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Phosphorus Retention, Accumulation, and Movement in Six Feedlot Runoff Vegetative Treatment Areas

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Abstract
Increased environmental awareness has prompted the need for improved feedlot runoff control. Vegetative treatment systems (VTSs) provide a cost effective option that may enhance environmental security. Vegetative treatment systems are typically designed on the basis of hydraulic performance, which may result in over-application of nutrients, especially phosphorus. This study assessed the retention, accumulation, and movement of phosphorus in vegetative treatment areas used for runoff control on six Iowa feedlots over a four year period. Phosphorus loadings and retention were calculated based on measured settled feedlot effluent, or vegetative infiltration basin, and vegetative treatment area runoff volumes and phosphorus concentrations. Results indicated that between 61 and 89% of all applied phosphorus was retained within the treatment area, resulting in phosphorus loadings of 124 to 358 kg P/ha-yr. Measurements of harvested vegetation phosphorus concentration and yield indicated that between 13 and 61 kg P/ha-yr were removed with vegetation harvest. However, this only accounted for 6 to 13% of all applied phosphorus, which suggests that these systems have potential for rapid phosphorus accumulation in surface soil, which could potentially lead to reduced treatment and loss of soluble phosphorus. Projected soil phosphorus accumulation was compared to annual measurements of soil Melich-3 phosphorus concentrations increases. Both approaches found similar increases in soil phosphorus levels, indicating that the majority of the phosphorus retained in vegetative treatment areas was due to interaction and retention in the surface soil. Deep soil sampling (0 to 122 cm) was utilized to evaluate vertical phosphorus movement of phosphorus through the soil profile. Sampling indicated that most accumulation was in the surface soil, but that signs of vertical transport and leaching were occurring after four years of operation especially near the VTA inlet.

Keywords
Phosphorus, feedlot runoff, mass balance, soil phosphorus, Melich-3 phosphorus

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Introduction

Open-lot animal feeding operation (AFO) runoff has been recognized as a potential pollutant to receiving waters because it contains nitrogen, phosphorus, organic matter, solids, and pathogens. The U.S. Environmental Protection Agency (EPA) developed a set of effluent limitation guidelines (ELGs) that described the design and operating criteria for feedlot runoff control systems on concentrated animal feeding operations (CAFOs) (Anschutz et al., 1979). These effluent limitation guidelines historically required collection, storage, and land application of feedlot runoff; however, recent modifications allowed the use of alternative treatment systems when the performance of the alternative systems, based on the mass of nutrients released, was equivalent to or exceeded that of an appropriately sized and managed containment system (EPA, 2006). Vegetative treatment systems (VTSs) are one possible alternative runoff control technology that has been proposed.

A VTS is a combination of treatment components, at least one of which utilizes vegetation, to manage runoff from open lots (Koelsch et al., 2006). Vegetative treatment areas (VTAs) and vegetative infiltration basins (VIBs) are two possible treatment components for VTSs. A vegetative treatment area is a band of planted or indigenous perennial vegetation situated down-slope of cropland or animal production facility that provides localized erosion protection and contaminant reduction (Koelsch et al., 2006). As vegetative treatment technology has matured different types of treatment systems have developed; examples including sloped, level, pumped, and sprinkler vegetative treatment areas and vegetative infiltration basin Bond et al. (2011). Briefly, a sloped VTA is an area level in one dimension with a slight slope along the other, to facilitate sheet flow, planted and managed to maintain a dense stand of vegetation (Moody et al., 2006). Operation of a sloped VTA consists of applying solid settling basin effluent uniformly across the top of the vegetated treatment area and allowing the effluent to sheet-flow down the slope, whereas a level VTA uses a flood effect to distribute the effluent over the VTA surface. A pumped VTA has the increased flexibility of allowing the treatment area to be located upslope of the cropland or animal production facility, but still relies on flow to distribute effluent over the length of the vegetative treatment area surface. A sprinkler VTA has the same location flexibility as a pumped VTA, but has the additional advantage of ensuring uniform effluent application over the treatment area surface. Ikenberry and Mankin (2000) identified several possible methods in which effluent was treated by VTAs, including settling solids, infiltrating the runoff, and filtering of the effluent as it flowed through the vegetation. Additionally, interactions between the soil and soil fauna and the flowing effluent could provide additional mechanisms of nutrient retention. A VIB is a flat area, surrounded by berms, planted to perennial vegetation. A VIB uses a flood effect to distribute effluent over the surface. These areas have drainage tiles located 1 to 1.2 m (3.4 to 4 ft) below the soil surface to encourage infiltration of effluent. The tile lines collect effluent that percolates through the soil profile. The effluent then receives additional treatment, often through use of a VTA. Nutrient and pathogen removal in the VIB relies on effluent filtration as it percolates through the soil, plant uptake and harvest, degradation of the nutrients and pathogens by soil fauna, and sorption of contaminants to soil particles.

Two design approaches, one utilizing a hydraulic balance and the other a nitrogen balance, have been proposed for sizing VTAs (Woodbury et al., 2006). Previous work by Woodbury et al. (2005) has shown that if designed using the nitrogen balance approach, VTSs can successfully utilize applied nitrogen. However, in many cases VTSs have been designed based on hydraulic performance. This typically resulted in smaller VTSs, which may cause deep percolation of runoff water below the root zone and over-application of nutrients, especially nitrogen and phosphorus (Woodbury et al., 2006). As VTSs rely heavily on the soil-plant system to filter nutrients and contaminants, there is a need to understand the impacts this phosphorus application in excess of agronomic demand has on soil quality, phosphorus mobility, and the ability of the plant-soil system to retain future phosphorus applications. Research has shown that continued application of phosphorus in amounts greater than crop need causes an accumulation of phosphorus in soil surface horizons (Sui et al., 1999). Moreover, this phosphorus accumulation is often associated with concentrated animal feeding operations and repeated manure applied (Sharpley et al., 1984) and has the potential to lead to losses of soluble phosphorus in surface runoff (Sharpley, 1995; Pote et al., 1996; Pote et al., 1999). Additionally, increases in soluble phosphorus in soil drainage and in subsurface horizons have been reported (Smith et al., 1995; Eghball et al., 1996; James et al., 1996); however, because of the high phosphorus fixing capacity of most soils, vertical movement and leaching of phosphorus through the soil profile is usually negligible.

