacrylamide for furrow-irrigation erosion control. *Irrigation Journal* 46:8–11.

Sojka, R. E., J. A. Entry, W. J. Orts, D. W. Morishita, C. W. Ross, D. J. Horne. 2005. Synthetic- and bio-polymer use for runoff water quality management in irrigation agriculture. *Water Science and Technology* 51:107–115.

Spackman, R. A. 2006. Irrigated pasture contribution of soluble phosphorus to surface water. Ph.D. dissertation, University of Idaho, Moscow.

Tate, K. W., G. A. Nader, D. J. Lewis, E. R. Atwill, and J. M. Connor. 2000. Evaluation of buffers to improve the quality of runoff from irrigated pastures. *Journal of Soil and Water Conservation* 55:473–478.

Thomas, G. W. 1996. Soil pH and soil acidity. In *Methods of soil analysis, part 3: Chemical methods*, ed. D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnston, and M. E. Sumner, 475–490. Madison, Wisc.: Soil Science Society of America.

Turner, B. L., and M. P. Haygarth. 2000. Phosphorus forms and concentrations in leachate under four grassland soil types. *Soil Science Society of America Journal* 64:1090–1099.

USDA-NRCS. 2008. *Soil extent mapping tool*. Available at http://www.cei.psu.edu/soiltool/semtool.html

USEPA. 2001. *Ecoregional nutrient criteria fact sheet* (EPA-888-F-01-010). Available at http://water.epa.gov/scitech/swguidance/standards/criteria/nutrients/upload/2007_09_27_criteria_nutrient_ecoregions_9docfs.pdf

Vadas, P. A., P. J. A. Kleinman, and A. N. Sharpley. 2004. A simple method to predict dissolved phosphorus in runoff from surface-applied manures. *Journal of Environmental Quality* 33:749–756.

Vaughan, R. E., B. A. Needelman, P. J. A. Kleinman, and A. L. Allen. 2007. Vertical distribution of phosphorus in agricultural drainage ditch soils. *Journal of Environmental Quality* 36:1895–1903.