The issues of phosphorus accumulation and fate are especially relevant in land application waste management systems where the build-up in soil phosphorus can be a major factor affecting the life expectancy of the system (Hu et al., 2006). One method of estimating the phosphorus treatment life expectancy of land application waste management systems is to determine the soil's maximum phosphorus sorption capacity and use this to estimate the amount of phosphorus the soil could potentially retain (Hu et al., 2006). This approach is based on observations that when material containing phosphorus is applied to soil, the soluble forms of phosphorus decrease with time (Holford et al., 1997), preventing losses of soluble phosphorus in runoff and leaching to groundwater but also reducing plant availability (Sui and Thompson, 2000). It has been suggested that this added phosphorus can be immobilized by organic matter, adsorbed (or absorbed) by soil particles, or quickly react with other ions in the soil to form precipitates (Hu et al., 2006). This phosphorus isotherm-mass balance approach was used by Baker et al. (2010) to estimate probable life expectancies of four VTA's in Iowa and to evaluate the impact of different design and management strategies for increasing the design life; however, the approach utilized was not validated.

Thus the objective of this work was to (1) evaluate if a mass balance approach was capable of predicting changes in soil phosphorus concentrations on six vegetative treatment areas in Iowa (2) evaluate significant changes in soil phosphorus concentrations, and (3) use deep soil cores to evaluate if leaching or vertical redistribution of applied phosphorus was occurring. Although not a rigorous mass balance, since leaching of soluble phosphorus was not monitored, the approach utilized here still provides valuable insight into phosphorus accumulation patterns within the soil profile (both with depth in the soil profile and down the length of the vegetative treatment area) and provide insight into the fate of applied phosphorus.

Methods and Materials

Site Descriptions

Six vegetative treatment systems were monitored as part of this study. These treatment systems were located on concentrated animal feeding operation (CAFO) sized open beef feedlots throughout the state of Iowa. The sites were described in detail in Andersen et al. (2011a) and are only briefly discussed here. Data summarizing the characteristics of the Iowa State University (ISU) monitored portions of the feedlots and VTSs is provided in table 1. Information shown includes the feedlot capacity, the VTS configuration, the size of the drainage area (feedlot and additional contributing area), the volume of the settling basin, the area of the VIB (where applicable), and the area of the VTA.

Table 1. Summary of the feedlot capacity, system configuration, and component sizes for vegetative treatment systems at each of the six sites.

Site	No. of Cattle	VTS Components	Drainage Area (ha)	SSB (m^3)	VIB (ha)	VTA (ha)
Central Iowa 1	1,000	1 SSB - 2 VTA	3.09	4,290	--	1.49
Central Iowa 2	650	1 SSB - 1 VIB - 1 VTA	1.07	560	0.32	0.22
Northwest Iowa 1	1,400	1 SSB - 1 VTA	2.91	3,710	--	1.68
Northwest Iowa 2	4,000	1 SSB - 1 VIB - 1 VTA	2.96	1,120	1.01	0.60
Southwest Iowa 1	2,300	1 SSB - 10 VTA	7.49	11,550	--	4.05
Southwest Iowa 2	1,200	1 SSB - 1 VTA	3.72	6,275	--	3.44

Central Iowa 1 (CN IA 1) was a 3.09 ha feedlot permitted for 1,000 head of cattle. Runoff effluent drained into a solid settling basin designed to hold 4,290 m^3 of effluent. The VTA consisted of two channels operated in parallel; each channel was 24 m wide and averaged 311 m long. Central IA 1 VTA soil consisted of Clarion loam, Cylinder loam, and Wadena loam (Soil Survey Staff, NRCS USDA, 2010). The VTS at Central Iowa 2 consisted of a SSB, VIB, and VTA. Runoff from the 1.07 ha feedlot drained into a concrete SSB which released effluent into a 0.32 ha VIB. Effluent captured in VIB tiles was pumped onto VTA. Soils in the VIB consisted of Nicollet loam and Webster clay loam and the VTA was Harps loam (Soil Survey Staff, NRCS USDA, 2010). Northwest Iowa 1 (NW IA 1) consisted of a 2.91 ha feedlot permitted to hold 1,400 head of cattle. Feedlot runoff was collected in a SSB with a volume of 3,700 m^3. The SSB outlet pipe discharged onto VTA consisting of Galva silty clay and Radford silt loam soils (Soil Survey Staff, NRCS USDA, 2010). Northwest Iowa 2 (NW IA 2) had an SSB-VIB-VTA system designed to control runoff from a 2.96 ha concrete feedlot. A settling basin collected the feedlot runoff and released it to a 1.01 ha VIB drained by 15 cm diameter perforated tiles installed 1.2 m deep and spaced 4.6 m apart. Flow from the tile lines was collected in a sump and pumped onto the VTA divided into two 27 m wide channels. The channel receiving effluent was switched manually by the producer. Northwest IA 2 consisted of Moody silty clay loam (Soil Survey Staff, NRCS USDA, 2010). Southwest Iowa 1 (SW IA 1) was a 7.49 ha feedlot with an 11,550 m^3 solid settling basin that released effluent to a 4.05 ha VTA was divided into ten channels. Tile lines, installed to control water table depth below the system and enhance infiltration of effluent into the soil, surrounded each of the VTA channels. Soils in the VTA consisted of mostly Judson silty clay loam and smaller areas of Colo-Ely complex (Soil Survey Staff, NRCS USDA, 2010). Southwest Iowa 2 (SW IA 2) was a 3.72 ha feedlot. Runoff drained into a solid settling basin and was released to a 3.44 ha VTA constructed with earthen berm spreaders along the length. The spreaders slowed the flow of effluent through the system, increasing the time for infiltration. Southwest IA 2 VTA soil consisted of Kennebec silt loam (Soil Survey Staff, NRCS USDA, 2010).

Development of Soil P Prediction Methodology

A mass balance approach, based on the analysis presented in Baker et al. (2010), was used predict soil phosphorus concentrations and assess the results of soil phosphorus monitoring done for this study. The full mass balance equation is presented as equation 1. In this equation, all terms are expressed in kg of phosphorus per hectare of the vegetative treatment area. $P_{applied}$ is the mass of phosphorus applied to the vegetative treatment area from solid settling basin or vegetative infiltration basin effluent, P_{runoff} is the amount of phosphorus lost from the vegetative treatment area due to overland flow releases from the VTA, $P_{vegetation}$ is the mass of phosphorus removed by harvesting vegetation, $P_{leached}$ is the amount of phosphorus lost with percolating water, and $\Delta Soil_{phosphorus}$ is the change in the amount of phosphorus stored in soil profile depth that was sampled. This can be related to changes in soil phosphorus concentration by equation 2. In this equation ρ_b is bulk density of the soil (kg/m^3), d is the depth of soil sample monitored (m),C_p is the concentration of phosphorus in the soil (mg P/kg soil), and $C_{p,i}$ is the background concentration of soil phosphorus before use of the vegetative treatment area (mg P/kg soil). Combining the two equations allows direct estimate of the change in soil phosphorus concentration as shown in equation 3.

$$\Delta Soil_{phosphorus} = P_{applied} - P_{runoff} - P_{vegetation} - P_{leached} \qquad (1)$$

$$\Delta Soil_{phosphorus} = \rho_b d\left(C_P - C_{P,i}\right) \qquad (2)$$

$$\Delta C_p = \frac{P_{applied} - P_{runoff} - P_{vegetation} - P_{leached}}{\rho_b d} \qquad (3)$$

Use of this mass balance equation required monitoring of inflows and outflows from the vegetative treatment area, phosphorus concentrations in these flows, sampling of the harvested vegetation for both phosphorus concentrations and yields to determine removal, and an estimate of the amount of phosphorus lost due to leaching. In this analysis, the amount of phosphorus lost due to leaching was assumed to be negligible since it is usually strongly retained in the soil. This assumption will be investigated by looking at the results of deep soil cores that measured phosphorus changes to a depth of 122 cm and by evaluating potential leaching losses by performing a water balance. All other parameters were monitored in this study, including changes in soil phosphorus. Monitoring methods are described below.

To test the viability of the mass balance method for understanding soil phosphorus concentrations the measured change in soil phosphorus concentrations was regressed against the projected change in soil phosphorus concentration using the mass balance approach. This was performed in two ways. In the first method the annual change in phosphorus concentration was compared to the projected change for that year. In the second method the projection was ran cumulatively, that is the change in monitored phosphorus concentration was always compared to the baseline (pre-system operation) soil phosphorus concentration and regressed against the change the cumulative amount of phosphorus application would have caused. The advantage of the second method is that it provides a larger range of values in which to test the methodology and the impact of any errors present in estimates of phosphorus loading, removal with vegetation, and in soil phosphorus concentrations will be minimized since these values get progressively smaller in comparison to the underlying trend in the data.

Monitoring Effluent Flows and Phosphorus Concentrations to and from the VTA

VTS monitoring data at CN IA 1, CN IA 2, NW IA 1, and NW IA 2 was collected June 2006 through December 2009. Data collection at SW IA 1 and 2 began in fall and spring of 2007 respectively and ended in December 2009. The data collected included daily precipitation depths, effluent volumes released from each VTS component, and the effluent concentrations for multiple parameters. Complete descriptions of the monitoring methodologies can be found in Andersen et al. (2011a).

Precipitation depths were measured using an ISCO 674 tipping-bucket rain gauge (Teledyne ISCO, Lincoln, NE). A passive rain gauge installed on site was used to ensure rainfall data accuracy. Iowa Environmental Mesonet data (http://mesonet.agron.iastate.edu/) were used to determine precipitation depths for events occurring between 1 November and 1 April, generally snowfall.

The effluent monitoring method used at the settling basin was dependent on outlet design. An ISCO 750 low-profile area-velocity sensor (Teledyne ISCO, Lincoln, NE.) was used at settling basins with pipe outlets. An ISCO 720 submerged probe (Teledyne ISCO, Lincoln, NE.) in conjunction with a 0.45 m (1.5 ft) H-flume was used to monitor outflow for non-pipe outlet locations. In 2006, the settling basins were passively managed and one sample was collected and sent for analysis from each SSB release. If the release continued for more than one day, an additional sample was collected for each additional day. In 2007, the producers at CN IA 1, CN IA 2, NW IA 1, SW IA 1, and SW IA 2 began actively managing SSB releases (NW IA 2 began managing SSB releases in 2008). When the SSB outlet was actively managed, the producers released small amounts of SSB effluent on consecutive days. Collecting one sample per day of SSB release proved expensive; to reduce sampling cost, a new sampling protocol was developed. This was to collect a SSB sample from the first SSB release after a rainfall event; samples from the following two days were archived in a freezer. On the third day an additional sample was sent for analysis.

At sites with a VIB, the effluent captured in the tile lines was collected in a sump and pumped onto the VTA. The pumped volume was measured using a Neptune 5 cm (2 in.) turbine flowmeter (Neptune Technology Group, Tallassee, AL). An ISCO sampler was interfaced with the turbine meter with an ISCO 780 Smart 4-20 analog interface module (Teledyne ISCO, Lincoln, NE). This allowed the amount of effluent applied to the VTA to be calculated on a daily basis. Samples were collected and shipped following the protocol described for managed SSBs.

Flow monitoring at the VTA outlet was accomplished using similar methods as those at the settling basin outlet. An ISCO 750 low-profile area-velocity sensor (Teledyne ISCO, Lincoln, Neb.) was used on sites where the VTA had a pipe outlet, and an ISCO 720 submerged probe (Teledyne ISCO, Lincoln, Neb.) in conjunction with a 0.45 m (1.5 ft) H-flume was used on the other VTAs. One sample was collected per day of release.

The mass of each parameter released during each event was calculated by multiplying the measured sample concentration and the monitored flow volume. If a representative sample wasn’t collected for a release event, the geometric average (Andersen et al., 2011a) for that year and component was substituted. The yearly mass of each parameter released was the sum of the event release totals. Calculated mass release data was then used to determine yearly reductions in contaminant mass transport.

Vegetation Sampling for Phosphorus

Vegetation sampling was conducted to determine the mass of phosphorus removed by harvesting vegetation. Vegetation samples were collected within a week of harvest. This was done by collecting vegetation samples near the inlet, outlet, and every 61 m (200 feet) down the length of the treatment area (mirroring the protocol used for soil sampling). A random spot near each sampling location was selected for sampling. A 0.093 m^2 (1 ft^2) area was harvested by cutting the vegetation 2.5 cm above the surface. The sample was dried to constant moisture (approximately 72 hours) in a convection oven at 35°C. Yield was calculated based on the total dry mass of sample collected and the area sampled. The dry sample mass was recorded to provide an estimate of yield which was verified by comparing to producer recorded masses of the harvested round bales. If values didn’t agree within 10% the producer’s harvested mass was used instead. The sample was ground to pass a 1 mm sieve using a Thomas Model 4 Wiley Mill (Thomas Scientific, Swedesboro, NJ). A 2-gram subsample of the ground sample was sent to the Iowa State University Soil & Plant Analysis Laboratory for analysis of total phosphorus and total nitrogen. Multiplying the measured phosphorus concentration of the harvested biomass times the yield provided an estimate of phosphorus removal.

Soil Sampling for Phosphorus

Surface Soil Sampling

Surface soil samples were collected on an annual basis in the fall and once before system operation began; these samples represent soil in the zero to thirty centimeter (zero to 12 inch) depth range. A soil surface sample was collected near the VTA inlet, the VTA outlet, and every 61 m (200 feet) along the length of the VTA. At each sampling location, 10 soil cores from a radius of 3 m (10 feet) around the sample location were collected and composited to make one sample. Each sample location was marked with GPS coordinates so the same location could be subsequently sampled in following years allowing change in soil nutrient content with time to be tracked. The soil samples were delivered to the ISU Department of Agronomy Soil Laboratory where they were tested for Melich-3 phosphorus content.

Statistical analysis of the soil phosphorus data was performed using SAS version 9.2 software (SAS Institute Inc., Cary, NC). Analysis was performed separately for each site. The analysis was run as a block design, using sample location as the blocking variable and year as the fixed factor. The year x sample location interaction term was used as the error term to test for differences in average concentration. Fisher’s protected least significant difference test was used for mean separation.

Soil bulk density was monitored once at each site in the summer of 2007. At each site three 7.62 cm (3 inch) diameter by 46 cm (18 inch) soil cores were collected. The soil core was dried to constant weight at 105°C (approximately 24-36 hours). Soil bulk density measurements from all three cores were averaged across both depths to determine the bulk density of the VTA soil. This bulk density was assumed constant throughout all four years of monitoring. Although bulk density most likely did vary with time, the overall fluctuation was most likely small enough to have minimal impact on the results. For instance, a change in density of 0.1 g/cm^3 change would only change the estimated amount of phosphorus in the soil by approximately 6%.

Deep Soil Sampling

Deep soil sampling was conducted prior to system operation and then again after 2.5 and 3.5 years of system operation. A deep soil sample was collected near the VTA inlet and also near each VTA outlet. Each sample location was marked with GPS coordinates so the same location would be subsequently sampled in following years allowing change in soil nutrient content with time to be tracked. At each soil sampling location, a soil sampling probe (Giddings Machine Company, CO) was used to collect a 2.54 cm (1 inch) diameter soil core that was 122 cm (48-inches) long. The sample was then cut into segments to represent the 0-15.4 cm (0-6 inches), 15.4-30.5 cm (6-12 inches), 30.5-61 cm (12-24 inches), 61-94.4 cm (24-36 inches), and 94.4-122 cm (36-48 inches) depths. Each of these segments was put in a soil sampling bag and sent for analysis to the Soil and Plant Analysis Lab in the Agronomy Department at Iowa State University. These soil samples were analyzed for Melich-3 phosphorus.

Results and Discussion

Vegetation Sampling

As discussed previously, vegetation harvest and removal is critical for vegetative treatment system sustainability as it offers the only acceptable means of phosphorus removal from the treatment area. Both the yield and the amount of phosphorus removed with the vegetation exhibited substantial variation among the six sites. This was often related to the number of cuttings the producer was able to harvest each year. In most cases the ability of the producer to harvest the vegetation was related to weather and soil conditions present within the vegetative treatment area. For example, vegetation was only harvested one year at Central Iowa 2; this treatment system utilized a vegetative infiltration basin that drained continuously and kept a large portion of the small vegetative treatment area in a saturated or nearly saturated condition making harvest difficult. At the remaining sites vegetation was harvested either once or twice a year as weather and soil conditions permitted. In certain instances, the VTA was only partially harvested during some of the cuttings as certain areas were too wet to support the harvest equipment. The yields of these six sites ranged from 5.29 to 14.8 Mg/ha (table 2). These yields are similar to those suggested by a University of Minnesota extension pamphlet on reed canarygrass where 13.4 to 15 Mg/ha yields are reported for 2-cut forage systems near St. Paul, Minnesota (Sheaffer et al., 1990). The lower yields reported from the VTAs may be related to the opportunity for only one harvest in some years or from the fact that the systems were managed to optimize runoff disposal, not forage yield.

In general the amount of phosphorus removed trended with the mass of biomass harvested (r = 0.95). However, this wasn't always the case as Northwest Iowa 1 tended to have lower phosphorus removals than the higher amounts of biomass removed would suggest. The vegetation at this site tended to be dominated by smooth bromegrass rather than the reed canarygrass that dominated the other sites. This data suggests that bromegrass is less able to utilize excess phosphorus than the canarygrass. This is supported by the conclusion of Kovar and Claassen (2009) that canarygrass is more effective than bromegrass in depleting the soil solution of phosphorus under high phosphorus input conditions. Similarly, Sheaffer et al. (2008) found that reed canarygrass had significantly greater phosphorus uptake than bromegrass when used in a potato-process wastewater land application area. In their study Sheaffer et al. (2008) found that under the potato processing wastewater application that canarygrass phosphorus uptake was 31 kg P/ha while smooth bromegrass uptake averaged 25 kg P/ha. Based on this evidence, canarygrass appears to better vegetation choice when excess phosphorus application is probable, such as in vegetative treatment systems.

Table 2. Yields and phosphorus removal from harvesting vegetative treatment area vegetation for Central Iowa 1 (CN IA 1), Central Iowa 2 (CN IA 2), Northwest Iowa 1 (NW IA 1), Northwest Iowa 2 (NW IA 2), Southwest Iowa 1 (SW IA 1), and Southwest Iowa 2 (SW IA 2).

		CN IA 1	CN IA 2	NW IA 1	NW IA 2	SW IA 1	SW IA 2
2006	Yield (Mg/ha)	6.25	0	9.21	5.29	---	---
	P Removal (kg/ha)	24	0	28	16	---	---
2007	Yield (Mg/ha)	7.15	8.26	14.8	6.79	7.22	8.34
	P Removal (kg/ha)	28	29	44	21	36	32
2008	Yield (Mg/ha)	9.34	0	12.3	4.49	3.55	12.5
	P Removal (kg/ha)	36	0	38	13	16	56
2009	Yield (Mg/ha)	13.3	0	11.4	7.7	8.45	14.4
	P Removal (kg/ha)	56	0	36	26	37	61
Total P Removed (kg/ha)		144	29	146	76	89	149
% of Applied P Removed		13	6	10	6	13	16

In a second experiment, Sheaffer et al. (2008) found that phosphorus uptake could be greatly enhanced by increasing the yield of the canarygrass through supplemental addition of nitrogen fertilizer. By adding supplemental nitrogen they were able to increase phosphorus uptake to 72 kg P/ha. Their results for phosphorus uptake are similar to those found in this study without supplemental nitrogen application as we monitored phosphorus uptake of up to 61 kg P/ha. The feedlot runoff vegetative treatment areas received substantially higher nitrogen application rates

(593-1866 kg N/ha-yr) than the potato processing wastewater application sites (250 kg N/ha-yr), thus it is probable that sufficient nitrogen was available at these sites to achieve the higher yields without supplemental nitrogen application.

As discussed in Baker et al. (2010) ensuring an adequate balance between phosphorus inputs and outputs is necessary to prolong the phosphorus saturation life of the vegetative treatment area and suggested that between 30-60% of the annual phosphorus inputs should be harvested. At the sites monitored in this study only between 6 and 16% of the applied phosphorus was harvested. To achieve the phosphorus balance suggested by Backer et al. (2010), at a minimum these vegetative treatment areas need to be two to five times their current size or technologies that improve phosphorus retention within the settling basin need to be developed. The current imbalance between inputs and outputs indicates that the potential for rapid accumulation and vertical movement exists within these systems. As such, it is critical to monitor phosphorus within the treatment area to watch for signs of vertical transport or leaching.

Surface Soil Sampling

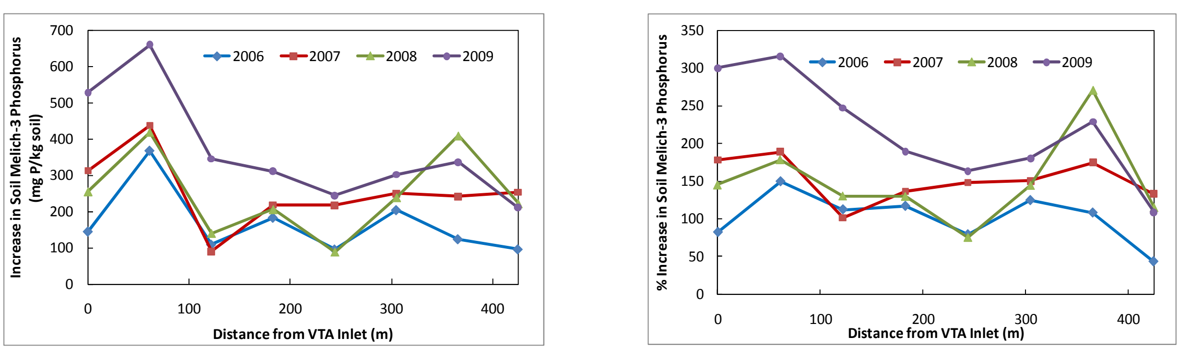
Surface soil phosphorus contents offer the first means of assessing phosphorus accumulation in the soil. Iowa soils are considered “very high” in phosphorus if the Melich-3 extractable phosphorus level exceeds 31 mg P/kg soil; as seen in table 3 the background soil phosphorus concentrations at all six of these sites was well in excess of these levels (ranging from 96 to 717 mg P/ kg soil). Although these values may seem high, it needs be recognized that this recommendation on Melich-3 phosphorus is interpreted as the amount phosphorus at which a yield increase wouldn’t be expected from additional phosphorus application, not as a potential for phosphorus to be lost from the soil, and as such does not provide an indication of the likeliness of phosphorus losses from the system.

Table 3 provides average Melich-3 phosphorus concentrations for each of the vegetative treatment areas before application of feedlot runoff commenced and then annually (sampled in November) thereafter. In general all sites responded similarly with phosphorus levels increasing quickly and significantly after application of feedlot runoff commences. Although this holds true as a general trend, there were expectations to this pattern; most notably at Central Iowa 2 and Southwest Iowa 1 which both exhibited significant increases in phosphorus concentration during their first year of operation, but then stabilized around their new phosphorus level. At Central Iowa 2 this occurred because phosphorus removal within the vegetative infiltration basin substantially limited phosphorus inputs to the VTA; however, no obvious explanation exists as to why levels in the Southwest Iowa 1 stabilized. Both Central Iowa 1 and Northwest Iowa 1 exhibited strong patterns of increasing phosphorus concentrations with significant differences in soil phosphorus concentrations occurring every one or two years of system operation; however, within each site there were anomalies to this pattern. Specifically, the phosphorus concentration at Central Iowa 1 showed a significant decrease in 2009 as compared to 2008 levels while at Northwest Iowa 1 2008 concentrations were similar to 2007 levels. Reasons for these exceptions are not clear, but they may be related to conditions that were conducive to vertical transport of phosphorus deeper in the soil profile or concentrated flow paths within the VTA that either minimized inputs to the specific sampling locations or encouraged excess phosphorus application during the previous year. At both Northwest Iowa 2 and Southwest Iowa 2 phosphorus concentrations showed a trend of increasing concentration with time.

Table 3. Average surface soil (0-30 cm) Melich-3 phosphorus concentration (mg P/kg soil) for Central Iowa 1 (CN IA 1), Central Iowa 2 (CN IA 2), Northwest Iowa 1 (NW IA 1), Northwest Iowa 2 (NW IA 2), Southwest Iowa 1 (SW IA 1), and Southwest Iowa 2 (SW IA 2). Values within a column that do not share the same letter are significantly different at the 0.05 level.

		CN IA 1	CN IA 2	NW IA 1	NW IA 2	SW IA 1	SW IA 2
Melich-3 P Content (mg P/kg soil)	Initial	286^{a}	96^{a}	190^{a}	172^{a}	132^{a}	717^{a}
	2006	326^{ab}	175^{b}	355^{b}	205^{ab}	---	---
	2007	386^{b}	173^{b}	442^{c}	324^{bc}	---	817^{a}
	2008	445^{c}	176^{b}	438^{c}	354^{bc}	200^{b}	1040^{b}
	2009	345^{ab}	156^{b}	557^{d}	451^{c}	191^{b}	1128^{b}

Along with the average phosphorus concentrations it is also important to consider how the phosphorus is distributed down the length of the VTA. This is illustrated for the Northwest Iowa 1 VTA (figure 1). The plots show (a) the absolute change in soil phosphorus concentration (as compared to the initial soil sample) and (b) the relative change normalized as the percent change in soil concentration. Both plots showed a general pattern of greater accumulation within the upper portion (near the inlet) of the VTA which was expected since this would be the area where solids eroded from the feedlot and escaping the settling basin would be expected to settle. Additionally, smaller settling basin release events would not distribute the applied effluent over the entire VTA, but instead only load the effluent over a fraction of the total treatment area. This trend is present in all years, but becomes especially evident in 2009. Although this appears true as a general trend, exceptions occurred; most notably the 365-m point in 2008 which exhibited a significant increase in phosphorus concentration. The VTA experienced heavy hydraulic and phosphorus loading during this year which may have created concentrated flows paths and greater phosphorus transport and accumulation at this sampling location. Corrective actions by the producer to level and reduce channeling appear to have alleviated this in 2009, although remnants of the 2008 accumulation remain. This illustrates two things, first it is critical for the producer to watch for concentrated flow and to take corrective action as soon as possible to correct the situation, and second higher hydraulic loadings are prone to creating concentrated flows.



(a) (b)

Figure 1. Illustration of how soil Melich-3 phosphorus increases along the length of the Northwest Iowa 1 vegetative treatment area. (a) Increases in soil phosphorus and (b) percent increase in soil Melich-3 phosphorus concentration as compared to initial sample.

Comparing Predicted and Measured P Accumulation

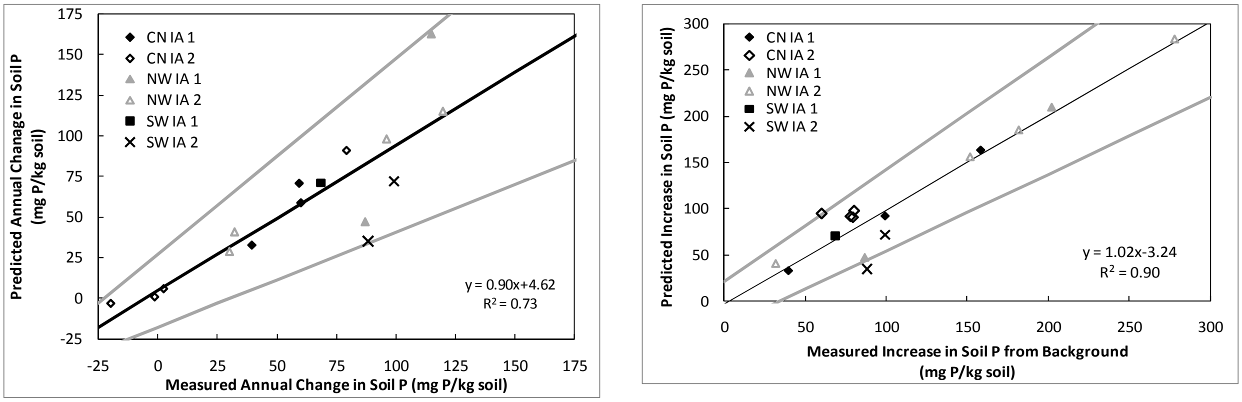
Since the general trend in the surface soil samples was increasing phosphorus concentrations with time we wondered if the increase in phosphorus could be directly predicted by the phosphorus mass balance. To test this theory the bulk density of the soil at each site was required; the bulk densities are shown in Table 4. The predicted concentration changes were then compared to the monitored change in soil phosphorus concentrations. To make this comparison a few of the sample results were discarded, specifically 2009 for Central Iowa 1 which showed a significant decrease in soil phosphorus that couldn't be explained. Additionally, the Southwest Iowa 2 2008 data point wasn't used; however, in this case dirt work performed to modify the system from a settling bench to a settling basin was believed to be the primary cause of the unexpected change in soil phosphorus concentration.

Table 4. Average surface soil (0-30 cm) bulk densities (mg/cm^3) Central Iowa 1 (CN IA 1), Central Iowa 2 (CN IA 2), Northwest Iowa 1 (NW IA 1), Northwest Iowa 2 (NW IA 2), Southwest Iowa 1 (SW IA 1), and Southwest Iowa 2 (SW IA 2).

	CN IA 1	CN IA 2	NW IA 1	NW IA 2	SW IA 1	SW IA 2
Bulk Density (mg/cm^3)	1.61	1.65	1.80	1.47	1.70	1.40
(Standard Deviation)	(0.12)	(0.07)	(0.10)	(0.14)	(0.08)	(0.13)

In general the remaining data points showed a reasonable fit between the predicted and measured increases in soil phosphorus concentration. This is shown graphically in figure 2 on (a) an annual change basis and (b) on a cumulative change from background basis. In both cases the predicted change fits reasonably well with the monitored change although some discrepancies exist. These errors could be caused by numerous factors including measurement errors in the amount of phosphorus applied or lost with the runoff effluent, discrepancies in the amount of phosphorus removed with harvested vegetation, or inaccuracies in surface soil sampling. Of these three sources, non-representative soil samples are most likely as flows and concentrations were intensively monitored over the four year period and errors in overestimating loading from one event would tend to cancel with underestimating those from the next event. Although errors in sampling vegetation were certainly present, these would have little impact on the overall mass balance as phosphorus harvested with vegetation was a relatively small portion of the total phosphorus applied. Soil samples could be influenced by concentrated flow paths within that VTA that would result in either an under- or over- estimation of phosphorus accumulation within the soil. Although sampling at multiple points and compositing ten cores from around the sample location should help reduce the impact of soil variability and effluent channeling, it won't eliminate the impact. Additionally, soil conditions during sampling could have had some influence on results, especially if phosphorus had been recently applied. Finally, this approach assumes that no phosphorus was lost below the 30 cm sampling depth and that all applied phosphorus is in a form that is extractable by the standard Melich-3 extraction technique. Thus it is possible that a high prediction of soil phosphorus could indicate that phosphorus was leached below the 30-cm depth or indicate that some of the applied phosphorus was fixed to a non-extractable form, alternatively a low prediction would tend to indicate non-uniform application that results in concentrated flows around the sampling points.

Both methods of analysis, the annual and cumulative change basis's, provided reasonable agreement between the monitored and predicted change in soil phosphorus. For both model fits the intercept of the best fit line was not significantly different than zero and the slope was not significantly different than one at 95% confidence interval. This indicates that the mass balance method does an adequate job of predicting monitored changes in soil phosphorus. The cumulative data model fit was slightly better (R^2 = 0.90) than the annual change methodology (R^2 = 0.73); this conceptually makes sense as the cumulative analysis is able to utilize a larger range of data and the impact of the sampling errors would tend to be minimized by comparing to the larger change in soil phosphorus concentration.



(a) (b)

Figure 2. Comparison of soil phosphorus accumulation predicted using the mass balance approach and the phosphorus accumulation monitored shown on (a) annual basis and (b) cumulative basis.

Deep Soil Sampling

The final part of this investigation focused on if phosphorus was migrating vertically through the soil profile. This was done by collecting deep soil samples and analyzing them for increases in Melich-3 phosphorus concentration and was supplemented by an analysis of phosphorus leaching potential. Results of the deep soil samples are illustrated graphically for four sites (Central Iowa 1, Northwest Iowa 1, Northwest Iowa 2, and Southwest Iowa 1) in figure 3. The analysis shows the average phosphorus concentration as a function of depth in the soil profile. This allows a view of the concentration front, which can be examined for both increases in concentration and for movement vertically in the soil profile. All the sites showed similar trends, increasing phosphorus concentrations near the soil surface, which is in agreement with the surface soil sampling results, and that the phosphorus front is slowly migrating vertically through the soil profile. The movement of the phosphorus front appears to become more pronounced in the fourth year of system operation. This would seem to support the hypothesis of Baker et al. (2010) that the soil will reach its phosphorus saturation limit and then migrate vertically through the soil, i.e., that several years are required to saturate the surface profile with phosphorus and that once saturated phosphorus will be leached to lower soil horizons where sorption sites are still available. In most cases phosphorus at lower depths, i.e., greater than 0.3 meters, appears to not yet have been affected by phosphorus applications. The migration of the saturation front appears to have not yet occurred at Southwest Iowa 1. This was the last system to come into operation; thus it is probable that sufficient amount of phosphorus has not been applied to saturate the soil profile.

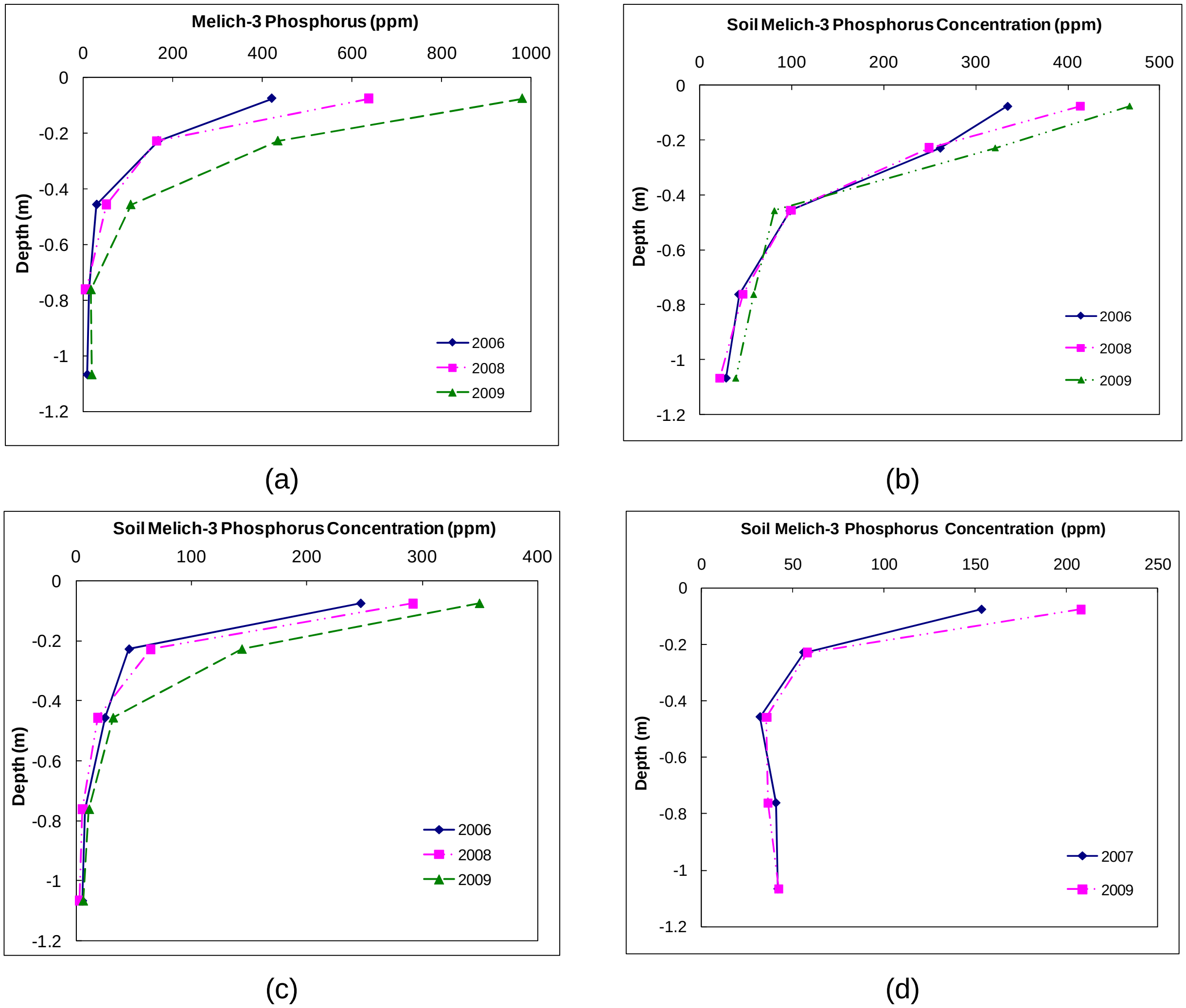


Figure 3. Melich-3 phosphorus concentration profiles from the surface to a depth of 1.2 m at (a) Central Iowa 1, (b) Northwest Iowa 1, (c) Northwest Iowa 2, and (d) Southwest Iowa 1.

As discussed previously in the surface soil sampling section the distribution of phosphorus along the vegetative treatment area is also important. In this case we were most interested if this saturation and vertical transport was only occurring near the inlets of the vegetative treatment areas or if it was also occurring near the outlet. An example of the typical pattern of phosphorus in the vegetative treatment areas is shown in figure 4 for the Central Iowa 1 vegetative treatment area in 2009. It is clear from figure 4 that most of the leaching and phosphorus accumulation occurs near the inlets of the vegetative treatment area. As discussed previously, this is expected for gravity flow vegetative treatment areas as the effluent loading isn't expected to be uniform. The inlet samples show high levels of phosphorus accumulation and are already showing signs of phosphorus leaching while the outlet samples show a much lower amount phosphorus accumulation. One other interesting feature of the figure is the degree to which phosphorus leaching has appeared to occur near the outlet of VTA 2. A small berm was built to prevent releases from the VTA; however, this berm causes ponding and saturated condtions to occur near this deep soil sampling point. It appears that these periods of saturaiton may be facilitating vertical phosphorus transport without first saturating the soil with phosphorus.

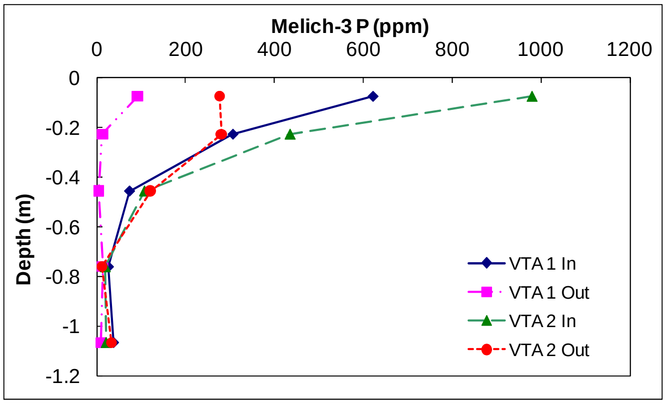


Figure 4. Comparison of Melich-3 phosphorus concentration profiles at vegetative treatment area inlets and outlets at Central Iowa 1 after four years of use.

The final area of phosphorus dynamics explored was the potential for leaching. Neither phosphorus concentrations in soil water leachate nor amount of water leaching was monitored. Thus several assumptions were required to formulate an estimate. The amount of water leached was estimated based on a water balance (shown as equation 4).

$$L = P + I - R - ET \quad (4)$$

In this equation L is the amount of water leached (m^3/ha), P and I represent inflows of water from precipitation and effluent application respectively (m^3/ha), and R is the amount of runoff from the vegetative treatment area (m^3/ha). Measurement of these three parameters was discussed in the materials and methods section. Evapotranspiration (ET) was estimated using potential evapotranspiration measurements available from the nearest weather station available on the ISU Agronomy Mesonet site. Change in soil moisture was not included in the estimate because moisture changes would be negligible on a yearly water balance. Using this approach the amount of water leached annually ranged from -2300 m^3/ha to 5300 m^3/ha. Setting all years with negative leaching volumes to 0 m^3/ha, since after leaching the phosphorus would interact with the soil preventing it from also migrating upwards with the evaporating water, resulted in average leaching volumes of 955, 2467, 2133, 2582, 1302, and 114 m^3/ha for CN IA 1, CN IA 2, NW IA 1, NW IA 2, SW IA 1, and SW IA 2 respectively.

Phosphorus concentrations in the leachate were not available, so they were estimated to be equal to the equilibrium phosphorus concentrations determined by Andersen et al. (2011b) based on phosphorus sorption curves after five years of use as vegetative treatment areas. They found phosphorus concentrations of 1.25, 0.00, 3.82, 2.93, 0.61, and 2.15 mg P/L for CN IA 1, CN IA 2, NW IA 1, NW IA 2, SW IA 1, and SW IA 2 respectively. Assuming these concentrations are representative of drainage water from the VTA suggests that between 0 and 8 kg P/ha-yr could have potential been leached and accumulated deeper within the soil profile as observed in figure 3. Based on this analysis it appears that these systems are still retaining the majority of its phosphorus inputs in the surface soil; however, large precipitation and application events that move the effluent through the soil profile without allowing sufficient reaction time for the soil to sorb and remove phosphorus may result in greater amounts of phosphorus leaching.

Conclusion

The objective of this work was to perform a preliminary phosphorus balance on six vegetative treatment systems on open beef feedlots in Iowa. The monitoring results indicated that while canarygrass and bromegrass yields were substantial and capable of removing up to 60 kg P/ha it only accounted for 6-13% of the total phosphorus retained in the vegetative treatment area.

This indicates that the soil plays the key role in phosphorus retention and treatment within these systems. Previous research has shown that high rates of phosphorus application can result in accumulation and eventually vertical transport of the phosphorus through the soil profile. This was confirmed in this study which showed a significant increases in Melich-3 extractable phosphorus concentration in the top 30 cm of the VTA soil profile, with increases often occurring rapidly, i.e., within one to two years of system operation. The monitored increases in soil phosphorus were strongly correlated with the mass of phosphorus applied to the VTA which. Moreover, soil cores collected to a depth of 122 cm indicated that after four years vertical transport of phosphorus was detectable. This indicates that a sound design should consider a phosphorus balance prior to construction to minimize the rate at which phosphorus will accumulate within the soil and to minimize vertical transport through the soil profile. Unfortunately, specific sizing suggestions are beyond the scope of this manuscript as an economic analysis that evaluate the construction and operating costs and benefits associated with variously sized systems and includes their design life is required; however, this work shows that a phosphorus balance provides a reasonable approach to determining the design life.

Based on this analysis we provide the following suggestions for both operating and managing successful vegetative treatment systems.

- Settling basin effluent should be captured and held until after a storm event. Allowing a day or two to pass until distribution to the VTA improves performance and reduces phosphorus loading to the vegetative treatment area. This can be achieved with a valve on the settling basin outlet(s). Other pretreatments that have the potential to remove phosphorus prior to application should be considered.
- Good vegetation is critical to success; this vegetation not only slows the flow and improves structure and infiltration, but its harvest provides the only acceptable method of phosphorus removal. Canarygrass appears to have greater potential for phosphorus uptake than other grasses and should be used within the VTA if possible.
- VTA designs should consider using multiple channels and allow the producer to determine which channels are receiving effluent. This would allow the producer to utilize the treatment system while preparing and harvesting one of the channels.
- Producers must be vigilant in watching for signs of flow channelization and maintaining uniform sheet-flow over the vegetative treatment area. Gullies and rills must be repaired by filling and reseeding the areas. This will improve hydraulic and phosphorus distribution over the VTA area.
- Soils provide the majority of phosphorus retention in the system. Selecting sites with an ability to sorb and fix large amounts of phosphorus is key to extending the life of the system.
- Methods that improve effluent distribution down the length of the VTA should be considered. Options include both sprinkler systems and surging effluent on the VTA to distribute effluent more evenly over the length of the treatment area.

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